Geotechnical Characterization, Field Measurement, and Laboratory Testing of **Municipal Solid Waste**

Proceedings of the 2008
International Symposium
on Waste Mechanics

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Edited by
Dimitrios Zekkos, Ph.D., P.E.

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GEOTECHNICAL CHARACTERIZATION, FIELD MEASUREMENT, AND LABORATORY TESTING OF MUNICIPAL SOLID WASTE

PROCEEDINGS OF THE 2008 INTERNATIONAL SYMPOSIUM
ON WASTE MECHANICS

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New Orleans, Louisiana

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ABOUT THE WASTE MECHANICS SYMPOSIUM

In March 2008, an International Symposium on Waste Mechanics was held in New Orleans. The Symposium provided a unique opportunity for researchers and engineers practicing in the field of waste mechanics to present recent research findings and case histories, as well as interact and exchange ideas. The Symposium's objectives were the following:

1. Develop consensus on procedures and guidelines for waste characterization, field testing, and laboratory testing of Municipal Solid Waste;
2. Summarize the state of knowledge on waste properties for use in research and engineering practice; and
3. Identify research needs in waste mechanics.

The Symposium included the following activities:

- Three paper presentation sessions that were part of the main program of the Geo-Institute Geoenvironmental Congress on Tuesday and Wednesday March 11-12, 2008;
- An international panel discussion on research needs that was held on Wednesday March 12, 2008 also as part of the Conference's main program; and
- A one-day workshop with break-out sessions that was held on Thursday March 13, 2008.

Paper Presentation Sessions
The three sessions included presentation of 16 papers that were reviewed by two or three reviewers. These papers can be found in the Geocongress 2008 volume on "Geotechnics of Waste Management and Remediation" (GSP No. 177). A list of the papers that were presented in the sessions as part of the Symposium is provided below:

Session I: "Waste shear response and stability"

- Towhata, I., Uno, M., "*Laboratory Tests on Creep and Shear Behavior of Municipal Solid Waste and Mitigation of Its Long-Term Subsidence*".
- Reddy, K. R., Gangathulasi, J., Hettiarachchi, H., Bogner, J., "*Geotechnical Properties of Municipal Solid Waste Subjected to Leachate Recirculation*".
- Zekkos, D., Bray, J. D., Stokoe, K., Kavazanjian, E., Rathje, E., Athanasopoulos, G. A., Riemer, M., Matasovic, N., Lee, J. J., Seos, B., "*Recent findings on the static and dynamic properties of Municipal Solid Waste*".
- Athanasopoulos, G., Grizi, A., Zekkos, D., Founta, P., Zisimatou, E., "*Municipal Solid Waste as a Reinforced Soil: Investigation Using Synthetic Waste*".
- Chen, Y., Zhan, T.L.T., Ling, W., "*Mechanical properties of municipal solid waste from Suzhou landfill in China*".

Session II: "Waste Compressibility, degradation and time effects"

- McDougall, J., "*Geomechanics and Long-term Landfill Settlement*".
- Singh, M.K., Fleming, I.R., "*Estimation of the mechanical properties of MSW during degradation in a laboratory compression cell*".
- Castelli, F., Maugeri, M., "*Experimental analysis of waste compressibility*".

- Hossain, M.D.H, Gabr, M. A., Haque, M.A., "*Deformation of MSW Bioreactor Landfills: Properties and Analysis Approach*"
- Kavazanjian, E., "*The impact of degradation on MSW shear strength*".

Session III: "Waste characterization and hydraulic properties"

- Powrie, W., Beaven, R., Hudson, A., "*The influence of landfill gas on the hydraulic conductivity of waste*".
- Borgatto, A.V.A., Izzo, R.L.S., Mahler, C. F., "*Application of a Morphologic Classification of Brazilian MSW*".
- Zhan, T.L.T., Ling, D., Zhang, W., Chen, Y. "*Hydrogeological characterization of Suzhou landfill of municipal solid wastes*".
- Dixon, N., Langer, U., "*Relationship Between Classification and Shear Behavior of MSW*".
- Izzo, R.L., Mahler, C.F., Munnich, K., Bauer, J., "*MBT Waste Used as a Capillary Barrier in a Sanitary Landfill*".
- Stoltz, G., Gourc, J.P., "*Variation of fluid conductivity with settlement of domestic waste*".

Panel Discussion

An international panel discussion on research needs in waste mechanics was also held. Panel members from different countries were invited to submit an opinion paper prior to the conference and made a 5-minute presentation on research needs. A discussion among participants followed. The opinion papers are included in this volume.

One-day workshop

A one-day workshop was held and included plenary and break-out sessions. Morning plenary and breakout sessions focused on procedures and guidelines for waste characterization, laboratory testing and field measurements. Afternoon plenary and breakout sessions focused on a review of the state of understanding on waste properties with emphasis on shear strength, settlement behavior, hydraulic properties and dynamic properties of Municipal Solid Waste.

Organization and Participants

The Symposium was organized by:

- Jonathan Bray, Professor, University of California at Berkeley
- Susan Burns, Associate Professor, Georgia Institute of Technology
- Jeff Dunn, PhD, Kleinfelder
- Edward Kavazanjian, Professor, Arizona State University
- Ellen Rathje, Professor, University of Texas at Austin
- Dimitrios Zekkos, PhD, (Chair), Assistant Professor, University of Michigan at Ann Arbor

Attendance to the paper presentation sessions and the panel discussions was generally unrestricted, whereas participation to the one-day workshop required pre-registration at no cost to the participant. A total of 31 researchers and practicing engineers from 9 countries participated in the Symposium. The names of the participants (alphabetically) and their affiliation is listed below.

Name	*Affiliation*
Mohamed Arab	Arizona State University, Arizona, USA
George Athanasopoulos	University of Patras, Greece
Adda Athanasopoulos-Zekkos	University of Michigan at Ann Arbor, USA
Christopher Bareither	Univ. of Wisconsin-Madison, Wisconsin, USA
Richard Beaven	University of Southampton, UK
Jonathan Bray	Univ. of California at Berkeley, California, USA
Susan Burns	Georgia Institute of Technology, Georgia, USA
Young Min Cho	University of Florida, Florida, USA
Neil Dixon	Loughborough University, UK
Jeff Dunn	Kleinfelder, California, USA
Rami El-Sherbiny	Cairo University, Cairo, Egypt
Jeffrey B. Fassett	Golder Associates, Texas, USA
Ian Fleming	University of Saskatchewan, Canada
Patrick Fox	Ohio State University, Ohio, USA
Jean-Pierre Gourc	Grenoble University, France
Beth Gross	Geosyntec Consultants, Texas, USA
Edward Kavazanjian	Arizona State University, USA
Milind Khire	Michigan State University, Michigan, USA
Claudio Mahler	Federal University of Rio de Janeiro, Brazil
Mario Manassero	Politecnico di Torino, Italy
Neven Matasovic	Geosyntec Consultants, California, USA
Michelle Maugeri	University of Catania, Italy
John McDougall	Napier University, UK
Scott Merry	Kleinfelder, Arizona, USA
Marina Pantazidou	National Technical University of Athens, Greece
Krishna Reddy	University of Illinois - Chicago, Illinois, USA
Janardhanan Ganga Thulasi	University of Illinois - Chicago, Illinois, USA
James Tinjum	CH2M Hill, Pennsylvania, USA
Ikuo Towhata	University of Tokyo, Japan
Dimitrios Zekkos	University of Michigan at Ann Arbor, USA

The Symposium was held under the auspices of the ASCE Geoinstitute Geoenvironmental Engineering Technical Committee, and was funded by the ASCE Geo-Institute, Kleinfelder Inc, and Geoengineer.org. The Symposium's website is available online by Geoengineer.org at the following address: http://wastesymposium.geoengineer.org. The Symposium's website includes additional information on the symposium as well as Powerpoint slides from the 1-day workshop

ABOUT THIS VOLUME

The field of waste mechanics has advanced significantly since the early admirable attempts in the 1980s and early 1990s with many of the scientific contributions in the field made by practicing engineers who needed to address the serious issues associated with solid waste disposal. Many of these issues, such as containment, stability, settlement, gas generation and leachate management, are common worldwide. Subsequent research efforts focused on providing a scientific understanding of the complexities of waste behavior. From a geotechnical perspective, municipal solid waste is a very interesting and challenging material. It is heterogeneous in nature consisting of distinctly different organic and inorganic constituents that vary significantly with depth as well as laterally, and has compressibility that is comparable to peaty soils. It is also highly anisotropic and many of its constituents contribute a fibrous reinforcement that only now we begin to understand. It is also degradable and in that process generates gas that impacts its hydraulic and mechanical behavior. This volume attempts to integrate our understanding of the MSW and provide guidance to researchers and practicing engineers who confront issues related to waste behavior.

The three paper presentation sessions and the panel discussion of the international waste mechanics symposium provided an excellent opportunity for interaction and exchange of ideas among researchers and practitioners in the field of waste mechanics worldwide. The one-day workshop attempted to review and integrate the state of the art and practice in the field of waste mechanics as well as reach some consensus among waste mechanics experts on some of the aspects of laboratory testing, field measurements and characterization of MSW.

This volume consists of three parts:

In part 1, a review of the state of the art in some of the most critical properties of Municipal Solid Waste is provided: Chapter 1 focuses on the saturated and unsaturated hydraulic properties of MSW; Chapter 2 summarizes the stress-strain response and shear strength of MSW; Chapter 3 addresses our understanding of the settlement behavior and compressibility of MSW landfills and; Chapter 4 summarizes the dynamic properties of MSW. It is important to note that although, extensive references are made to numerous previous studies, an exhaustive review of the available literature was not the objective and was not attempted in all cases. However, the literature is reviewed critically and the reader will benefit from the extensive treatment of each topic.

In part 2, an attempt to reach some consensus or provide some minimum requirements or recommended procedures for waste characterization (Chapter 5), field measurements (Chapter 6) and laboratory testing (Chapter 7) is made. A review of the available literature is also presented, but the objective is not the comprehensive review of the subject. The chapters are intended to be a first step forward in providing some systematic guidance on the characterization and testing of MSW.

The chapters presented in part 2 essentially mirror the themes of the break-out sessions of the one-day workshop. Leaders of each break-out session had been identified prior to the symposium. Each leader prepared a set of slides that were used during the break-out session by the participants as a basis for discussion. In many cases amendments were made by the participants. After the workshop, the leaders prepared each chapter and asked the members of the break-out session to review it and provide feedback. In certain cases, depending on the participants' feedback, participants were included as co-authors of the chapter. Because significant effort was expended in preparation for the symposium discussions, most of the chapter content is limited to contributions published up to 2008, although in some cases, some more recent contributions have been included too.

Part 3 includes five opinion papers submitted by the invited panelists of the panel session titled "International perspectives on Research Needs". The five papers are authored by participants from the United Kingdom, Brazil, Canada, Japan and the United States. All papers were submitted prior to the panel discussion and are included in this volume to stimulate the interest of researchers.

This volume includes the results of a systematic effort to integrate our understanding of waste behavior and provide some guidance to researchers and practitioners in the field of waste mechanics. The authors of these chapters deserve to be complemented for the significant level of effort that they expended to make this volume a reality. I would also like to thank the Past and Present Chairs of the Geoenvironmental Engineering Technical Committee, Prof. Susan Burns from Georgia Tech and Prof. Krishna Reddy from the University of Illinois, Chicago, respectively, as well as the members of the Geoenvironmental Technical Committee for their support to the symposium and this volume. I would also like to thank, Anna Kathleen James, undergraduate student in the Department of Civil and Environmental Engineering of the University of Michigan, for her valuable assistance in the final states of the preparation of this volume.

In reviewing this volume and its content, one realizes that, indeed, a lot of progress has been made, but there is still much to be learned. An improved understanding of waste mechanics will allow our Profession to make a valuable contribution to society by improving our waste disposal practices nationally and worldwide.

Dimitrios Zekkos
Editor
Assistant Professor
Dept. of Civil and Environmental Engineering
University of Michigan
Ann Arbor
July 2010

Contents

Part I: Review of the State of Knowledge

Part II: Recommended Procedures and Guidelines

Part III: International Perspectives on Research Needs

Indexes

Chapter 1

Hydraulic properties of MSW

Richard P Beaven[1], FGS; William Powrie[2], FICE and Kiriaki Zardava[3]

[1]Principal Research Fellow; Waste Management Research Group, School of Civil Engineering and the Environment, Highfield, University of Southampton, Southampton UK. S017 1BJ
[2]Professor of Geotechnics; Waste Management Research Group, School of Civil Engineering and the Environment, Highfield, University of Southampton, Southampton UK. S017 1BJ
[3]Researcher; Waste Management Research Group, School of Civil Engineering and the Environment, Highfield, University of Southampton, Southampton UK. S017 1BJ

1.1 INTRODUCTION

The distribution and movement of water within a waste landfill are important for two main reasons. First, water represents a major potential pathway for pollution of the surrounding environment. As liquid passes through the waste to emerge as leachate, it dissolves or carries in suspension substances that could cause contamination through interaction with the natural groundwater. Artificial and natural barriers help to prevent this, but it is usually also necessary to control leachate pressures (levels) – usually by pumping from wells or drainage blankets – so as to minimise head differences acting on a sealing layer or a natural barrier boundary. Leachate movement through the waste mass in response to pumping is controlled by the hydraulic conductivity or permeability of the waste. The distribution of permeability within the waste, which will vary as a result of anisotropy, heterogeneity, partial saturation and changes in waste density or effective stress, is also of vital importance. The total and drainable porosity of waste will control the rate of build up of leachate levels in response to infiltration or other water inputs, and the rate of decline when dewatering a site. It is also necessary to understand and control the impact of pore pressures on mechanical stability.

Secondly, water and water flow are essential to achieving landfill completion, i.e. bringing it to a stable, non-polluting state in a controlled way. Municipal solid wastes (MSW) have for the past 50 years contained a high proportion of biodegradable components: water is essential to the biochemical decomposition of organic substances (Pohland 1975; Leckie and Pacey 1979; Klink and Ham 1982). Water flow is also needed for the leaching out of soluble compounds, even in an inert or organically stabilised waste.

The important role of water in a landfill is further illustrated by the current move towards operating landfills as bioreactors in the USA and elsewhere around the world. Water contents are increased and leachate flows are controlled so as to accelerate the degradation and biological stabilisation of organic matter, releasing increased quantities of commercially exploitable landfill gas (Tchobanoglous *et al,* 1977; Leckie *et al,* 1979). The most common approach is the introduction of liquid and recirculation of leachate to increase the water content of waste and move nutrients and bacteria around the landfill. As it is important to access the whole of the mass of waste, heterogeneity and anisotropy of permeability and the scale of anomalies become particularly important.

The flow and distribution of water in landfills is complicated because:

- waste is a heterogeneous material (on a variety of scales);
- there is a wide variety of particle and pore size and shapes, and solid material types;
- waste and landfill anisotropy (e.g. layers of daily cover) lead to conditions that can be difficult to predict or interpret, for example perched leachate levels;
- the hydraulic properties of waste will vary with stress (depth) and potentially over time (through compaction and degradation);
- the presence of landfill gas within the waste will interact with and affect water flow; and
- both saturated and unsaturated flow occur.

Some of these complexities are found in other hydrogeological systems, while others are unique to landfills. The combination of all these processes in one system makes understanding, quantifying and predicting liquid flow in waste landfills a difficult and challenging subject area. Nonetheless, it is one that landfill operators need to understand, especially as landfills become more actively managed to prevent pollution and accelerate stabilisation. The aim of this chapter is to review current knowledge of the parameters influencing the movement of liquid through waste landfills, viz. (1) the total and drainable porosity, which control rates of wetting and drainage during transient (i.e., non steady-state) flow, and the storage capacity of the waste; and (2) the hydraulic conductivity (permeability) – which controls advective flow according to Darcy's Law. Both saturated and unsaturated conditions are considered.

The modelling of infiltration and moisture movement within a porous medium requires information on the moisture retention and hydraulic conductivity properties. In landfilled waste, the particle and pore size distribution, heterogeneity of waste composition and leachate chemistry complicate the determination of moisture retention and hydraulic properties.

Predicting the moisture distribution, leachate generation and flow in landfilled waste using unsaturated flow theory is dependent both on the validity of the flow theory and on the hydraulic properties of the landfilled waste. Unsaturated flow has been extensively researched in the fields of soil physics, hydrology, and geotechnical engineering. Although the unsaturated hydraulic properties of conventional soils have been investigated extensively, there is very limited evaluation of landfilled waste (Korfiatis et al. 1984; McDougall et al. 1996).

This chapter does not deal with the topic of contaminant transport in waste materials.

1.2 CHARACTERISATION OF THREE-PHASE SYSTEMS

1.2.1 Definition of Terms and Phase Relations

Landfilled waste is a porous medium with particulate solid material and pore space distributed throughout the volume. The pore space may be filled with liquid and/or gas. The porous medium most closely comparable to solid waste landfills in terms of structure, porosity and gas content is often considered to be unsaturated soil (McDougall et al. 2004). However, a waste is rather more complicated not least because of the potential for biological and chemical actions and interactions, and the fact that the solid phase comprises a wide range of different material types with vastly different mechanical and physical properties.

A porous medium is conventionally idealised as a solid permeated by an interconnected network of pores filled with a fluid (liquid and/or gas), as indicated in Figure 1. The state of the porous medium is conventionally defined by the relationships between the phases (solid, liquid and gas), either by mass or by volume. Unfortunately, the same term is sometimes used (usually in different branches of science) to mean different things. An example of this is the water content, which may be defined by mass or by volume, and expressed as the ratio of the mass/volume of water to that of the whole or of the solids alone. Definitions of the phase relations most commonly used, and where appropriate the relationships between them, are summarised in Table 1. These originate mainly in the soil mechanics or soil science literature. An additional refinement that is useful for wastes, but not normally needed with soils, is the distinction between retained and drainable water. In a waste, water may be retained through sorption into certain types of materials (e.g. paper, card and textiles), or by being trapped in a closed-ended container such as a bottle or a can. The phase relationships in Table 1 are derived from the basic masses and volumes of each element defined in Figure 2, with the volume of liquid V_w split into drainable (V_{w-d}) and retained (V_{w-r}) components. ρ_w is the density of water, ρ_g is the density of gas, and ρ_s is the density of the solid particles. The ratio ρ_s/ρ_w is the particle relative density, G_s. In wastes, ρ_s may vary considerably (for example, from 0.6 Mg/m^3 for dry wood to 7.8 Mg/m^3 for steel), and the choice of an appropriate particle density is both a challenge and a potential source of error.

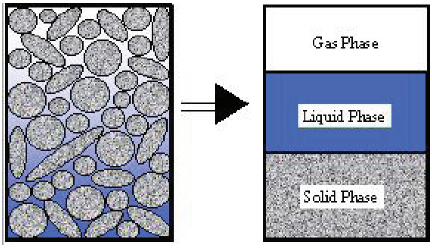

FIG. 1. Three-phase porous medium.

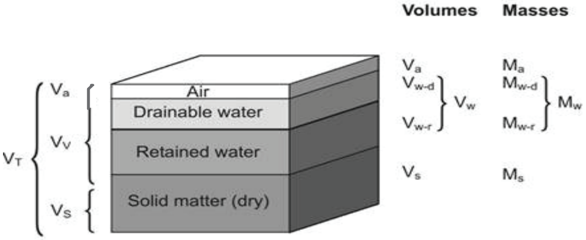

FIG. 2. Volume/mass relationships.

Table 1. Basic definitions and phase relations for porous media.

Parameter and symbol	**Definition**	**Equation and inter-relationships**
void ratio, e	volume of voids/volume of solids	$e = V_v/V_s$
porosity, n	volume of voids/total volume	$n = V_v/V_t = e/(1+e)$
specific volume, v	total volume/volume of solids	$v = V_t/V_s = (1+e) = 1/(1-n)$
drainable or effective porosity, n_e	volume of drainable water/total volume	$n_e = V_{w-d}/V_t$
gravimetric water content, w	mass of water/mass of solids	$w = M_W/M_S$
volumetric water content, θ	volume of water/total volume	$\theta = V_w/V_t = w.Gs/(1+e)$
Degree of saturation S	volume of water/volume of voids	$S = V_w/V_v = w.G_s/e$
Gas content, G	volume of gas/volume of voids	$G = V_g/V_v = 1-S$
Bulk density, ρ_{bulk}	total mass/total volume	$\rho_{bulk} = G_S.\ \rho_W.(1+w)/v$ $= (G_s+e).\ \rho_w/v$
Dry density, ρ_{dry}	the bulk density a waste would have at the same void ratio but dry (w = 0)	$\rho_{dry} = G_S.w/v$

The different definitions of water content (mass of water ÷ mass of dry solids; mass of water ÷ total (wet) mass; and volume of water ÷ total volume) commonly used in waste science can cause confusion, especially as not all authors make it clear which one they are using. The inter-relationship between the gravimetric and volumetric water contents was noted by Franzius (1979) and elaborated on by Beaven (2000). Indicative variations in gravimetric water content by dry mass, bulk (wet) density, and gravimetric water content by dry mass for a waste whose volumetric water content remains constant at 40% while its dry density changes are shown in Figure 3.

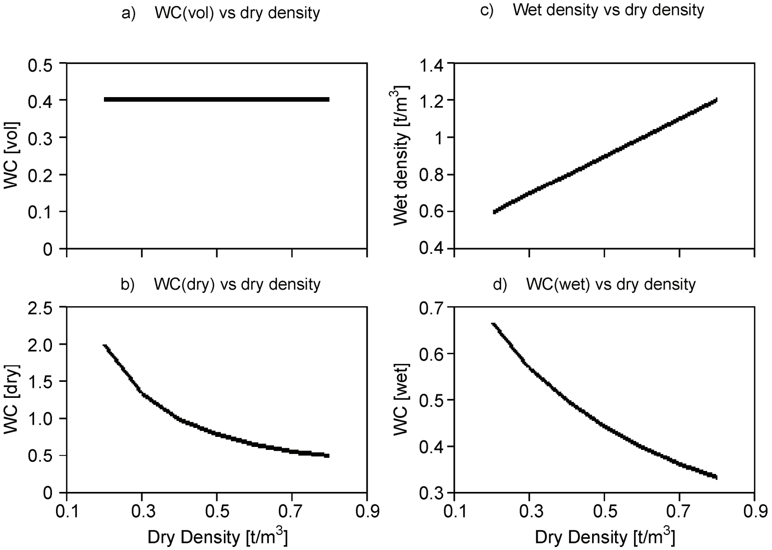

FIG. 3. Illustrative relationships between density and water content (Beaven 2000).

The gravimetric water content by dry mass is arguably the most suitable measure: the problem with both of the other measures (gravimetric by wet mass and volumetric) is that the mass or volume of the water features in both the numerator and the denominator of the expression. Nonetheless, these other measures are often used for convenience as they occur naturally in certain mathematical analyses and derivations.

A further complication with waste is that the void ratio will in general change as degradation occurs. This may be quantified by the parameter Λ (McDougall and Pyrah 2004 and McDougall 2007) defined as the ratio dV_v/dV_s where dV_v is the change in void volume that occurs when the volume of solids changes by an amount dV_s. If $\Lambda = 0$, the volume of voids does not change and the change in total volume is equal to the change in the volume of solids. If $\Lambda = -1$, the volume of voids increases by the same amount as the volume of solids lost and degradation takes place at constant total volume (leading to a more open structure and the potential for sudden collapse). If Λ = e (the void ratio), then the void ratio does not change as a consequence of degradation, and if Λ> e then the change in void volume exceeds the loss of solids, leading to densification and possible increase in strength.

1.2.2 Distribution of Gas and Liquid

The way in which gas and liquid are distributed within waste, and the flow regimes of each, will depend primarily on the water content and degree of saturation. Single phase flow of liquid (if the porous medium is saturated: Figure 4a) is the most straightforward condition to analyse, but as will be discussed later is still quite complex. If gas bubbles are small and uniformly distributed throughout the liquid, and do not move independently of it, flow might still reasonably be treated as single phase with a permeant fluid of reduced density. As a porous medium is drained or further gas generated, water is replaced or displaced by gas in the largest pores first. Initially the gas bubbles may be immobile (Figure 4b), but are able to move through the liquid in response to internal or external pressure differences (Figure 4c). As the degree of saturation decreases further, the bubbles expand and join together until a continuous gas phase is formed. At this point, liquid and gas may flow continuously and independently through the waste.

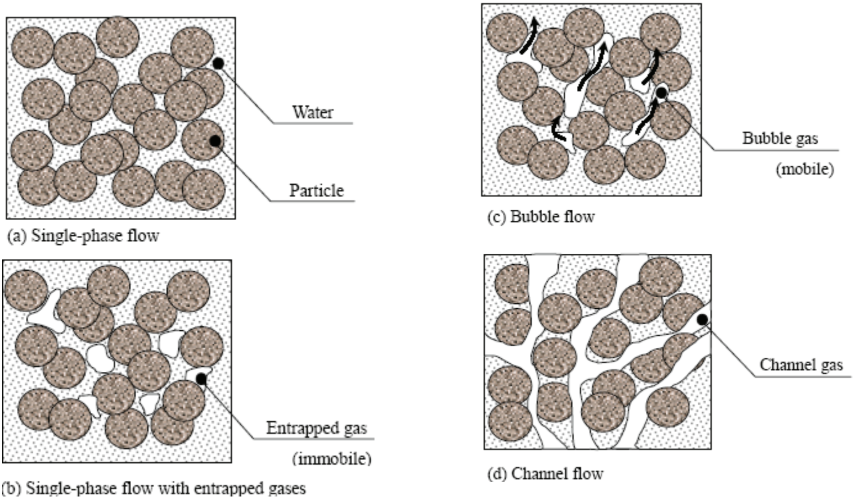

FIG. 4. Schematic illustrations of fluids flow in porous media.

Saturated flow (Figure 4a), especially with respect to saturated hydraulic conductivity is discussed in section 1.4, and classical unsaturated flow (Figure 4d) in section 1.5.

The transition between Figure 4b and Figure 4c in waste is not yet fully understood, but the impact of increasing gas within a predominantly saturated waste is addressed in sections 1.3.4 and 1.4.5.

The transition from bubble (Figure 4c) to channel (Figure 4d) flow in a porous medium is governed by the ratio of buoyancy forces driving upward flow to surface tension (capillary) forces arising from the contact between the gas/liquid interface and the solid grains that tend to retard bubble flow, and is quantified by the Bond number, Bo: (Brooks et al 1999):

$$Bo = \frac{(\rho_w - \rho_g) * g r_p^2}{\gamma} \tag{1}$$

where ρ_w and ρ_g are the liquid and gas densities, r_p is a characteristic pore dimension (length) and γ is the surface tension of the interface. When Bo>1, buoyancy forces dominate indicating bubble flow. When Bo<1, capillary forces dominate indicating channel flow.

1.3 MEASUREMENTS OF PHASE-RELATED PARAMETERS IN WASTES

1.3.1 Water Content

The water content of a typical MSW may include both water held in macro or freely draining pores and water "absorbed" into micro-pores within individual waste components such as paper, cardboard, textiles, food etc. In general, the water content of MSW within a landfill will vary between its initial water content on collection and a water content representing fully saturated conditions. However, there may also be circumstances when the water content of a waste will reduce on landfilling (e.g. through compaction, water consumed in anaerobic reactions, capillary drying etc).

Tchobangolous et al. (1993) reported water contents of fresh MSW in the USA on collection varying generally between 15 - 40 % on a wet weight basis (i.e. mass of water ÷ total mass). Obviously this will depend on local climatic conditions at the time of collection and on waste composition: MSW with high contents of food waste or organic matter (typically occurring in a significant number of East Asian countries – e.g He et al. 2007) will also have high water contents (up to ~74 % w/w).

1.3.1.1 Field measurements of water content

Most studies of the *in situ* water content of MSW in landfills have been based on gravimetric determinations from recovered core samples (e.g. Blight et al. 1992; Zornberg et al. 1999; Yuen et al. 2001; Yazdani et al. 2006; Skhiri et al. 2006; Haydar et al. 2008; Kumar et al. 2009 and USEPA 2006). Imhoff et al. (2007) reviewed alternative non-invasive monitoring techniques, including neutron probes, which can track changes in moisture conditions but cannot accurately measure the volumetric water content; electrical resistivity and TDR sensors, which tend to produce rapid but somewhat biased results; and a Partitioning Gas Tracer Test which appears to be able to produce reasonable results correlated against gravimetric determinations. Fiber optic sensors and electrical resistivity tomography also appear to have promise, but need further refinement.

A common feature of many gravimetric measurements of core samples taken from landfills is the very wide scatter in results obtained. One clear example of this is the data obtained from the Outer Loop landfill where almost 300 core samples have been taken over a 5 year period in 4 discrete monitoring events. (Haydar et al. 2008 and USEPA 2006). Figure 5 shows the very wide range in values obtained.

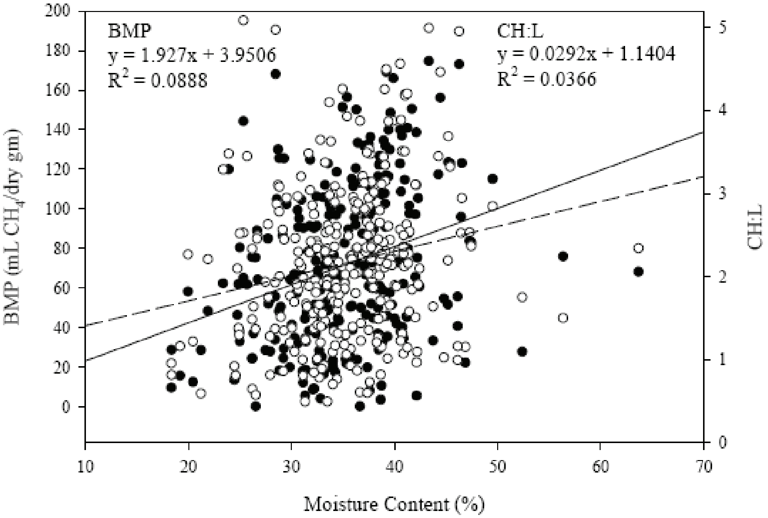

FIG. 5. Moisture Content in Outer Loop control cell (reproduced from USEPA 2006)

In another very detailed study, Zornberg et al. (1999) measured the water contents of eighty samples of waste recovered from depths of up to 65 metres from a landfill in Southern California. The average gravimetric water content was 28% (with a standard deviation of about 10%) and there was a small increase in water content (from 25 % near the surface to ~30%) with depth. The estimated unit weight of the landfill varied between 12 and 14 kN/m^3, with a slight increase in the average with depth. Expressed volumetrically, the water contents demonstrated a larger increase from approximately 20% near the top of the landfill to 30% at depth (again with a standard deviation of about 10%).

It is possible to detect trends in changes in water content over time if sufficient samples are taken. For example, at the Yolo County bioreactor average water contents measured in 3 sets of core samples from a bioreactor cell (NE cell) increased from 18.4% to 40.8% over a 3 year period during which leachate recirculation had been practiced. Water balance calculations indicated that the increase should only have been to 29.3%: the difference was attributed to the limited number of samples collected, and the substantial spatial heterogeneity of landfilled MSW.

Skhiri et al. (2006) determined the water contents of MSW cores obtained by drilling at varying distances from a leachate injection well. At a distance of 5 metres after a one year period of leachate injection, the gravimetric water content by wet weight had increased from an initial value of 27% to 33-39 % at a depth of 6- 8 metres.

1.3.2 Total Porosity

The total porosity of a waste is defined as the ratio volume of voids ÷ total volume, and is the same as the saturated volumetric water content. The total porosity is generally determined by measuring the water content of a saturated waste, and is an important parameter for any water balance or contaminant transport model.

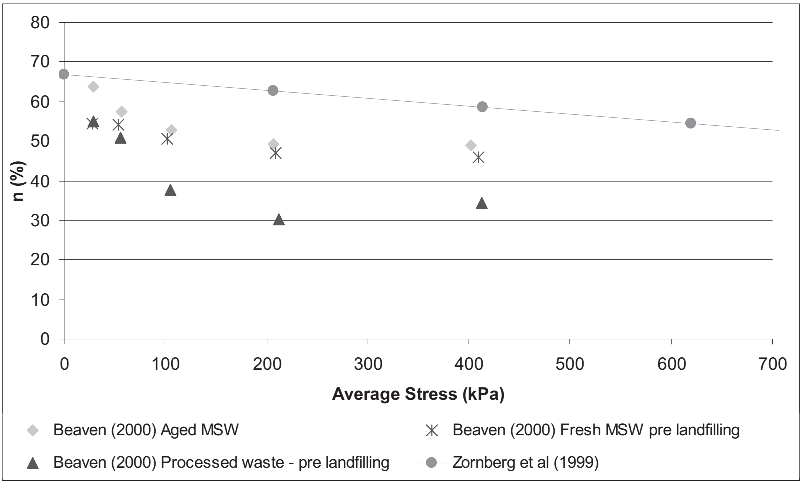

FIG. 6. Relationship between (total) porosity and stress.

Wastes tested by Beaven (2000) in a large (2 m diameter) compression cell exhibited a reduction in porosity with stress up to about 200 kPa, but little further reduction with increasing stress thereafter (Figure 6). For the two wastes most representative of MSW in landfills (a fresh MSW and an aged MSW excavated from a landfill), the total porosity levelled out at approximately 45% at stresses above 200 kPa. Zornberg *et al*

(1999) measured a linear reduction in total porosity with depth in tests on landfill waste recovered from drill cores carried out in a 450 mm diameter compression cell. Zeiss and Major (1993) determined total porosities of between 58% and 47% for waste compacted to densities between 0.17 tonne/m^3 and 0.3 tonne/m^3. It is not clear whether these densities are by wet or dry weight, but either way, they are rather small.

1.3.3 Drainable Porosity

If a fully saturated waste material is allowed to drain under gravity, its water content will decrease as drainable pores empty. It will eventually reach a state (termed the field capacity) when no further drainage occurs. The amount of freely draining water per unit volume of waste defines the drainable porosity. The drainable porosity is given by the difference between the saturated volumetric water content and the volumetric field capacity. The drainable porosity is the same as the specific yield, which is well established in the hydrogeology literature as the amount of liquid that will drain from a unit volume of soil following a unit reduction in the water table level. (The field capacity is discussed in a later section, but it is important to note that the field capacity will vary depending on the density of the waste, whether the material is being drained or wetted, and its elevation in a landfill relative to the line of zero gauge pore leachate pressure or leachate level: Vorster 2001). The drainable porosity may be determined directly under laboratory conditions, or in the field from pumping tests or a detailed water balance.

Knox (1992) estimated drainable porosities (specific yields) of 10-20% on the basis of water balance calculations for a number of leachate level fluctuation events at several different landfill sites. Oweis et al. (1990) carried out pumping tests on 30 m deep waste with a 10.7 m saturated zone. Analysis of the drawdown curves indicated a drainable porosity of 5%, although they considered that gravity drainage was far from complete and that a long term drainable porosity (specific yield) as high as 10% could reasonably be assumed. Beaven (1996) reported the results of a pumping test at a 9 m depth of refuse with a 5-6 m saturated zone, which gave a drainable porosity of 4%. A further pumping test was undertaken on the same refuse after landfilling had increased the depth of waste to 23 m and the thickness of the saturated zone to 6-7 m indicated an increase in drainable porosity to 7%.

Burrows et al. (1997) reported the results of over 50 pumping tests at four UK landfill sites. The majority of the tests were of relatively short duration (3-8 hours) and drawdown data from pumped wells only were analysed. However, there were several tests of longer duration (between 2 and 4 weeks) on single wells and multiple pumped and observation well sets. Drainable porosities in the range 9-16% were determined, mainly from tests where data from observation wells were available. Knox and Shaw (2006a, 2006b) investigated the hydraulic response of landfills to infiltration and dewatering events by installing vibrating wire piezometers in a basal drainage system of a 20 m deep landfill cell. By correlating the volume of leachate pumped and drawdowns in individual dewatering events, they estimated the drainable porosity of the lower part of the waste to be between 1.6 and 6.5 %.

Powrie and Beaven (1999) and Beaven (2000) reported measured reductions in drainable porosity with applied stress for three different waste types. A very rapid reduction in drainable porosity was demonstrated in response to increasing the applied stress and consequent waste compaction. Loosely compacted wastes, corresponding to average stresses less than 50 kPa, had drainable porosities in excess of 15%. At stresses in excess of 200 kPa, drainable porosities had fallen to ~ 2% or less.

Zornberg et al. (1999) presented data on changes in volumetric water content with depth in a landfill, from which a relationship between drainable porosity values and stress may be derived. Their analysis indicated a linear reduction in n_e with depth (and stress) from approximately 15% at the surface to less than 3% at a depth of 60 metres, which they equate to a stress of slightly over 800 kPa. This is not consistent with the trend of drainable porosity reducing with the logarithm of the applied stress reported by other researchers (Figure 7). Olivier and Gourc (2007) reported a drainable porosity determined in the laboratory of 2.4 – 3% for a reconstituted household waste that had been compressed to 120 kPa and allowed to degrade anaerobically for ~2 years: this is consistent with the data of Beaven and Powrie (1999) and Beaven (2000) (Figure 7).

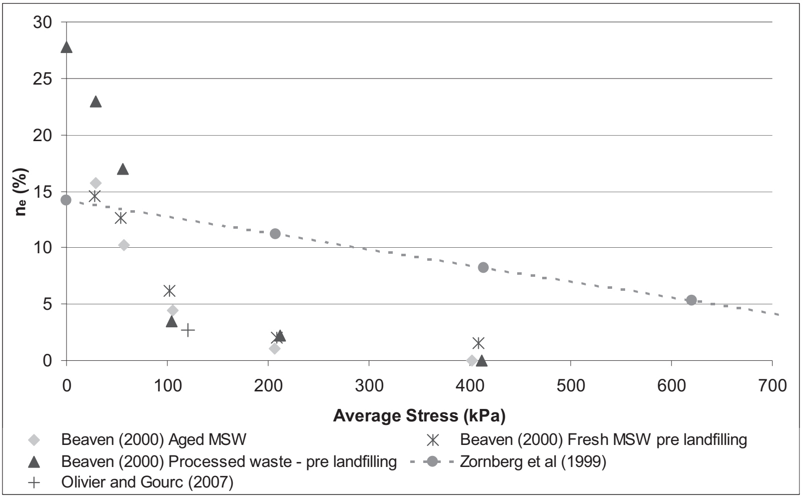

FIG. 7. Relationship between Drainable porosity and stress (Beaven 2000).

1.3.4 Effect of Landfill Gassing on Drainable Porosity

The generation of landfill gas below the leachate level (i.e., in the notionally saturated zone of the landfill), and its ability to vent (e.g. through open leachate monitoring wells) could both impact measured leachate heads. If discrete bubbles of gas, unconnected to the atmosphere, are present within the notionally saturated zone, the initial response to pumping from a leachate well and the consequent reduction in pore water pressure could be an increase in leachate levels as the gas expands and the density of the fluid (gas/liquid) mixture is reduced, and a reduction in the water content of the waste. Such short term increases in leachate levels were observed during pumping tests by Burrows et al. 1997. A reduction in the average water content has been detected in geophysical surveys of landfills in the vicinity of leachate pumping systems (e.g. Jolly et al. 2007; Rosqvist et al.2007).

Hudson *et al* (2001) investigated changes in the drainable porosity of MSW in response to gas generation within initially saturated waste in a compression cell. Figure 8 indicates how gassing significantly reduces the drainable porosity of waste, and how drainable porosity is also affected by pore water pressure (as a result of changes in gas volume). These data provide laboratory evidence for the field observations noted above.

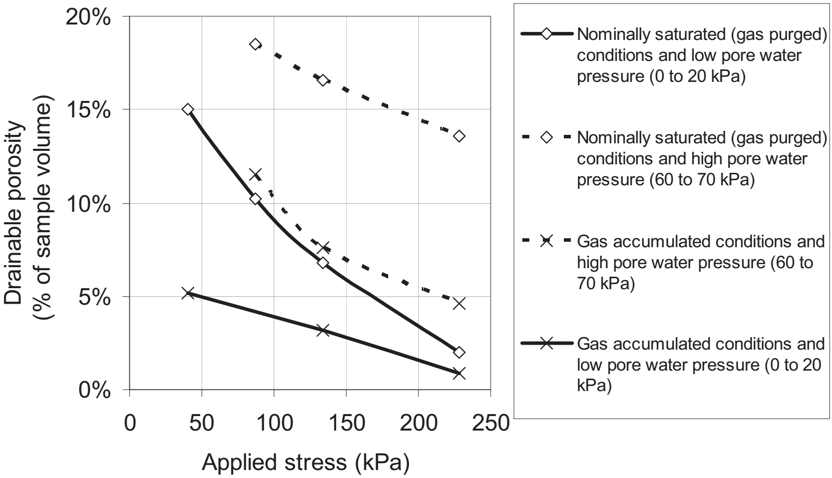

FIG. 8. Comparison of drainable porosities for sample DN1 according to stress and gas conditions / pore water pressure.

1.3.5 Field Capacity and Absorptive Capacity

A waste at field capacity is at the maximum water content it can sustain under conditions of free downward drainage under gravity: in hydrogeology or soil science, it is termed the specific retention, S_r. Field capacity is often used qualitatively, but can be quantified as a water content either volumetrically, or gravimetrically in terms of dry or wet mass.

Blight et al. (1992), El-Fadel et al. (1997) and Yuen (1999) indicated that field capacity is a function of the waste composition, density and porosity. It would also be expected to change with time as degradation of the waste alters its composition. The typical range of field capacity for MSW landfills reported in literature is between 0.20 and 0.40, expressed on a volumetric basis (Korfiatis et al. 1984; Zeiss and Major 1993; Yuen *et al.* 2001). In most laboratory determinations, waste samples were first saturated before being drained, and the field capacity taken as the residual volumetric water content of the sample. A slightly more rigorous definition of field capacity used in HELP (Schroeder et al. 1994), is the volumetric water content of the waste at a suction of 33 kPa. In practice, the term is often applied to an entire waste body (for example for water balance purposes) – in this case, it must be borne in mind that the field capacity will vary with depth within the landfill

It is pointed out by Vorster (2001) that, even for a given waste in a particular state, the field capacity is not absolute but will depend on the elevation in a landfill above the leachate level or line of zero pore pressure. This is because the suction in the waste will vary with elevation above the leachate level, and the water content will vary with suction. The water content at a given suction will also depend on whether the waste is being wetted or drying (see Section 1.3.6.1).

Generally, when MSW waste is placed in a landfill it will be at a water content less than the field capacity and consequently has the ability to absorb water before any free draining leachate is produced. Values for typical as placed water contents of waste were given in section 1.3.1. The potential increase in the water content of waste in a landfill on wetting to field capacity is referred to as the total absorptive capacity (e.g. Knox 1991). To reflect field experience, the total absorptive capacity of a waste is sometimes split into primary and secondary components. The primary absorptive capacity is the amount of water that can be added to refuse without the creation of any freely draining leachate. Secondary absorptive capacity is taken up more gradually, after leachate production has started, and is probably only fully utilised if the waste becomes completely saturated and is then subsequently drained. A similar type of behaviour was also noted by Korfiatis et al. (1984) and Major and Zeiss (1993). Korfiatis et al. observed that in small scale column experiments where channelling of flow and capillary sorption away from primary flow paths resulted in a gradual increase in the water content of the waste, whilst drainage from the base of the columns occurred. There are perhaps two different phenomena in play here: the first may reflect channelling and a dual porosity structure which results in access to some sorbent components of the waste being slower than others, while the second reflects the fact that the water content at a given suction is greater on drying than on wetting (section 1.3.6.1). Major and Zeiss (1993) investigated the distribution of water uptake in household waste in lysimeters 1.8 m high and 0.57 m in diameter. They demonstrated (at this scale) the presence of water flow channelling and concluded that in most situations it would be very unlikely for a landfill to ever reach field capacity as defined by HELP. This corresponds to the concept of primary absorptive capacity noted by Knox, and is consistent with the idea that the phenomenon is in part a result of a dual porosity structure of the waste.

The total absorptive capacity of a waste is essentially the difference between two water contents, the initial or as placed water content and the water content at field capacity. The absorptive capacity may therefore, like water contents, be expressed in a variety of different ways. Absorptive capacity expressed in kg (or perhaps litres) of water per dry tonne of waste is probably of most scientific use and the least likely to be misinterpreted. However, on full scale landfills operators do not tend to measure the water content of the wastes as emplaced. Therefore, to be of practical use in water balance calculations, absorptive capacity is usually expressed in terms of litres of water per tonne of refuse at its original *in-situ* water content. This is potentially confusing as the absorption of water will increase the wet density of the refuse.

The majority of studies on absorptive capacity were undertaken in the 1970s and early 1980s in the UK, USA, Canada and Europe, generally in lysimeter scale experiments usually less than 10 m^3 in volume. Results from a number of these early studies were summarised by Knox (1992) and are reproduced in Table 2.

Table 2. Reported values of absorptive capacity for household wastes (MSW).

SOURCE	Test Cell Size and Refuse type	Density **t/m^3**	Original WC$_{wet}$ **%**	Final WC$_{wet}$ **%**	Primary Absorptive Capacity **l/t$_{wet}$**	Total Absorptive Capacity **l/t$_{wet}$**
Newton (1976)	8 m^3 pulverised MSW	0.5			230	
Robinson *et al*(1981)	8 m^3 pulverised MSW		40			225
Blakey (1982)	300 m^3 crude MSW	0.57				330
Blakey (1982)	0.2 m^3 pulverised MSW	0.76	26		165	290
Campbell (1982)	4000 m^3 crude MSW	0.66	25		100	
	4000 m^3 crude MSW	0.95	25		41	
	4000 m^3 crude MSW	1.01	25		24	
Holmes (1980)	0.2 m^3 drums 17 yr old MSW	0.96	31.5			115
	0.2 m^3 drums 17 yr old MSW	0.64	31.5			307
Harris (1979)	0.2 m^3 drums crude MSW		26.5			570
Fungaroli (1979)	Indoor lysimeter crude MSW	0.33				867
Kinman *et al* (1982)	6 m^3 crude MSW	0.5	35	54		425
Jones & M (1982)	6 m^3 crude MSW	0.4	14.7		345	
Pohland (1975)	1.6 m^3 simulated pulverised MSW	0.4				1300
Rovers & F (1973)	9 m^3 and 1.8 m^3 crude MSW	0.33				372.5

Table modified from Knox (1992)

There have been a number of studies relating absorptive capacity and water content at field capacity with waste density. Early work by Holmes (1980) and Campbell (1982) established a link between increasing waste density and decreasing absorptive capacity. As the dry density increased from 0.5 to 0.75 tonne/m^3, Campbell (1982) reported that the absorptive capacity of waste decreased from approximately 140 litres/dry tonne to 30 litres/dry tonne. This reduction is consistent with the reduction in water content at field capacity (calculated on a gravimetric dry mass basis) with increasing bulk density reported by other researchers, as shown in Figure 9.

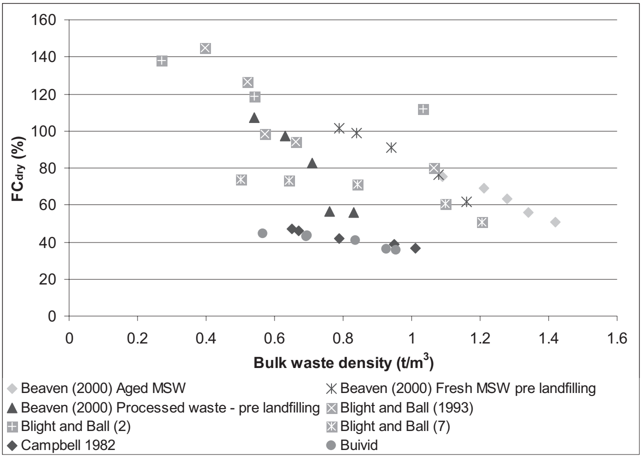

FIG. 9. Field capacity (expressed as dry weight) vs waste density.

If the water content at field capacity is expressed in volumetric terms, an increase in water content with bulk density is apparent, up to an apparent limit of 40-50% at bulk densities in excess of 0.8 tonne/m^3 (Figure 10). The reason for the difference between the trends in Figure 9 and Figure 10 lies in the relationships between the parameters involved. In the case of Figure 9- using the symbols defined in Table 1– $w = (m_w/m_s)$ is plotted against $\rho_{bulk} = (m_t/V_t)$. For a constant mass of solids m_s, the total volume V_t is reduced as the bulk density ρ_{bulk} is increased. The mass of water m_w that the solid matrix can hold at field capacity also decreases; hence so does the gravimetric water content w and there is a trend of reducing w with increasing ρ_{bulk}. In the case of Figure 10, the trend in the volumetric water content $\theta = (V_w/V_t)$ as the bulk density is increased is dominated by the reduction in V_t rather than the reduction in V_w at field capacity – hence θ increases with ρ_{bulk} until some limiting value (perhaps corresponding to full saturation) is reached.

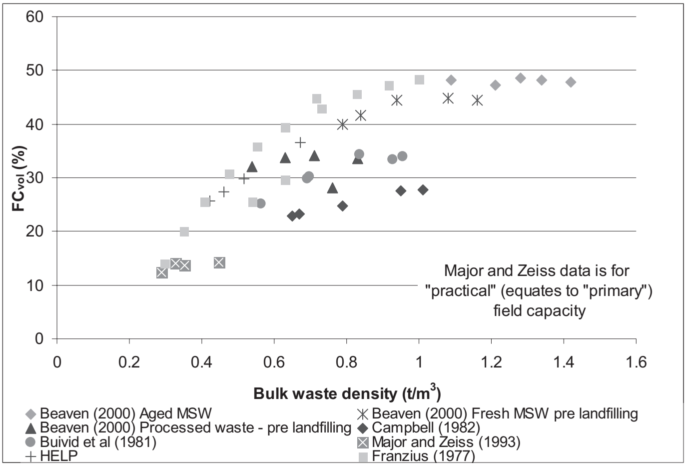

FIG. 10. Volumetric Field capacity vs waste density.

1.3.6 Water Content-Suction Relationship

1.3.6.1 Background and definition

When the water content of an unsaturated waste is below field capacity, water in the pores is held by surface tension (capillary tension) and the physical attraction (adhesion) between the water and the particles (adhesion). These forces are responsible for developing negative pressure heads or suctions (ψ), sometimes referred to as the matric suction (e.g. Hillel. 1971). Suction gradients control liquid flow in the unsaturated zone at water contents below field capacity; hence an understanding of the factors governing suction is important.

Suction (ψ) increases with reducing water content, as moisture retreats into smaller and smaller pores. At a given water content, the suction will depend on a number of intrinsic properties of the porous medium including the matrix structure, inter-particle voidage, and particle size, shape and texture. The relationship between the suction and the water content is conventionally expressed by the water retention curve (WRC; also known as the soil water characteristic curve, SWCC). It is conventional to use the volumetric water content θ for this purpose, although there is no reason why the gravimetric water content or even the degree of saturation S_r (= V_w/V_v) should not be used. The water retention curve is viewed as a fundamental hydraulic property of a porous medium, and is needed to solve Richards' (1931) equation for water flow in the unsaturated zone.

At a given suction, the water content during drainage is larger than during wetting; i.e., the water retention curve exhibits hysteresis. Hysteresis can be attributed to the "ink-bottle" effect (water remaining trapped in closed-bottomed voids during drainage that are inaccessible on wetting from the bottom up), trapped air, and the difference in contact angle between a solid surface and an advancing and a receding liquid front (Hillel. 1998). The main drying curve and the main wetting curve initiate from points of θ_s (saturated moisture) and θ_r (residual moisture). Cycles that do not initiate from these two points result to paths within the region enclosed by the main curves and are referred to as scanning curves (Figure 11).

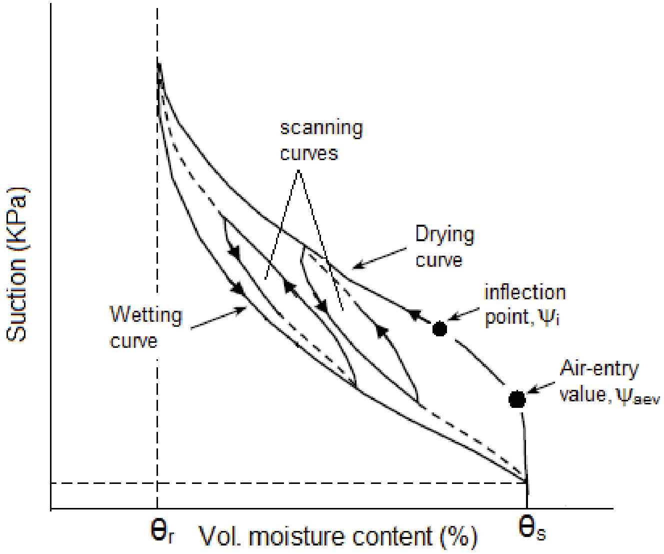

FIG. 11. Schematic water retention curve and hysteresis effect (after Kazimoglu 2007)

The suction at which the material starts to desaturate is defined as the air entry value, ψ_{aev}. As the suction increases above ψ_{aev}, the water content decreases following an S-shaped curve with an inflection point, ψ_i (Figure 11), towards the residual value, θ_r. The air-entry value depends on the maximum pore size and the pore-size distribution. Materials with large, uniformly shaped pores have relatively low air entry values of suction. The slope of the water retention curve indicates the amount of liquid taken up or released by the waste as a result of a change in pore suction.

1.3.6.2 Functional Forms of Moisture Retention Curve

A number of empirical mathematical expressions have been proposed for suction - volumetric water content relationships in soils. The most important of these, and the ones that have been applied to waste, are detailed below. These expressions permit the numerical solution of Richards' equation for unsaturated flow (see section 1.5), and are used with the saturated coefficient of permeability to predict the hydraulic conductivity function for an unsaturated porous medium.

Four of the more important forms of expression for water retention curves that have been applied to wastes, as summarized in Table 4, are:

Van Genuchten (1980) after Mualem (1976):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\alpha|\psi|\right)^n\right]^m} \tag{2}$$

The parameter α is related to the air-entry value, *n* is related to the pore size distribution and *m* is an indication of the asymmetry of the curve.
It is commonly assumed that m=1-1/n.

Brooks and Corey (1964):

$$\theta = \theta_r + \left(\theta_s - \theta_r\right)\left(\frac{\psi}{\psi_{aev}}\right)^{-\lambda} \tag{3}$$

ψ_{aev} is the air-entry value, λ characterises the width of the pore-size distribution, and is referred to as the pore-size distribution index.

The effective saturation (or normalized water content) is defined as:

$$\theta_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

where θ_r and θ_s are the residual and saturated volumetric water content, respectively and vary between 0 and 1.

Hence equation (3) becomes: $\theta_e = \left(\frac{\psi}{\psi_{aev}}\right)^{-\lambda}$ for $\psi > \psi_{aev}$ and

$\theta_e = 1$ for $\psi < \psi_{aev}$

Campbell (1974):

$$\psi = \psi_s\left(\frac{\theta}{\theta_s}\right)^{-b} \tag{4}$$

where $\psi_s = \psi_{aev}$

The retention model used by Campbell (1974) is identical to the power function of Brooks and Corey (1964). However, the dependent variable is defined as the degree of saturation, S_r (= θ/θ_s) rather than the effective saturation, θ_e. The Clapp and Hornberger (1978) power law model also has an identical form to Campbell (1974).

The water retention curve of MSW has also been represented by the relationship proposed by:

McKee and Bump (1984):

$$\theta = \exp\left[-\left(\frac{\psi-\alpha}{b}\right)\right] \tag{5}$$

where ψ: suction head
α, b: curve fitting parameters

McDougall et al. (2006) modified the form given by McKee and Bump (1984) to

$$\theta = (-0.1)\ln\left(\frac{\psi-0.622}{-20.622}\right)$$

1.3.6.3 Moisture retention curves in waste

Determination of a water retention curve is always difficult, even in soils, owing to the effects of hysteresis and the dependence of the water content-suction relation on the characteristics of the material including state variables such as void ratio as well as properties such as particle and pore size distributions and shapes. In MSW, the likely wider range of particle and pore size and shape, heterogeneity of waste composition and possibly leachate chemistry complicate matters further.

The water retention curve represents a series of equilibrium states in which the water content and the corresponding suction are known. Water content measurement was discussed in Sections 1.3.1 and 1.3.1.1. It is usually determined by oven drying, although a neutron probe may be used. There are a number of methods for determining suction in the field and the laboratory. These methods are categorised as either ‘direct’ or ‘indirect’, depending on whether the suction is measured directly or indirectly through an intermediate medium or parameter. Direct methods include tensiometers (Tarantino and Mongiovi 2001), suction probes (Ridley and Burland 1993; Guan and Fredlund 1997), the hanging water column (Haines 1930; Vanapali et al. 2008) and pressure plate apparatus (Soilmoisture Equipment Corp. 2002). The pore water within the sample is allowed to come into equilibrium with a body of water at a known potential or suction, or is measured directly by a transducer. Tests in the pressure plate apparatus are carried out with the pore water pressure u_w atmospheric and elevated pore air pressures u_a, on the basis that the water content depends on the relative suction ($u_a - u_w$) according to the principle of axis translation (Marinho et al. 2008;

Vanapali et al. 2008) The technique may not be sensitive enough for some wastes at low suctions (< 5 kPa), and the equilibration time at higher suctions can be in the order of months (Kazimoglou 2007).

Indirect methods include the filter paper technique (Gardner 1937; ASTM 1997; Ridely 1999, gypsum block (Ridley and Wray 1995) and psychrometry (Spanner 1951; Campbell and Gardner 1971; Ridley and Wray 1995). These methods involve equilibration of the pore suction in the sample with that in a second medium (e.g. a filter paper or a gypsum block), whose water content-suction relationship has been determined in a previous calibration or correlation with a third parameter such as relative humidity (Agus and Schanz 2005). Changing the pore water chemistry may invalidate previous calibrations of intermediate media (Fredlund and Rahardjo 1993).

A number of researchers have determined water retention curves for MSW or waste-like materials, as summarized in Table 3, and have then usually applied one or more of the models described in section 1.3.6.2 to the data. Table 4 records the fitted parameters used and Figure 12 illustrates both experimental results (points) and the fitted curves. A number of researchers have applied standard unsaturated flow models to landfills (e.g. Haydar and Khire 2005 used HYDRUS; McCreanor and Reinhart 2000 used SUTRA, Yuen 1999 used SEEP/W). The model parameters used (where known) are also recorded in Table 4 and the resulting water retention curve shown on Figure 12.

Table 3. Summary of experimentally determined water retention curves for wastes and waste-like materials.

Author(s)	Material(s)	Method and comments
Korfiatis et al. (1984)	Solid waste	Column cell instrumented with two vertical lines of tensiometers
Kazimoglu et al. (2005,2006)	Waste from Lyndhurst landfill	Pressure plate
Imam (2003)	Synthetic waste	Filter paper method
McDougall et al. (2006)	Mix of partially humified peat and cocoa shells	Hanging water column
Münnich (2003)	MBT <60mm	Suction ceramic plate
Stoltz (2007)	Drilled domestic waste	Suction ceramic plate

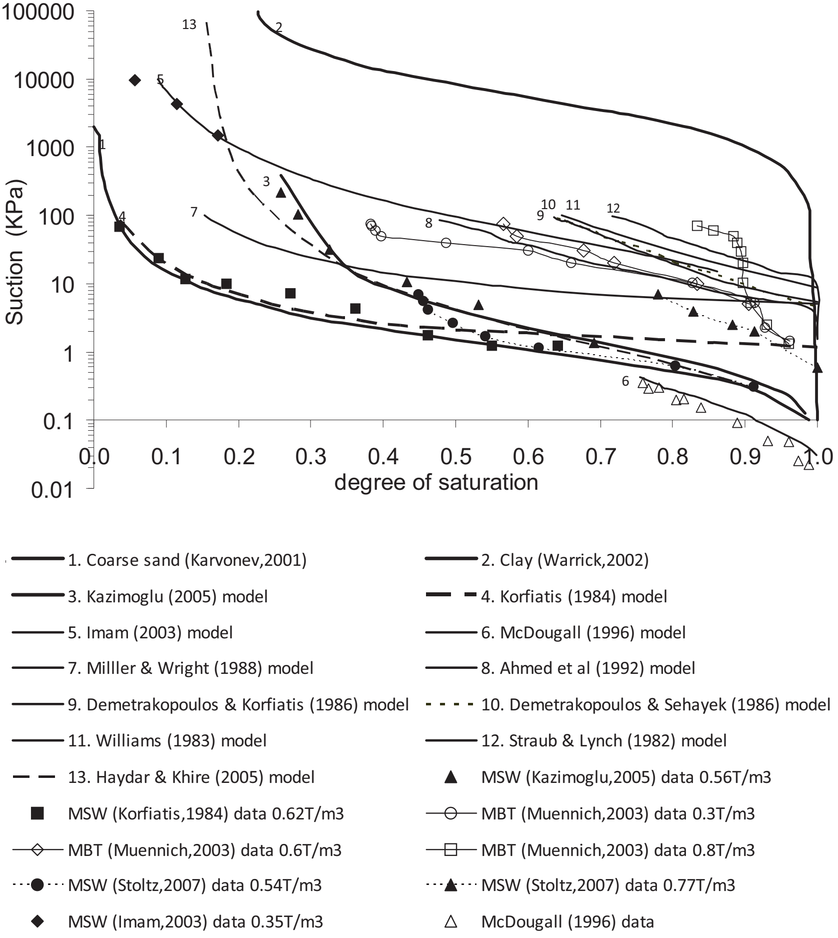

FIG. 12. Comparison of moisture retention curve for waste materials (Zardava 2009).

Table 4. Moisture retention parameters for modeled waste.

Author	Applied model	ψ_{aev} (kPa)	θ_s	b	θ_r	α (kPa^{-1})	n
Korfiatis et al. (1984)	Clapp and Hornberger (1978)	0.62	0.55	1.5			
Kazimoglu et al. (2005,2006)	van Genuchten (1980) Mualem(1976)		0.58		0.14	1.4	1.60
Imam (2003)	van Genuchten (1980) Mualem(1976)		0.35		0.01	0.049	1.45
McDougall et al. (2006)	Modified McKee&Bumb (1984)		0.82	-20.6		0.622	
Straub & Lynch (1982)	Campbell (1974)	10	0.375	7			
Demetracop. and Korfiatis (1986)	Campbell (1974)	4	0.40	7			
Demetracop. and Sehayek (1986)	Campbell (1974)	3.5	0.35	7			
Ahmed et al. (1992)	Campbell (1974)	4.6	0.417	4			
Haydar and Khire (2005)	Hydrus-vanGenuchten (1980)-Mualem(1976)		0.45		0.067	0.2	1.41

1.4 SATURATED FLOW

Most of the waste in a landfill will probably be above the leachate level and therefore experiencing unsaturated flow, through the vertical percolation of rainwater or other infiltrating liquid. It is generally only the bottom layers in a landfill below the leachate level and in a capillary saturated zone, or possibly perched horizons that will be fully saturated. The presence of landfill gas would also tend to reduce the degree of saturation, even at the base. However, saturated waste hydraulics is crucially important, as it is relevant to all leachate extraction and control measures at a landfill and also provides a stepping stone towards understanding unsaturated flow.

Flow in saturated waste is almost invariably characterised in terms of Darcy's law[1],

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[1] **A note on nomenclature**: Hydrogeologists and soil scientists usually use the symbol K to denote hydraulic conductivity and the symbol k for intrinsic permeability. Confusingly, geotechnical engineers reverse the use of these symbols, but this is the nomenclature we are adopting.

$$q = k.i.A \tag{6}$$

where q is the flowrate (e.g. m^3/s), A is the cross-sectional area of flow (m^2), i is the hydraulic gradient (defined as the rate of drop in head with distance along a flowline), and k is the hydraulic conductivity. K is related to the properties of the porous medium and the permeant by

$$k = K\gamma_f/\eta_f \tag{7}$$

where K is the intrinsic permeability of the porous medium (m^2), γ_f is the unit weight of the permeant (kN/m^3) and η_f is its dynamic viscosity (kNs/m^2).

While the model of uniform, Darcy flow may or may not be appropriate to wastes with their large range of particle size and material type, likely anisotropy and presence of preferential flow channels, it is analytically convenient and has formed the basis of nearly all studies of waste hydraulic behaviour. The hydraulic conductivity is the key parameter used to characterise and quantify liquid flow, and is the focus of much of the remainder of this chapter.

1.4.1 Hydraulic Conductivity

Jain et al. 2006 (among others) have collated data from various studies on the hydraulic conductivity of MSW, combining field and laboratory based tests. Hydraulic conductivities of MSW reported in the literature vary between approximately 1×10^{-3} m/s and 1×10^{-9} m/s, although more typically values are in the range 10^{-5} to 10^{-6} m/s. HELP uses a default value of 1×10^{-5} m/s. However, simply stating a range of hydraulic conductivities of waste is not particularly helpful - partly because the range is potentially very wide, but mainly because it masks the effects of factors such as waste composition and density which influence the hydraulic conductivity in an understandable and perhaps even predictable way. Also most tests, especially in the laboratory, have determined hydraulic conductivity in vertical flow whereas in a landfill the anisotropy resulting from the deposition and layering of the waste would be expected to result in preferential horizontal flow. Further complications arise from the effects of channelling and preferential flow, gas generation, random heterogeneity and waste processing and decomposition.

One of the most systematic series of large scale tests on the hydraulic conductivity of MSW has been that reported by Beaven and Powrie (1995), Powrie and Beaven (1999) and Beaven (2000), carried out in the Pitsea compression cell. This work will now be summarised briefly to provide for a context for the discussion of the wider literature in Sections 1.4.2 to 1.4.5 below.

The Pitsea cell accommodates a waste sample 2 m in diameter and up to 2.5 m high – a size necessary to obtain representative results from samples of generally highly heterogeneous wastes. Overburden pressures are simulated by applying a vertical stress via hydraulic rams acting on a platen on top of the waste. Typically, the applied stress is increased in five or six stages to a maximum of 600 kPa, representing landfill depths of up to 60 m. At the end of each compression stage, the bulk density, drainable porosity and saturated hydraulic conductivity of the waste may be determined.

Tests were carried out on four different samples of domestic waste (DM3, PV1, DN1 and AG1) to investigate the effects of particle size reduction, degradation and compression on the bulk vertical hydraulic conductivity. DM3 was fresh, unprocessed waste; PV1 was fresh waste that had been pulverized and passed through a 150 mm screen and heavy fines (including some putrescibles) removed; DN1 was fresh waste that had been partly sorted and tumbled in a drum using the Dano system ; and AG1 which was a 25 year old partly degraded waste containing a mixture of soil, crude waste and pulverised waste that had been recovered from a depth of less than 5 metres from a landfill site. Further tests were carried out on sample DN1 to investigate the effects of partial saturation and gassing. Full characterization analyses are given by Powrie and Beaven (1999) for sample DM3, by Hudson et al. (2001) for waste DN1, and by Beaven (2000) for wastes PV1 and AG1.

Raw data of hydraulic conductivity, drainable porosity and density at various vertical effective stresses are given for samples DM3, PV1 and AG1 by Beaven (2000), and for sample DN1 in high and low gas accumulation conditions and with high and low pore water pressures by Hudson et al. (2001). Figure 13 shows the permeability in notionally saturated conditions for all four wastes plotted as functions of (a) vertical effective stress in first loading; (b) density and (c) porosity.

On the basis of Figure 13, the following observations may be made.

1. There is a single correlation for all samples between the logarithm of the vertical hydraulic conductivity and vertical effective stress in first loading. Differences in hydraulic conductivity resulting from particle size reduction and waste degradation are essentially second order, but appear to become more significant at higher vertical effective stresses (with a spread of just over one order of magnitude in hydraulic conductivity at a vertical effective stress of 500 kPa).

2. There are individual correlations between the logarithm of the vertical hydraulic conductivity and density for each waste type, with an essentially linear relationship between the logarithm of the vertical hydraulic conductivity and the dry density.

3. There is a single correlation between the logarithm of the vertical hydraulic conductivity and the drainable porosity of the waste. This is not surprising, as the drainable porosity represents a measure of the size and degree of connectivity of the voids, both of which will have a major influence on the bulk hydraulic conductivity.

However, unlike the vertical effective stress, the drainable porosity is a difficult parameter to estimate a priori for design purposes, so the correlation between vertical hydraulic permeability and vertical effective stress is of more practical use.

It is important to emphasise that this correlation is with the vertical effective stress in first loading; if the waste has been compacted prior to landfilling, then an equivalent pre-compaction stress must be estimated.

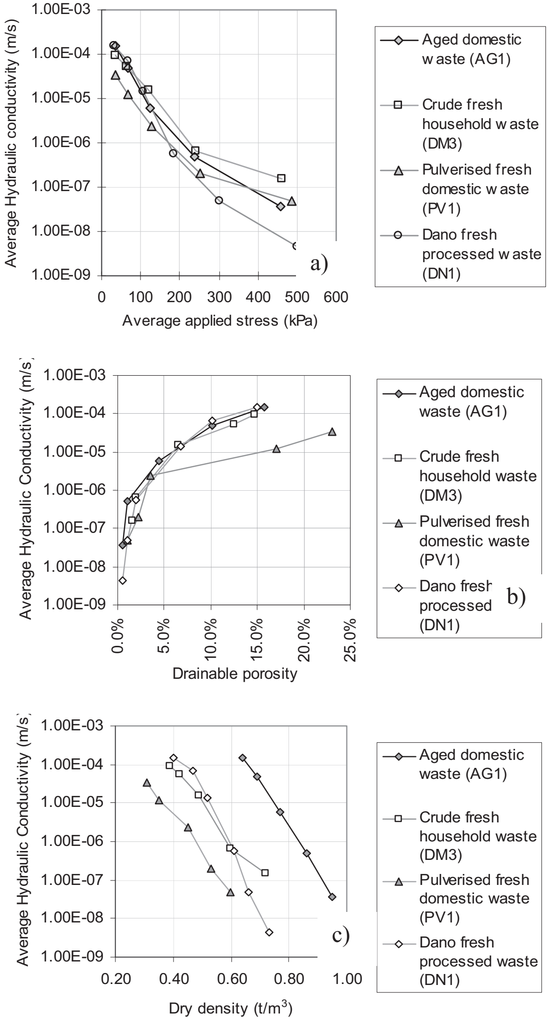

FIG. 13. Vertical hydraulic conductivity against (a) the logarithm of the vertical effective stress in first loading; (b) the drainable porosity; and (c) density, for four waste types (data from Beaven 2000 and Hudson et al. 2001)

1.4.2 Influence of Effective Stress and Waste Density on Hydraulic Conductivity

As illustrated by Figure 13c, relationships between hydraulic conductivity and the dry density appear to be well defined but are different for individual waste types. Many authors have presented data relating hydraulic conductivity to waste density, but the effects of waste composition and other variables apparent in Figure 5c make extrapolating such a relationship to different wastes and other situations rather difficult. An example of this is given by Landva and Clark (1986, 1990), who undertook large-scale percolation tests in pits excavated at the surface of various landfills in Canada. The hydraulic conductivity was estimated on the basis of the rate of fall of the water level and flow nets applicable to each stage. Hydraulic conductivities ranging between 4×10^{-4} m/s and 1×10^{-5} m/s were reported. The unit weights of the refuse excavated from the pits generally fell in the range 10 - 14 kN/m^3. However, there was poor correlation between hydraulic conductivity and refuse density, almost certainly due to variations in material composition between the different sites - a small amount of cover material mixed into a predominantly MSW matrix would affect the waste density considerably.

Other authors have taken a systematic approach to investigating the relationship between waste density and the logarithm of the hydraulic conductivity, in variously sized oedometer type apparatus. These studies are summarised in Table 5 and the results presented in Figure 14, in which the linear but individual nature of the relationship between hydraulic conductivity and dry density is consistently apparent.

Table 5. Summary of tests relating the vertical hydraulic hydraulic conductivity of MSW type materials to dry density.

Author(s)	**Apparatus**	**Waste tested**
Chen and Chynoweth (1995)	30 cm diameter rigid walled permeameter	different types of processed MSW, including a mix that combined paper, plastics and yard waste.
Bleiker et al. (1995)	falling head tests in a flexible walled permeameter	cored samples recovered from depths of 32 - 36 m in the Keele Valley landfill by drilling using a 100mm diameter auger and split spoon sampler.
Staub et al. (2009)	20 cm diameter rigid wall permeameter.	samples of shredded MSW recovered from two French landfill sites
Beaven (2000); Powrie and Beaven (1999)	2 m diameter rigid walled compression cell (Pitsea cell)	Various: see Figure 13 and Figure 14

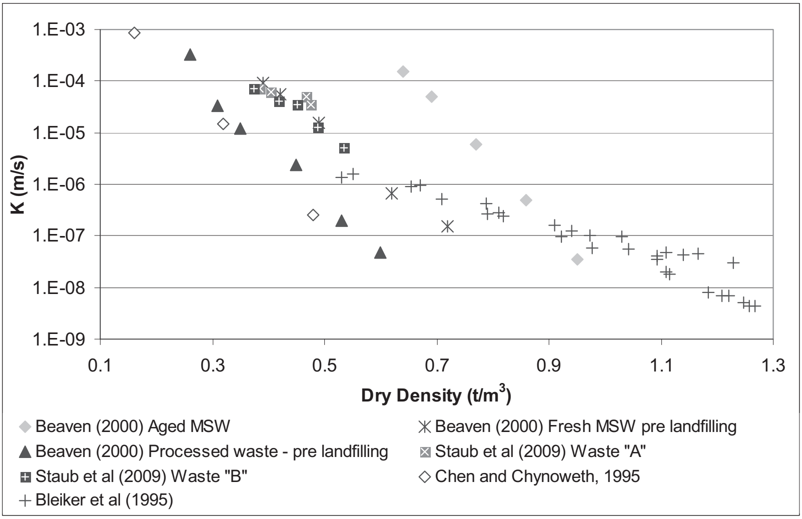

FIG. 14. Summary of relationships between $\log_{10}$ vertical hydraulic conductivity and waste dry density.

It is difficult to make sensible comparisons between the different waste types. For example, the processed waste of Beaven (2000) was actually a screened and shredded MSW to a size below 140 mm, and these data correspond to the data of Chen and Chynoweth, but not to the results for the French shredded MSW given by Staub et al. (2009). The samples recovered from depth within a landfill by Beaven and Bleiker have the smallest hydraulic conductivity for a given waste density, probably reflecting the amount of cover material that may have become intermingled with the samples. The very small sample size used by Bleiker - which implies a correspondingly small grain size - may also have had an effect.

1.4.3 Impact of Waste Degradation

There is little information in the literature on the direct effect of waste degradation on hydraulic conductivity – perhaps unsurprisingly, given the difficulty in obtaining a direct comparison between the fresh and degraded states of a given waste. However, comparison of the curves for the aged waste sample AG2 with the other data given in Figure 13 suggests that any effect of degradation on hydraulic conductivity is small in comparison with the effect of an increase in stress. The graph of hydraulic conductivity against vertical stress in first loading lies within the range given by the tests on fresh wastes, while the relationship between hydraulic conductivity and drainable porosity is similar. Figure 13c shows that the dry densities of the aged waste are generally greater than for the fresh waste samples,: this could be a result of degradation and/or of the inclusion within the sample of a proportion of soil materials used for daily cover. In any case, as has already been mentioned, the relationship between hydraulic conductivity and dry density is different for each waste type.

Gas generation is a consequence of waste degradation, and this will have its own effect on hydraulic conductivity as discussed below.

1.4.4 Waste Anisotropy

Hudson *et al* (2009) discuss the impact of anisotropy on the hydraulic conductivity of MSW-type materials. A review of the literature reveals a very wide variation in the ratio of horizontal to vertical hydraulic conductivity, k_h:k_v (Table 6).

Table 6. k_h : k_v ratios obtained by laboratory testing of wastes.

Researcher	Waste type	k_h : k_v ratio
Landva et al. (1998)	Artificial	0.5 to 1.0
Landva et al. (1998)	Spruce lake landfill	8
Buchanan and Clark (1997, 2001)	Processed waste fines (<38mm)	1.24 to 2.25
Munnich et al. (2005)	MBT waste	1 to 250

Data reported by Hudson et al. (2009) from tests on samples of a 20 year old waste recovered from a landfill (AG2) and a fresh, Dano-processed waste (DN1), carried out in the Pitsea cell, are reproduced in Figure 15 and Figure 16 in terms of the ratio k_h:k_v as a function of applied stress. The determination of k_h from flow tests was analytically quite complex and involved numerical modelling using MODFLOW, as described by Hudson et al. (2009). Error bars indicate possible systematic errors: there is some variation of individual data points away from the general trend, but this is to be expected given the difficulties of assessing hydraulic conductivities of wastes.

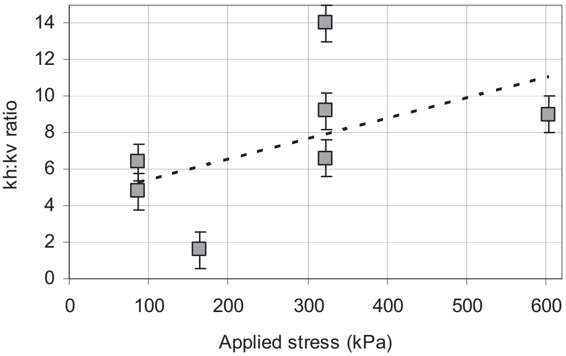

FIG. 15. k_h : k_v vs applied stress for sample AG2.

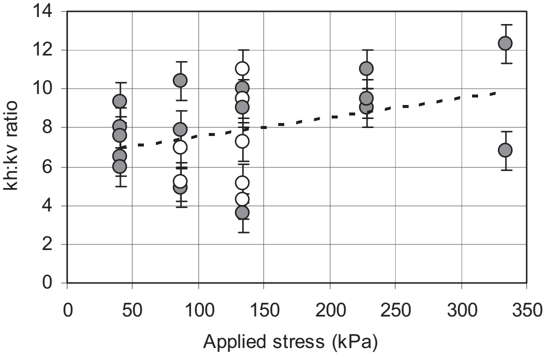

FIG. 16. k_h : k_v vs applied stress for sample DN1.
(*unshaded markers indicate tests run in gas accumulated conditions)*

All tests exhibited higher horizontal than vertical hydraulic conductivities, and there is a general trend of an increase in k_h:k_v ratios with an increase stress for both samples, between 5 and 7 at low stress (40 kPa) and approaching 10 at higher stresses (300 to 500 kPa). Sample DN1 generally exhibited slightly greater k_h:k_v ratios than sample AG2.

In Figure 16, data from tests carried out in gas accumulated conditions are indicated with open (unshaded) markers. (These are limited to applied stresses of 87 and 134 kPa, as no gas accumulation tests were carried out at 40 kPa and flow was too erratic in tests at higher stresses). Although both vertical and hydraulic conductivity were significantly lower in gas accumulated conditions than in nominally saturated conditions, the k_h:k_v ratios for both conditions are not obviously dissimilar. This suggests that gas accumulation has no significant effect on k_h:k_v ratio.

For the wastes tested, the general increase in k_h:k_v ratio with applied stress supports the conceptual mechanism of preferential horizontal hydraulic conductivity developing further at higher stress as items become increasingly aligned to the horizontal plane and compressible components are deformed. Interestingly, the research by Buchanan and Clark (1997, 2001) indicated a small *reduction* in anisotropy with stress. However in that case, tests were limited to the finer fraction of the waste and low densities. This, and the general variability apparent in the data summarised in Table 6, highlights that caution is required in extrapolating the findings of any study to other types of wastes; it is possible that highly processed wastes of smaller particle size may exhibit a lesser degree of anisotropy. It may also be necessary to consider the way that the waste was originally deposited. The method of sample placement and loading used by Hudson et al. (2009) is considered to be reasonably representative of normal tipping procedure. However deposition methods may vary, and this could alter the structure and hence anisotropy of flow through the waste. The stresses applied by on-site compaction plant would also need to be considered.

The slightly higher k_h:k_v ratios obtained for the fresh (DN1) waste than for the aged sample (AG2) may indicate a slight breakdown in the anisotropic structure of waste with decomposition. Although the accumulation of gas reduces the vertical hydraulic conductivity substantially, it does not seem to alter the ratio k_h:k_v.

1.4.5 Impact of Landfill Gas

Data presented by Hudson et al. (2001) and Powrie et al. (2005) from tests on a Dano-processed MSW waste sample (DN1) indicated a two orders of magnitude reduction in hydraulic conductivity as a result of the *in situ* generation and accumulation of gas. Increasing the pore water pressure then compressed the gas and reduced its effect on hydraulic conductivity. Further investigations into the effect of gas accumulation and pore water pressure on hydraulic conductivity at lower compression stresses, on sample of fresh shredded domestic waste (SW1) were reported by Powrie et al. (2008). The tests were carried out at constant volume following initial compression under applied stresses of 40 kPa and 87 kPa, representing landfill depths of approximately 4 m and 9 m respectively.

Figure 17 shows the changes in average bulk hydraulic conductivity and the volume of accumulated gas over a 27 day period for a test conducted at constant volume (corresponding to an initial applied stress of 40 kPa) with a relatively high average pore water pressure of 60 kPa. The reduction in hydraulic conductivity in response to the increase in the volume of gas contained within the sample is clear.

Table 7Table summarises the results of hydraulic conductivity tests undertaken by Powrie et al. (2008) at initial stresses of 40 kPa and 87 kPa under both high (60 kPa) and low (25 kPa) average pore pressure conditions. At both stresses the hydraulic conductivity was reduced by gas accumulation, by approximately two orders of magnitude in low pore water pressure conditions and one order of magnitude in high pore water pressure conditions. These reductions are explained by Powrie et al. (2008) by the large volumes of leachate displaced from the sample by gas accumulation, and the resulting high degree of unsaturation indicated in the last column of Table 7.

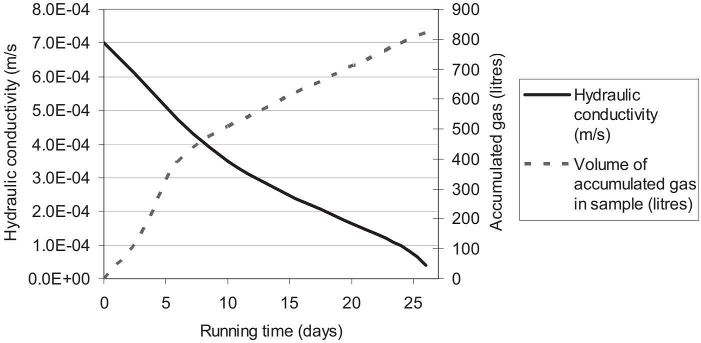

FIG. 17. Changes in hydraulic conductivity with time for sample SW1 at a constant volume corresponding to an initial applied stress of 40 kPa, with an average pore water pressure of 60 kPa.

Table 7. Summary of test results, sample SW1.

Applied Stress[1] (kPa)	Av. pwp (kPa)	Length of test (days)	Accumulated volume of gas (litres)	Initial K (m/s)	Final K (m/s)	% of drainable pore volume occupied by gas (range)
40	25	36	1064	1.0×10^{-3}	1.5×10^{-5}	77.7 – 87.3
40	60	27	820	7.0×10^{-4}	4.0×10^{-5}	57.7 – 67.2
87	25	37	297	1.1×10^{-4}	1.1×10^{-6}	36.5 – 59.9
87	60	34	571	1.5×10^{-4}	1.2×10^{-5}	93.1 – 100

[1] Initial stress at which constant volume was established

Figure 18 summarises the variation in hydraulic conductivity of fresh processed MSW varies following compression to stresses between 40 and 228 kPa, in different conditions of gas accumulation and pore water pressure.

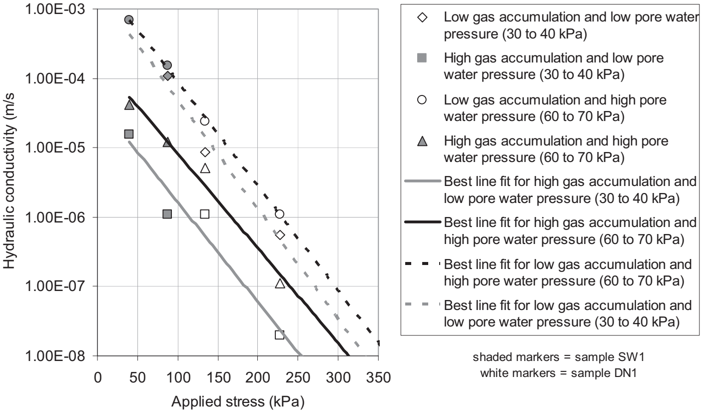

FIG. 18. Hydraulic conductivity for fresh processed MSW in different conditions of gas accumulation and pore water pressure.

The results indicate that gas accumulation in fresh, shredded MSW can significantly reduce the hydraulic conductivity, especially at lower pore water pressures. The reduction in hydraulic conductivity could be up to two orders of magnitude, compared with generally only a one order of magnitude reduction in the drainable porosity and hence the saturated area available for liquid flow. This implies that the intrinsic permeability for liquid flow is also reduced, for example because of a reduction in the size of the pore network through which flow occurs.

The hydraulic conductivity of a gassy waste must be expected to increase if the pore water pressure is increased (e.g. in the vicinity of leachate injection infrastructure), and to reduce if the pore water pressure is reduced (e.g. around a pumped leachate extraction well).

1.5 UNSATURATED FLOW

Although its relevance is perhaps more questionable than in saturated conditions, the Darcy model is usually adopted – at least implicitly – for liquid flow in unsaturated wastes as well. The hydraulic conductivity of a porous medium varies significantly with the degree of saturation (Fredlund and Rahardjo 1993), and this is true in wastes as in soils.

As a porous medium becomes unsaturated, the largest pores drain first, causing the hydraulic conductivity to fall quickly in the initial stages of de-saturation. The remaining fluid is confined to smaller and smaller pores, with smaller intrinsic permeability K. The unsaturated hydraulic conductivity, k, may therefore be related to the volumetric water content, θ. The relative permeability, $k_{r,L}(\theta)$ for the liquid phase may be defined as

$$k_{r,L}(\theta) = k_L(\theta)/k_{sat} \tag{7}$$

where $k_L(\theta)$ is the hydraulic conductivity at a volumetric water content θ and k_{sat} is the hydraulic conductivity in saturated conditions. The relative permeability $k_{r,L}(\theta)$ must lie between zero and one as the water content varies from unsaturated to saturated conditions. Owing to capillary hysteresis, the relationship between the relative permeability and the water content is different in wetting and drying. The interaction between gas and liquid in an unsaturated waste is complex, with gas restricting the flow of liquid and vice versa.

Direct measurement of unsaturated hydraulic conductivity is difficult in soils (Lam *et al*, 1987), and more so in waste because of the degradable, compressible and heterogeneous nature of the material. Thus it is tempting to try to estimate the unsaturated hydraulic conductivity on the basis of the water content (Campbell 1974). Several empirical relationships between unsaturated hydraulic conductivity and water content have been proposed, including:

Van Genuchten (1980) after Mualem (1976):

$$k_r(\theta) = \theta_e^{0.5}\left(1-\left(1-\theta_e^{m/(n-1)}\right)^m\right)^2 \tag{9}$$

where m=1-1/n, θ_e the effective moisture content and is estimated from the equation:

$$\theta_e = \frac{\theta-\theta_r}{\theta_s-\theta_r}$$

Clapp and Hornberger (1978):

$$k(\theta) = k_s\left(\frac{\theta}{\theta_s}\right)^B \tag{10}$$

Campbell (1974)

Campbell argued that the coefficient B should be replaced by the relationship B=2b+3.

$$k(\theta) = k_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{11}$$

The experimental study by Korfiatis et al. (1984) confirmed this relationship.

Brooks and Corey (1964):

$$k(\theta) = k_s\left(\frac{\theta-\theta_r}{\phi-\theta_r}\right)^n \tag{12}$$

Davidson et al. (1969):

$$K_r = 10^{10n(S-1)} \tag{13}$$

where n: porosity and S: degree of saturation.

Noble and Arnold (1991) compared the power law equations proposed by both Korfiatis *et al* (1984) and Straub and Lynch (1982) to an exponential relationship:

$$K = K_s e^{\gamma(\theta_e - 1)} \tag{14}$$

A relative gas conductivity, $k_{r,G}$, can be defined in the same way as the relative hydraulic conductivity. The form of the relative gas and liquid permeabilities, as a function of the water content, is indicated in Figure 19.

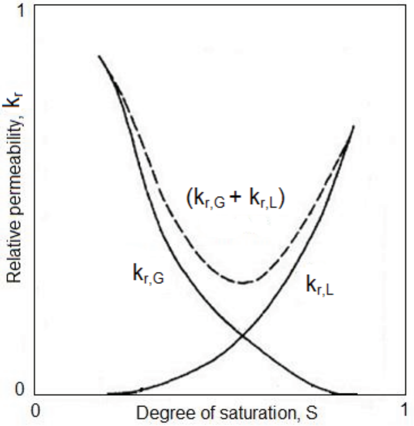

FIG. 19. A typical example of relative permeability curves (after Honarpur et al. 1986).

Relative permeability functions, based on one of the equations listed above, have been applied to experimental data or used (e.g. in models) by various authors. The shape of these various functions is shown in Figure 20 and values used in the equations are summarised in Table 8. Most data relate to real wastes although the relative permeability curve used in the modelling of Haydar and Khire (2005), who simulated unsaturated flow in a landfill, is based on the performance of a silt loam.

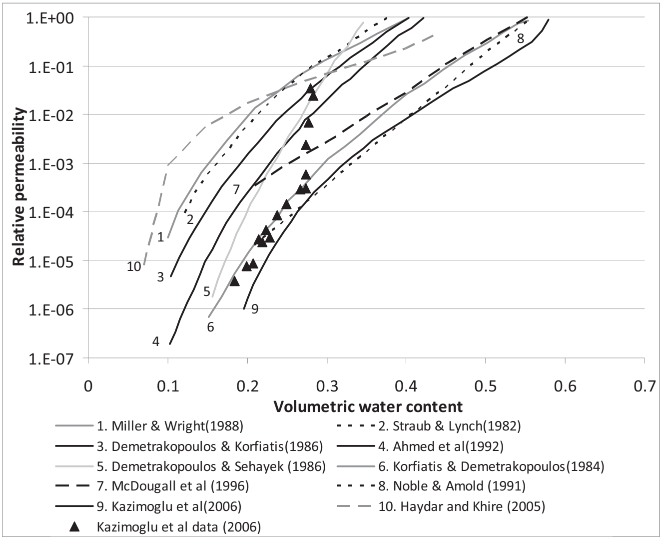

FIG. 20. Comparison of relative permeability functions for MSW (from McDougall 1996 and Kazimoglu 2007).

It has been suggested by several researchers including Bendz et al. (1997) and Yuen (1999) that the Darcy uniform flow model may be inappropriate for wastes, owing to the presence of preferential flow paths and/or the wide variation in pore size which leads to a dual porosity type behaviour. Strong evidence for this also comes from analysis of tracer experiments in waste (e.g. Beaven et al. (2001) and Bendz et al. (1997).

The sensitivity of the moisture content patterns and possibly flowrates in unsaturated waste masses calculated using Equations 8-13 to small changes in the relative permeability function and the air entry value (ψ_{aev}) have been reported by Korfiatis et al. (1984) and Yuen (1999) respectively.

Table 8. Parameters of the unsaturated hydraulic conductivity for modeled waste.

Author	Form of relationship	γ	Ks (m/s)	θ_s	θ_r	B	n
Noble and Arnold (1991)	Exponential equation	11	-	-	-	-	-
Korfiatis et al. (1984)	Clapp and Hornberger	-	1.2×10^{-4}	0.55	-	11	-
Ahmed et al. (1992)	Campbell	-	2.0×10^{-4}	0.42	-	11	-
Kazimoglu et al. (2006)	van Genuchten	-	1.0×10^{-5}	0.58	0.14	-	1.60
McDougall et al. (1996)	Davidson *et al* (1969)	-	-	0.82	-	-	0.35
Straub and Lynch (1982)	Campbell		$6.3\text{x}10^{-9}$	0.375	-	8	
Haydar and Khire (2005)	Hydrus-vanGenuchten-Mualem (1980)	-	10^{-5}	0.45	0.067	-	1.41

Kazimoglu et al. (2006) compared the unsaturated hydraulic conductivity of MSW obtained using Passioura's (1976) one-step outflow test method on waste with a dry density of 0.56 t/m^3 with calculations using van Genuchten's model (Equation 8: Figure 21). The measured and calculated values of $K(\theta)$ show good agreement at low moisture contents (high suctions) if K_S is taken to be about $5\text{x}10^{-4}$ m/s. This value is consistent with saturated hydraulic conductivities found in a crude household waste under low stresses (e.g. Beaven 2000), suggesting that the mechanism of flow at low moisture contents in waste is similar to that in soils. At higher moisture contents, the measured and calculated hydraulic conductivities diverge. This may be an indication of a dual porosity effect, as a result of the wide range of pore sizes present in wastes. At lower moisture contents, the hydraulic conductivity is controlled by the smaller pores. However at higher water contents, the onset of desaturation and the air entry value are governed by the larger pores: thus a single van Genuchten type curve cannot capture the whole range of behaviour. However, this problem might resolve itself at higher stresses, as the larger pores close and the range of pore size is reduced. The role of the air entry value in depicting the start of meaningful desaturation, and how it varies with stress, is a subject in need of further research.

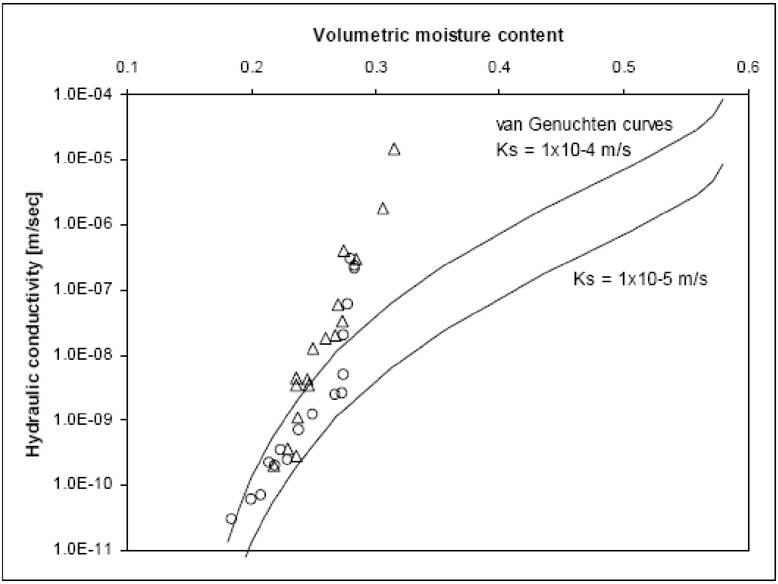

FIG. 21. Unsaturated hydraulic conductivity of MSW. One-step outflow tests results compared with van Genuchten model (Kazimoglu et al. 2006).

1.6 CONCLUSIONS

The science of understanding fluid flow in waste materials is both complicated and in a state of evolution. In general, however, it is possible to apply soil mechanics and hydrogeological principles to waste, although care needs to be taken with standard phase relationships for a number of reasons. Firstly, there is a great potential for confusion between terms, as landfill science has borrowed definitions from different disciplines which very often have slightly different meanings and derivations. Secondly, the impact of gas is a complicating factor, especially as it is being generated in situ. And finally ongoing degradation can cause a volume reduction in solids, a factor not dealt with in any other area involving fluid flow through porous media.

There has been a reasonable amount of research and understanding of saturated waste hydraulics. Darcy's law is routinely applied and appears satisfactory for most eventualities. Changes in effective stress on first loading appears to be the dominant influence on hydrogeological properties, especially hydraulic conductivity, with secondary influences coming from gas, differences in waste composition and possibly degradation. Waste anisotropy and heterogeneity are also other important considerations.

Less is known about unsaturated waste hydraulics, and indeed the applicability of standard unsaturated flow theory to waste has not been proven. For example there is considerable uncertainty about the nature and form of water retention curves for waste. Standard theory usually relates parameters to saturated conditions, but the link between saturated and unsaturated waste hydraulics is difficult to define, partly because ongoing gas generation in landfills probably mean that truly saturated conditions never exist. At present there is not enough data on the impact of gas generation, distribution and movement on unsaturated flow parameters.

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Chapter 2

Shear Strength of Municipal Solid Waste

Jonathan D. Bray[1], F. ASCE, Dimitrios Zekkos[2], M. ASCE, and Scott M. Merry[3], M. ASCE

[1]Professor, Dept. of Civil and Environmental Engineering, University of California, Berkeley, USA
[2]Assistant Professor, Dept. of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA
[3]Senior Professional, Kleinfelder, Inc., 2015 N. Forbes Rd., Suite 103, Tucson, AZ, USA

2.1 INTRODUCTION

While the engineering profession's understanding of the response of municipal solid waste (MSW) to monotonic and cyclic loadings has improved over the past two decades, several important issues remain unresolved. Characterization of the shear strength of MSW is a critical step in performing reliable static and seismic stability analyses of landfills. Landfill stability analyses can be no more reliable than the reliability of the engineer's estimate of the shear strength of the waste. Furthermore, the stress-strain response of MSW needs to be considered to provide compatibility between the mobilized shear strength and the level of deformation along potential failure surfaces.

Relevant studies of MSW shear strength are summarized in this state-of-knowledge chapter. Large-scale laboratory test data, which includes direct shear (DS), triaxial (TX), and simple shear (SS) test results, and back-analyses of failed and stable landfill slopes in the field are considered. Findings from a recent comprehensive study by Zekkos (2005) are emphasized.

There is large variability in the shear strength of MSW reported in the literature. Obstacles to characterizing the shear strength of MSW include its age, heterogeneity and the difficulty in recovering and testing representative waste samples due to the large size of some waste constituents. Differences in testing procedures employed and in the assumptions made when interpreting the test results also contribute to the variability of the shear strength of MSW. A consistent conceptual framework to perform and to evaluate the results of the laboratory and in-situ tests performed on MSW is required. It is hoped that the recommendations provided as part of the first "International Waste Mechanics Symposium" will address this issue and work toward providing a common framework for advancing the profession's understanding of waste properties and mechanics through developing consensus on the performance and reporting of laboratory and field testing procedures.

Published data reported in the literature on the shear strength of MSW are discussed in sections on large-scale tests and back-analyzed assessments. This literature review does not provide complete descriptions of the works completed by researchers, as this information is available in detail in the referenced papers. Instead, key findings are summarized. Following the literature review, a summary of the state-of-knowledge of MSW stress-strain response and strength is presented and recommendations are made for developing a consistent framework for performing and reporting shear strength data on MSW. Currently unresolved issues are also identified.

2.2 LABORATORY AND IN SITU TESTS

2.2.1 Initial Studies (1986-1999)

Landva and Clark (1986) performed a series of large-scale DS tests on waste specimens from different Canadian landfills. The DS device had plan dimensions of 434 by 287 mm, and the specimens were sheared at a rate of about 1.5 mm/minute, unless pore water pressure development required the reduction of the shear rate. The interpreted cohesion value (c) was between 10 and 23 kPa and the estimated friction angle (ϕ) varied between 24 degrees and 42 degrees. When specimens of old refuse from Blackfoot/Burbank were tested for the first time, the cohesion and friction angle were estimated to be 16 to 19 kPa and 38 to 42 degrees, respectively. The material was then stored in plastic containers, and when it was tested a year later, the shear strength parameters were reduced to16 kPa and 33 degrees, respectively. Initially, the authors stated that this could be a result of decomposition. Later, Landva and Clark (1990) reported that the reduction in strength was within the variability of the shear strength values and should not necessarily be attributed to decomposition effects. Landva and Clark (1986) also report data from Edmonton, which included large amounts of plastic sheets. The relatively low friction angle of 24 degrees was attributed to the fact that sliding largely occurred between plastic sheets that were oriented parallel to the direction of the imposed shearing. They also reported that the cohesion of the material should be attributed to interlocking of the particles. The shear strength parameters measured for wood-waste in ring shear tests agreed with those from the DS tests. Landva and Clark (1990) performed additional testing using the large-scale DS device mentioned previously in this study. Their results are shown in Figure 1. The interpreted cohesion was between zero and 23 kPa while the friction angle ranged between 24 and 41 degrees. Additional tests on plastic bags stacked horizontally and allowed to slide along the horizontal shear plane provided a friction angle of just 9 degrees.

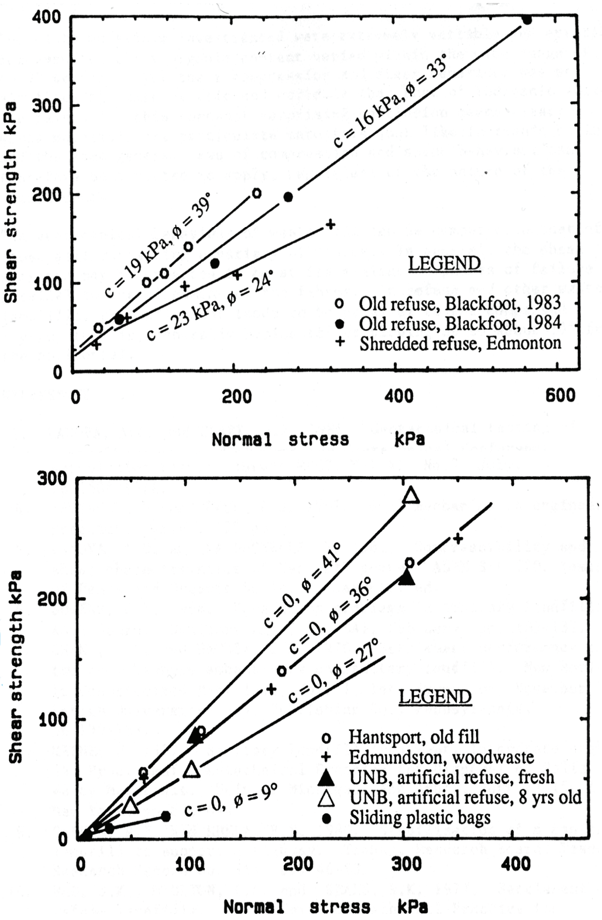


FIG. 1. Large-scale DS test results on MSW from Canada (Landva and Clark, 1990).

Siegel et al. (1990) reported results from their investigations on the OII landfill located in Los Angeles, California. Acrylic-tube samples of refuse having a diameter of 13 cm and retrieved from a depth of 4.6 to 25 m were used in DS testing. The specimen height was 7.6 to 10.2 cm. For all the tests the peak or maximum shear stress corresponded to shear displacements substantially exceeding 10% of the specimen diameter, i.e. 16% to 39%. The mobilized shear stresses at a shear displacement of 10% of the specimen diameter as a function of the applied normal stress are shown in Figure 2. The composition of the MSW specimens differed significantly in that some specimens contained large amounts of soil particles. Strength Interpretation 1 with a lower bound ϕ estimate of 39 degrees (c=0) was employed for those specimens containing large amounts of soil. Strength Interpretation 2 with a lower bound ϕ estimate of 53 degrees was employed for the other MSW. The authors also reference TX test results on anisotropically consolidated specimens of two-year old milled domestic refuse performed by Stoll (1971), which produced zero cohesion and a ϕ of 44 degrees.

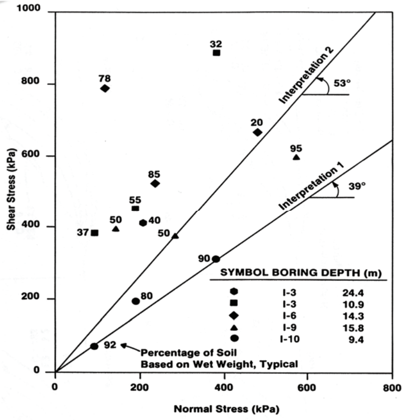


FIG. 2. Siegel et al. (1990) interpretations of DS test results at OII Landfill.

Singh and Murphy (1990) presented a graph that included laboratory data on MSW from different sources, most of which are from small size specimens. It showed a wide range of *c* values and corresponding ϕ values for MSW. Cohesion values varied from 0 to 70 kPa and ϕ varied from 19 to 42 degrees, although one test series was characterized as $c = 35$ kPa and $\phi = 0^o$. Richardson and Reynolds (1991) reported large-scale DS test (plan view area of 1.5 m^2) results on MSW from a landfill in Central Maine. The authors do not mention if these values represent peak shear stress conditions or mobilized shear stress at some limiting displacement. Oweiss (1993) discussed the results of laboratory strength testing of MSW. He observed that the laboratory determination of shear strength of MSW is usually estimated as the shear stress mobilized at a strain level of 15 to 20%, because MSW specimens do not fail. Among others, the author cites the results of DS tests performed from Schoenberger and Fungaroli (1971) on incinerated residue material. A friction angle of 45 degrees was reported on specimens with a unit weight of 15.4 kN/m^3. Its relatively high strength was attributed in part to the high angularity of the particles in the waste material. Withiam et al. (1995) reported data from in situ DS tests on a landfill near New York City. The DS device had dimensions of 1.5 m by 1.5 m by 1.5 m. Five tests were performed at three normal stresses that ranged between 0 and 21 kPa using a multi-stage loading procedure. The method consisted of applying increasingly higher shear stresses to the same specimen at progressively higher normal stresses until the specimen was near failure at each normal stress level. The Mohr-Coulomb strength parameters were estimated to be c = 10 kPa and $\phi = 30^{\circ}$.

Gabr and Valero (1995) performed small-scale Consolidated Undrained (CU) TX compression tests and small-scale DS tests on 15 to 30 year-old waste. The dry unit weight of the CUTX specimens was 7.4-8.2 kN/m^3. The TX specimen diameter was about 71 mm. All larger particles greater than 12.5 mm were excluded. Strength parameters were evaluated at 20% axial strain. As shown in Figure 3, the cohesion intercept decreased from 100 kPa to 40 kPa as the water content of the waste specimen increased from 55% to 72%. Cohesion also increased as the effective confining pressure increased. In general, the authors estimated c = 17 kPa and $\phi = 34^{\circ}$ in these CUTX tests. The DS test specimens had a diameter of 63.5 mm and a dry unit weight of 10 to 12.1 kN/m^3. The specimens exhibited increasing strength at horizontal displacements much higher than 10% of the specimen's diameter, and none of the specimens reached peak strength. Values of cohesion and friction angle were evaluated at displacements equal to 5% and 10% of the specimen's diameter. The authors found that cohesion ranged from 0 to 28 kPa and friction angle ranged from 20 to 39 degrees. The friction angle increased with increasing horizontal displacement while cohesion remained constant. Figure 4 summarizes the results of the strength parameters evaluated by the tests performed by Gabr and Valero (1995) along with data published in the literature.

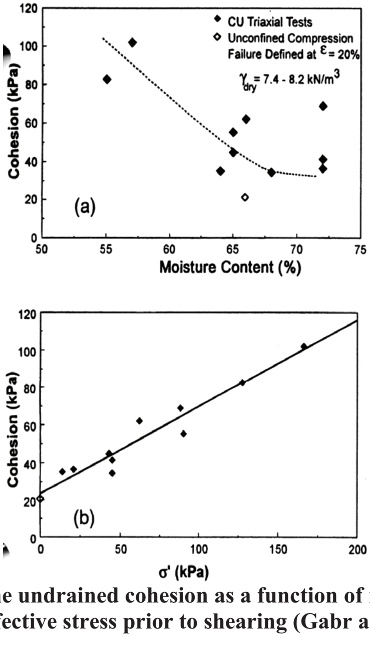


FIG. 3. Variation of the undrained cohesion as a function of moisture content and as a function of effective stress prior to shearing (Gabr and Valero, 1995).

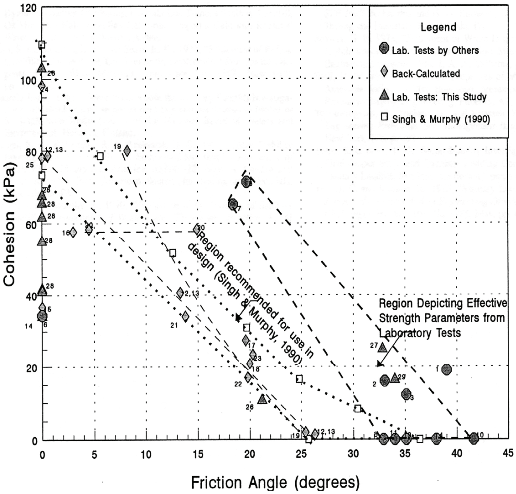


FIG. 4. Summary of MSW strength parameters by Gabr and Valero (1995)

Grisolia et al. (1995) performed large-scale TX tests on MSW. The specimens had a diameter of 25 cm and a height of 65 cm, and their composition was 6% cloth and wood, 32% paper, 8% plastic, 32% rubble, and 22% organic matter. The unit weight of the specimens was not reported, but it was probably relatively low. Stress-strain plots are shown in Figure 5. Initially, the stress-strain curves are concave downward. An almost straight-line section follows this initially curved downward response. Interestingly, the stress-strain curves bend upwards at larger strains (i.e., they are now concave upwards). The shear stress mobilized at different strain levels was used to define the shear strength of MSW. Both cohesion and friction angle increased with increasing strain.

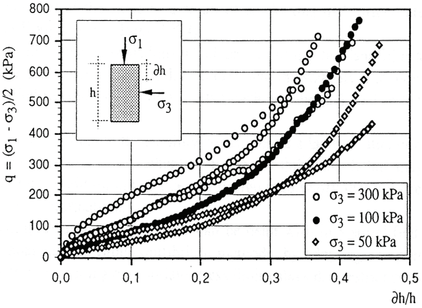


FIG. 5. Large-scale triaxial compression test results by Grisolia et al. (1995).

Jessberger and Kockel (1995) performed large-scale (i.e., specimen diameter, d = 30 cm and height, h = 60 cm) and small-scale (i.e., d = 10 cm and h = 20 cm) TX tests. Tests were performed on untreated waste (uW), where the large particles were removed, and milled waste (mW). The unit weight of the MSW specimens was not reported. Triaxial compression tests were performed at a strain rate of 1%/min starting from isotropic conditions. The comparison of test results performed on uW and mW showed minor differences and for that reason results from mW only were presented as shown in Figure 6. Failure was not observed at high specimen compressions (large strains) and waste appeared to harden with deformation. Poisson's ratio was also estimated and it increased with increasing strain levels. Assuming zero cohesion, the effective friction angle at the maximum strain at each test was estimated to be between 31 to 49 degrees.

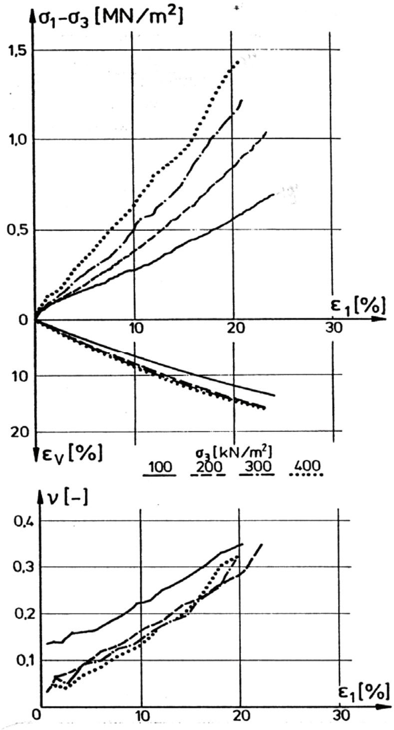


FIG. 6. Results of TX compression test on milled 1-3 years old MSW (Jessberger and Kockel, 1995)

Houston et al. (1995) report two direct shear tests using a large-scale square DS test box (i.e., 1.22 m x 1.22 m). The tests were performed at the Northwest Regional Landfill Facility located in rural northwestern Maricopa County, Arizona. When the shear stress leveled off during shearing, the vertical load was increased and testing continued, so that results at three different normal stresses could be obtained. Partial results are shown in Figure 7. The DS test results were interpreted to have a friction angle of 33 to 35 degrees with c = 5 kPa.

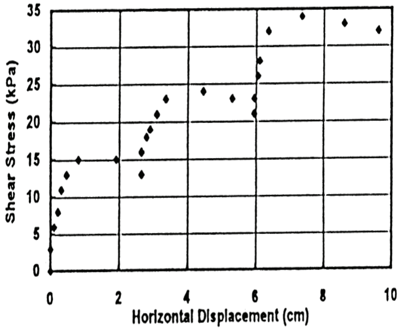


FIG. 7. In-situ large-scale multi-scale loading DS test on MSW from Arizona (from Houston et al. 1995).

Kolsch (1995) put forth the concept of “fibrous cohesion” that results from the reinforcement effect of the waste materials in MSW. He saw the analogy between MSW and reinforced soil. The fibrous cohesion is generated by tensile stress in the fibrous materials and was found to depend on the normal stress. He defined the angle of internal tensile stress (ζ) and measured this parameter by developing a device that allowed the performance of large tensile tests on MSW. The angle of internal tensile stress was found to be 35 degrees for fresh waste, 14 degrees for decomposed waste, and 0 degrees for specimens with no waste fibers.

Edincliler et al. (1996) performed DS tests on waste specimens with a diameter of 30 cm. Two different refuse samples and one sample of cover material were collected at different times from different locations of a landfill in Northeastern Wisconsin. Components found in refuse that were larger than 5 cm were removed. The authors noted that the waste material tested in this testing program should be weaker than the waste material in the field due to the removal of the larger reinforcement components of MSW. As shown in Figure 8, both of the refuse samples yielded similar shear strengths, and soaking of the specimens did not have a significant effect in the strength of MSW. The resulting Mohr-Coulomb strength parameters were estimated to be c = 27 kPa and $\phi = 42^{o}$. The authors surmised that the material that was tested in this study was primarily daily cover and for that reason a sample of daily cover was collected. The strength of the daily cover material had comparable strengths with c = 0 kPa and $\phi = 42^{o}$.

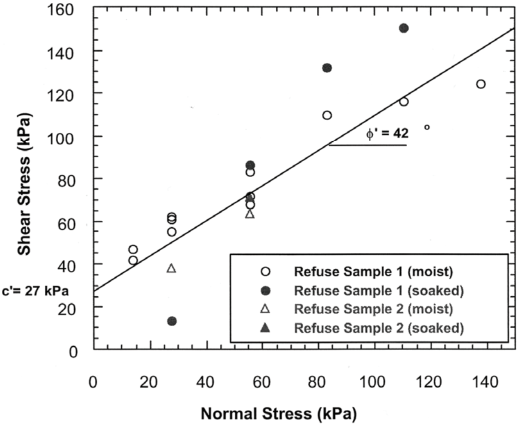


FIG. 8. Shear strength of two refuse samples from a landfill in Northeastern Wisconsin (Edincliler et al. 1996).

Aburatani et al. (1998) report results from large-scale TX tests (i.e., d = 30 cm and h = 60 cm) on incinerated waste. Incinerated ashes, gravel, and soil represented 80-90% of the waste material by weight. The results are shown in Fig. 9. The material response is in the form of a hyperbolic-shaped stress-strain curve with no dilatancy.

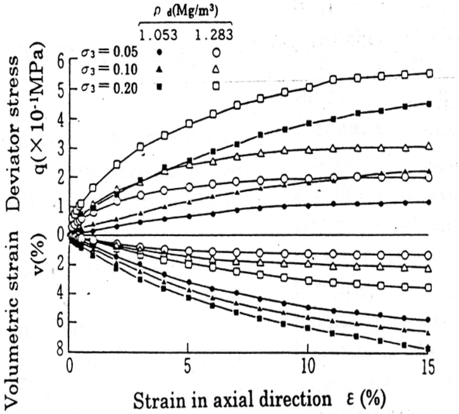


FIG. 9. Large triaxial tests in incinerated waste (Aburatani et al. 1998).

Mazzucato et al. (1999) performed large-scale DS tests in a landfill in Verona, Italy. The apparatus consisted of two steel rings each having a diameter of 800 mm and a height of 220 mm. The device was used to test reconstituted specimens from the waste material and also used to test "undisturbed" MSW by pushing the rings into the waste in situ. The unit weight of the specimens was estimated to be about 7 kN/m^3. The authors did not observe a significant difference in the peak shear strength between the reconstituted specimens and the in-situ values (Figure 10). The reconstituted specimens had a cohesion of 22 kPa and a friction angle of 17 degrees, and the "undisturbed" specimens yielded a cohesion of 24 kPa and a friction angle of 18 degrees. However, the in situ test specimens exhibited a slight post-peak shear stress reduction while the reconstituted MSW test specimens did not.

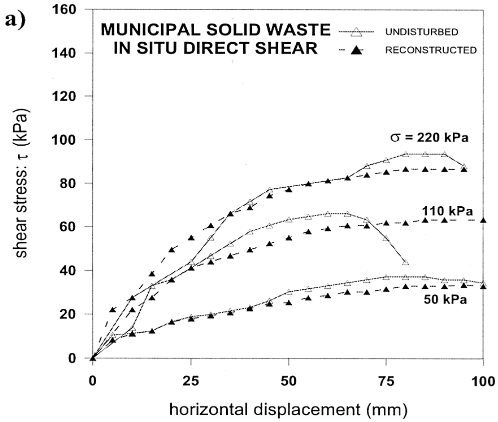


FIG. 10. Results of "undisturbed" and reconstituted specimens of MSW in a large direct shear device. (Mazzucato et al. 1999).

Kavazanjian et al. (1999) presented results of DS tests and simple shear tests (SS) performed on samples collected from the OII landfill in southern California. The tested specimens had a diameter of 460 mm. Their best fit DS failure envelope was characterized by $c = 43$ kPa and $\phi = 31^{\circ}$. Only specimens having less than 16% refuse fell below their best-fit failure envelope. SS tests showed the same ductile hyperbolic shape. The shear stress mobilized at a shear strain of 10% was selected as the criterion to evaluate the shear strength in the SS tests. Two different methods were used to interpret the SS test data. The first method assumes that the failure plane is horizontal. The vertical stress is plotted against the applied shear at 10% strain, similar to the DS tests. The strength envelope obtained by this method is characterized by zero cohesion and a friction angle of 30 degrees, which is consistent but slightly lower than the results from the DS tests. The second method of interpreting the SS results assumes that shear failure occurs on the plane within the test specimen with the largest principal stress ratio (i.e., the plane with the maximum obliquity). A K_o value of 0.6 was used in that interpretation. This second interpretation yields a lower bound strength envelope of c = 16 kPa and ϕ = 33° and an upper bound strength envelope of c = 30 kPa and ϕ = 59°. The authors comment that the results suggest that the shear strength on non-horizontal planes may be significantly higher than the shear strength on the horizontal plane.

2.2.2 Recent Studies (2000-2009)

Pelkey et al. (2001) performed a series of large-scale (450 mm long, 305 mm wide, and 600 mm high) DS and SS tests on reconstituted specimens of MSW from different landfills with unit weights of 9 kN/m^3 to 15.5 kN/m^3 and 10 to 12.7 kN/m^3 for the DS and SS tests, respectively. Water contents varied between 32% and 315%. Additional details are provided in Pelkey (1997). The peak shear strength of the MSW was mobilized at strains above 40% in the SS tests. As shown in Figure 11, the mobilized friction angle increases significantly as shearing increases for the SS tests. The mobilized friction angle ranged between 30 and 55 degrees at large shearing displacements. The materials friction angle decreased significantly as the applied normal stress increases, which indicated that like most soils, the Mohr-Coulomb parameters are stress-dependent and a curved failure envelope should be employed. In the interpretation of the SS tests the failure surface was assumed to be horizontal, which produces a conservative estimate of the material's friction angle. With this assumption, the strength envelope from the SS tests for peak shear stress conditions has zero cohesion and a friction angle of 29 degrees. The results from the DS tests indicate zero cohesion and friction angles ranging from 26 to 29 degrees, which are consistent with the SS strength values. These values are also consistent with the results by Kavazanjian et al. (1999) mentioned previously based on the first method of interpretation (i.e., that the failure plane is horizontal), which suggested a friction angle of 30 degrees.

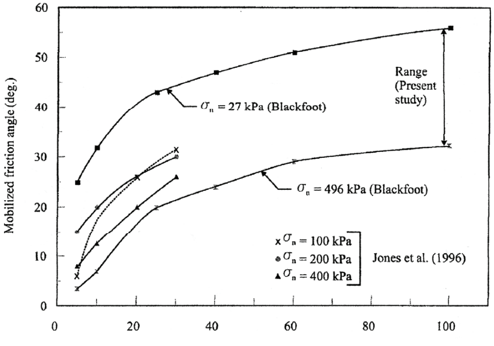


FIG. 11. Mobilized friction angle from SS results (Pelkey et al. 2001).

Caicedo et al. (2002a) performed in situ large-scale (cross sectional area of 0.63 m^2) and laboratory smaller-scale (cross sectional area of 0.09 m^2, i.e. 30 cm by 30 cm and 20 cm tall) DS tests on MSW as part of the geotechnical investigation program to evaluate the causes of a landslide at the Dona Juana landfill in Columbia. One-year old MSW specimens that have a diameter of 90 cm were tested in situ using the DS device, which was specifically designed for that purpose. The results of the in situ DS tests are shown in Figure 12. The shear strength of the MSW was characterized by $c = 78$ kPa and $\phi = 23^o$.

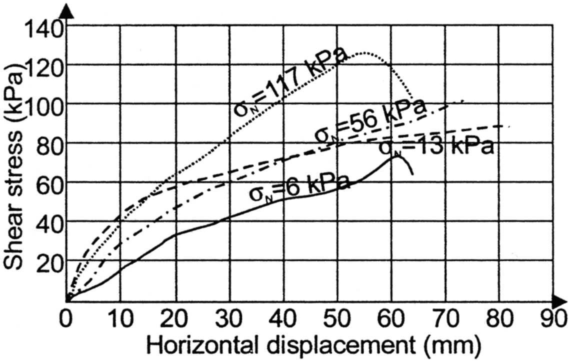


FIG. 12. Results of in situ DS tests on MSW (Caicedo et al. 2002a).

The testing program also included laboratory triaxial tests and in situ tests using a pressure-phicometer probe. The results from the large-scale CUTX tests (d=30 cm and h=60 cm) are shown in Fig. 13. The material did not reach a distinct peak strength during the tests, which were terminated at an axial strain of nearly 15%. However, the pore water pressures appeared to have stabilized at a maximum level. The authors do not report the unit weight or the B-values of the saturated specimens. The pressure-phicometer device was developed for the in situ estimation of the shear strength of MSW (Caicedo et al. 2002b). The method consists of a probe that is placed in a borehole to the desired depth and then inflated horizontal flaps are pushed into the waste through the use of internal pressure. The waste strength is estimated after an axial force is applied to the probe which pushes the extended flaps downward and thus shears the waste material. The results of the in situ pressure-phicometer tests were consistent with those from the in situ large-scale DS tests. The measured cohesion of the MSW in the pressure-phicometer was slightly less but the measured friction angle remained 23 degrees.

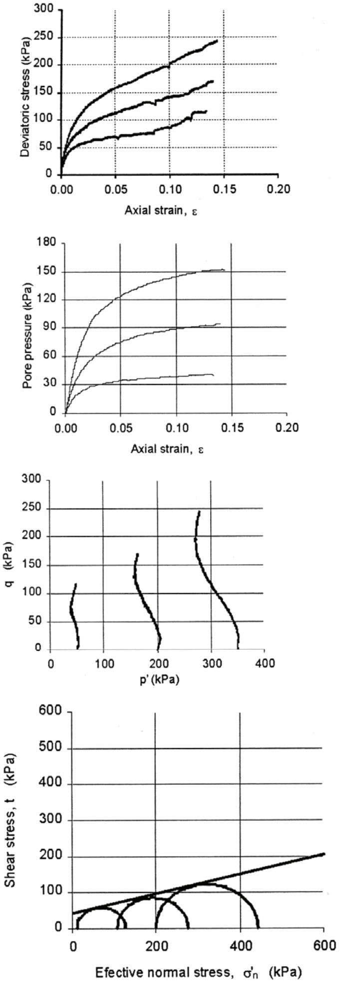
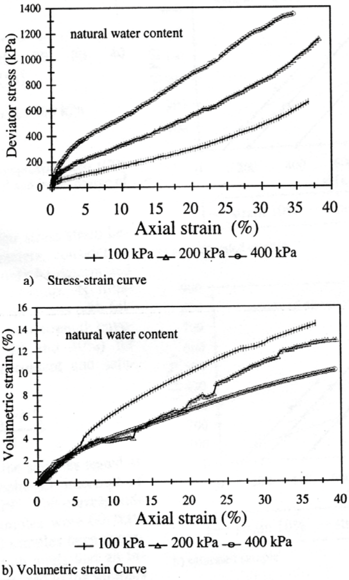


FIG. 13. Results of laboratory CU TX tests on reconstituted saturated MSW (Caicedo et al. 2002b).

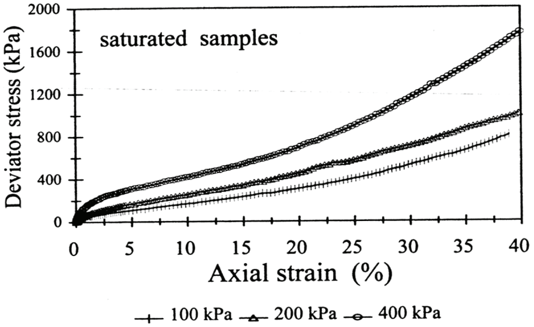
Vilar and Carvalho (2002) performed Consolidated Drained (CD) TX tests on waste specimens collected from the Bandeirantes Sanitary landfill near Sao Paolo, Brazil. The specimens had diameters of 150 mm and 200 mm and nominal unit weights of 10, 12, and 14 kN/m^3. During specimen preparation, the largest particles were replaced by an equal amount of finer particles so that the largest particle was not greater than 30 mm and 40 mm for the 150 mm and the 200 mm diameter specimens, respectively. The TX test results for the specimens with a unit weight of 12 kN/m^3 and natural water content of 67% are shown in Figure 14 and results for saturated MSW specimens with the same unit weight are shown in Figure 15. The tests show that the deviator stress increases continuously without reaching a well-defined peak. The shear strength mobilized at different strain levels of 10%, 20%, and 30% was estimated as shown in Figure 16. The difference in the shear strength envelopes is observed to be small, and hence, a unique shear strength envelope can reasonably represent the strength of both the saturated and partially saturated waste specimens. For this MSW at an axial strain of 20%, the effective cohesion was 44 kPa and the friction angle was 27 degrees. Unit weight was found to have a minor influence on the measured shear strength in this test program. The larger CDTX test specimens (d = 200 mm) mobilized slightly lower strength (about 10 to 20%) than the smaller CDTX test specimens (d = 150 mm). The authors state that "the increase of shear strength in the smaller samples can be in part credited to the heterogeneity of the samples but the reinforcement effect of the fibrous materials may play an important role in this behavior since the same dimensions of fibrous material was used in both specimens.



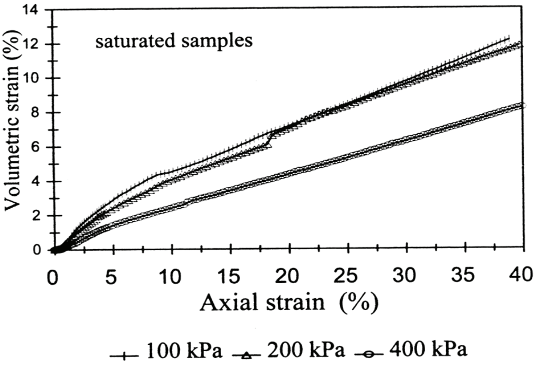
a) Stress-strain curve

b) Volumetric strain Curve

FIG. 14. Representative results from consolidated drained TX tests on partially saturated MSW with unit weight of 12 kN/m^3 and water content of 67% (Vilar and Carvalho, 2002).



a) Stress-strain curve



b) Volumetric strain Curve

FIG. 15. Representative results from consolidated drained TX tests on saturated MSW with unit weight of 12 kN/m^3 (Vilar and Carvalho, 2002).

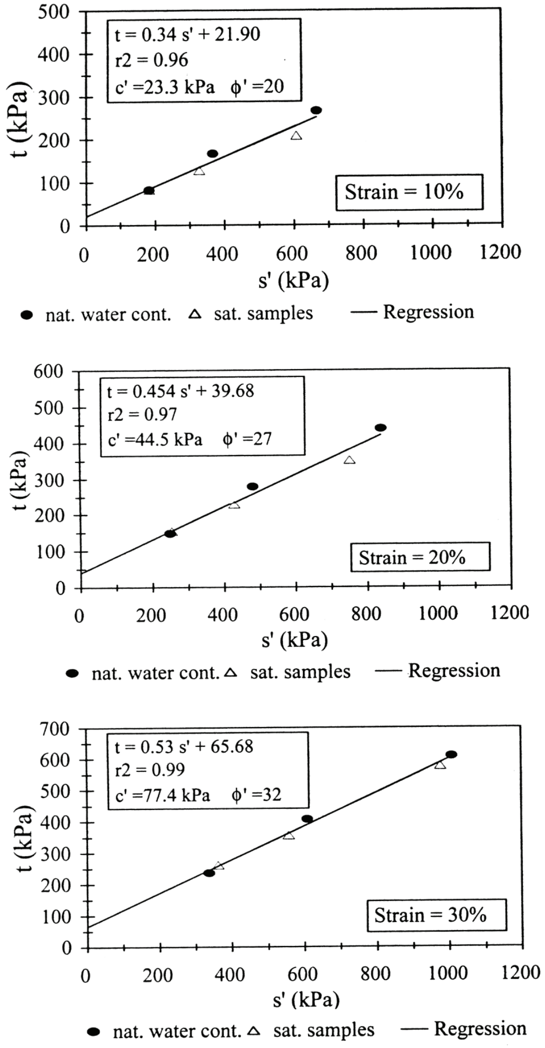


FIG. 16. Shear strength envelopes for triaxial specimens on MSW. Unit weight 12 kN/m^3 both saturated and unsaturated (Vilar and Carvalho, 2002).

Gomes et al. (2002) performed two TX tests under a confinement of 100 kPa on specimens collected from the Santo Tirso landfill. The resulting stress-strain relationships (as shown in Figure 17) are consistent with those published previously and all TX compression test results indicate a strain hardening response for strains up to 30 to 40%. The authors do not state the unit weight or the size of the specimen. Mahler and De Lamare Netto (2003) performed large-scale DS tests (400 x 250 x 100 mm) on waste in which particles greater than 20 mm were removed from the area of Rio de Janeiro in Brazil. With the larger waste particles removed, the stress-strain curves were hyperbolic in shape and exhibited a post-peak drop in strength. Towhata et al. (2004) performed TX tests (d = 10 cm and h = 20 cm) using only particles smaller than 1 cm. The authors tested organic waste imported from Germany as well as incinerated waste from Tokyo, Japan. The unit weight of the specimens ranged between 7.4 to 7.7 kN/m^3. The organic waste did not reach peak strength within the range of tested deformation with a linear stress-strain behavior observed until axial strains of about 20%. The authors attributed this response to the stretching of plastic sheets in the horizontal direction. To validate this concept the authors conducted tests on the same organic waste without any plastic sheets. This specimen yielded at axial strains of about 15%. The specimen was also stiffer in smaller strains due to its higher unit weight (i.e., 8.8 kN/m^3). A similar response with the organic material with plastics was also observed for the inflammable waste specimens from Tokyo, which had a unit weight of about 5 kN/m^3. The strength was defined as the shear stress mobilized at 15% axial strain, because the specimens did not yield.

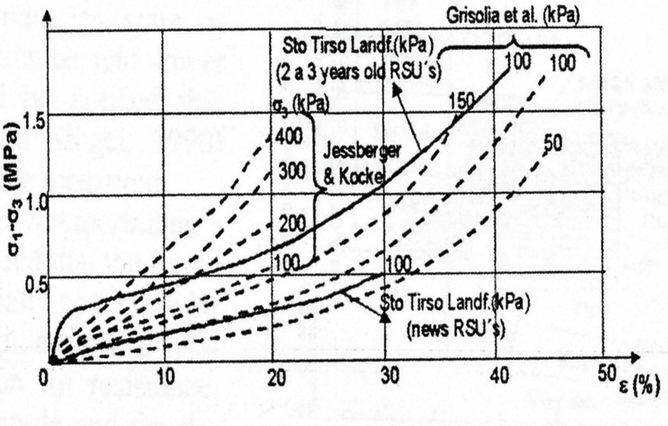


FIG. 17. Stress-strain relationships from TX tests performed by Gomes et al. (2002)

Reddy et al. (2009) presented results from small-scale laboratory tests performed on shredded fresh MSW collected from the working face of Orchard Hills Landfill located in Illinois, USA. Based on 63 mm diameter DS tests, drained cohesion values varied from 31 to 64 kPa and the drained friction angle ranged from 26 to 30 degrees. Small-scale CUTX tests (d=70 mm) performed on saturated MSW showed the total strength parameters (c and ϕ) to be 32 kPa and 12 degrees and the effective strength parameters to be 38 kPa and 16 degrees for a failure criterion of 15% axial strain starting from isotropic conditions. The stress-strain response did not exhibit a pronounced upward curvature as typically observed in large-scale testing of MSW.

Bray et al. (2009) report the results of a comprehensive large-scale laboratory testing program performed on MSW retrieved from a landfill in the San Francisco Bay Area of California. Waste samples collected at the Tri-Cities landfill were reconstituted and subjected to monotonic loading in three different large-scale testing devices. The DS box was 300 mm by 300 mm (h = 180 mm); the TX device was 300 mm in diameter (h = 610 mm); the SS device was 400 mm by 300 mm (h = 150 mm). A total of 23 DS, 27 TX, and 3 SS large-scale monotonic loading tests were performed. Additional testing was performed in a 71 mm diameter TX device. The effects of test device, waste composition, fibrous particle orientation, confining stress, rate of loading, stress path, stress-strain compatibility, and unit weight on the shear strength of MSW were evaluated. Additional details are presented in Zekkos (2005).

Triaxial compression testing on MSW material with and without fibrous waste (i.e., with and without material larger than 20 mm in dimension) was performed by Bray et al. (2009). As shown in Figure 18, the stress-strain responses from these TX compression tests exhibit upward curvature only for specimens that contained larger than 20 mm material (i.e., fibrous waste). In these specimens, the shearing surfaces cut across fibers to engage their reinforcing effect. The failure surface in a typical TX compression test on MSW is oriented at an angle of about 60 to 65 degrees from the horizontal so that it cuts across the predominantly horizontally layered fibrous waste particles. Additionally, MSW specimens compress significantly during axial loading and large axial strains (e.g., greater than 10 to 20%) are often required to mobilize friction angles of 30^o or more in isotropically consolidated TX compression tests. However, if the field K_o consolidation condition is taken into account, they showed that the strain-dependent mobilized shear strength in MSW in TX compression tests are consistent with back-calculated field and DS laboratory friction angles. The mobilized strength of MSW TXC at a limiting strain of 5% beyond an in situ stress state of K_o= 0.3 provides a secant friction angle on the order of 38^o to 42^o for confining stresses up to 200 kPa.

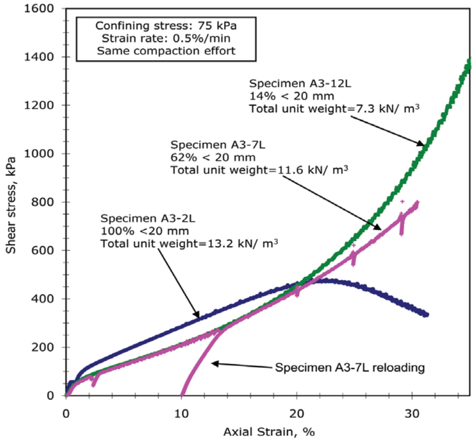


FIG. 18. Responses of MSW in monotonic triaxial compression testing for specimens with varying waste compositions (Bray et al. 2009).

TX unloading tests indicate substantial unconfined compressive strength for consolidated MSW. Their tests suggest that waste material that has been under relatively high confining stress has relatively high strength in unconfined conditions, especially if the test specimen has been unloaded significantly before shearing. The fibrous nature of larger waste particles, particle interlocking, and stress history effects on the "soil-like" finer waste fraction likely contribute to the relatively high strength of waste that has been unloaded. These tests results help explain field observations of unsupported high vertical cuts in consolidated MSW being stable for periods of months to years (e.g., Kavazanjian et al. 1995).

The Bray et al. (2009) results from performing DS tests on specimens in which the preferred orientation of the fibrous waste was oriented at different angles to the shear plane illustrate the anisotropic nature of MSW. As shown in Figure 19, when the fibrous waste particles are oriented parallel to the shearing surface (i.e., $i = 0^{o}$), they exert little influence on the DS response of the waste material. However, when the fibrous waste particles are oriented across the horizontal shear plane, the response of the MSW changes dramatically. The shear resistance of MSW measured in typical DS testing is representative of the shear resistance along a shear plane oriented such that the contribution of the fibrous waste materials is minimal (i.e., shearing is parallel to the preferred fiber orientation). When shearing is constrained to cut across long, fibrous waste particles, the shear resistance of MSW increases significantly and a strain hardening response is observed (i.e., there is an upward curvature of the stress-displacement response). These observations suggest that the upward curvature often observed in TX tests is attributable to the progressive contribution of the fibrous materials when the shear plane cuts across the long axis of the fibrous particles.

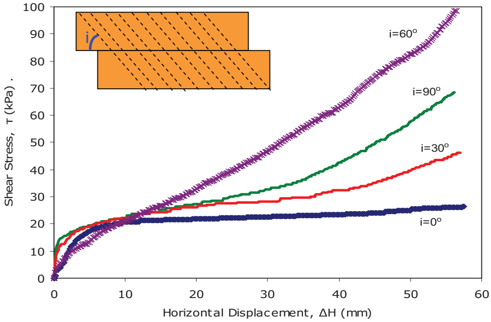


FIG. 19. Stress-displacement response for MSW specimens with plastic reinforcement oriented at different angles at a normal stress of 50 kPa (Bray et al. 2009).

Bray et al. (2009) developed a non-linear shear strength envelope that was independent of the amount of fibrous material in the MSW for assessing the case when shearing occurs parallel to the preferred orientation of the larger fibrous particles within MSW (Fig. 20a). As shown in Fig. 20b, the secant friction angle reduces with increasing confining stress. The DS strength of the Tri-Cities landfill waste materials from this initial test series was defined by:

$$\tau = c + \sigma_n \cdot \tan(\phi_\sigma) \tag{1}$$

where τ is the DS shear strength of Tri-Cities MSW, c is the cohesion intercept, σ_n is the total normal stress, and ϕ_σ is a normal stress dependent friction angle given by

$$\phi_\sigma = \phi_o - \Delta\phi \cdot \log\left(\frac{\sigma_n}{p_a}\right) \tag{2}$$

where ϕ_o is the friction angle measured at a normal stress of one atmosphere, $\Delta\phi$ is the change of the friction angle over one log-cycle change of normal stress, and p_a is atmospheric pressure (i.e., 101 kPa). The Tri-Cities landfill MSW DS test results are best characterized by $c = 15$ kPa, $\phi_o = 41^{\circ}$, and $\Delta\phi = 12^{\circ}$.

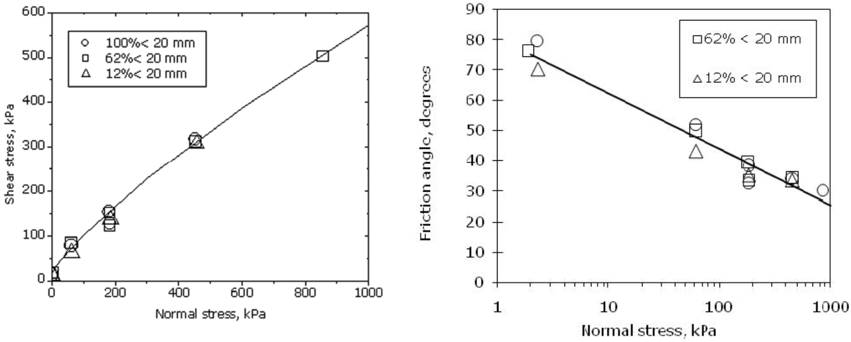


FIG. 20. Direct shear strength of Tri-Cities landfill MSW: (a) curved strength envelope for samples with varying waste composition, and (b) decrease in secant friction angle with increasing normal stress assuming c = 15 kPa (Bray et al. 2009.)

Bray et al. (2009) also investigated strain-rate effects by shearing MSW specimens at different strain rates. As shown in Figure 21, the shear stress mobilized at the higher strain rate is systematically higher than that mobilized at the lower strain rate imposed in this DS test on MSW. The mobilized shear stress was found to increase as the loading rate increased by approximately 10-15% per log cycle of strain rate (i.e., a trend similar to that observed with clayey soils). Strain-rate effects appear to be more pronounced for specimens with higher amounts of fibrous waste material. They recommended that a conservative estimate of the dynamic shear strength for MSW under earthquake loading rates is 1.2 times its static shear strength. Their recommendations are based on tests of MSW with a moisture content below its field capacity; cyclic degradation due to pore pressure generation was not been considered in this study.

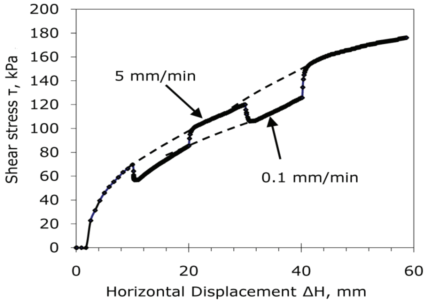


FIG. 21. Response of MSW with 62% less than 20 mm material in DS testing loaded at two displacement rates (Bray et al. 2009).

2.3 BACK-CALCULATIONS FROM FIELD CASES

Howland and Landva (1992) developed estimates of MSW shear strength from a landfill failure in New Jersey that occurred after approximately 50 feet of new waste was placed over 15-year old waste in a 4 to 5 month period. The failure apparently initiated in the underlying tidal marsh deposit and propagated up through waste. A significant amount of rain was reported over a three day period prior to the failure. The authors also back-calculated MSW shear strength based on a plate load test that was performed on top of the OII landfill in southern California. Inclinometers measured a maximum lateral movement of 43 cm during testing. The authors compared the back-calculated strength estimates with large-scale laboratory DS tests performed by Landva and Clark (1990) and in situ DS tests performed by Richardson and Reynolds (1991). They concluded that the back-calculated shear strength of MSW from field data is significantly lower than the strength measured in the DS tests. The reasons for this difference are unknown, but they could be due to scale effects, uncertainties in the soil properties assumed, and the assumption of a factor of safety (FS) of one. From these data, Howland and Landva (1992) developed a lower bound estimate of $c = 10$ kPa and $\phi = 23^{o}$.

In reviewing the understanding of the shear strength of MSW at that time, Kavazanjian et al. (1995) summarized multiple case histories, including the New Jersey landfill failure and the plate load test at the OII landfill. The authors noted that the back-calculation of the New Jersey landfill failure presented in Howland and Landva (1992) underestimates the shear strength of MSW because failure of the marsh foundation soil occurred at relatively small displacements and hence, only a portion of the shear strength of the MSW was mobilized. The authors also stated that the assumption of a FS = 1 was overly conservative for interpreting the OII landfill plate load test, because the test was terminated before the waste actually failed. Kavazanjian et al. (1995) presented the data shown in Figure 22, which is based primarily on shear strengths back-calculated from case histories and results of in situ DS testing. Laboratory data were not used with the exception of one data set from large-scale tests by Landva and Clark (1990). They assumed $c = 5$ kPa and utilized the modified Bishop method of slices with a FS = 1.2 to back-calculate their field shear strength estimates. As shown in Fig. 22, Kavazanjian et al. (1995) proposed a bilinear shear strength envelope for MSW defined by $c = 24$ kPa and $\phi = 0^{o}$ for normal stresses less than 30 kPa and $c = 0$ kPa and $\phi = 33^{o}$ for normal stresses greater than 30 kPa. With the exception of two data points (i.e., from the Lopez Canyon landfill), they note that this shear strength envelope is conservative.

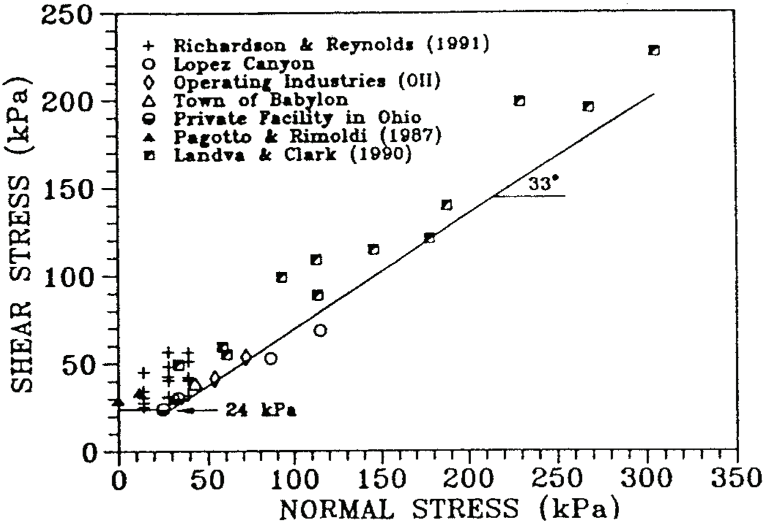


FIG. 22. Shear strength envelope proposed by Kavazanjian et al. (1995).

Augello et al. (1995) presented results of an investigation of the seismic performance of solid-waste landfills during the 1994 Northridge earthquake. They estimated the dynamic shear strength of MSW assuming the Kavazanjian et al. (1995) unit weight and shear wave velocity profiles for MSW. Strain-dependent shear modulus reduction and material damping curves recommended by Kavazanjian and Matasovic (1995) and by Vucetic and Dobry (1991) for PI=200 were used. Assuming a FS = 1.2 and *c* = 0, Augello et al. (1995) back-calculated static friction angles between 19 and 35 degrees from their limit equilibrium slope stability analyses. Their back-calculated dynamic friction angles were between 30 and 40 degrees. From these back-calculated values, they concluded that the dynamic shear strength of the MSW is higher than its static shear strength. Augello et al. (1998) developed improved estimates of the MSW properties using updated waste characterizations. The MSW shear wave velocity and unit weight profiles of MSW recommended by Kavazanjian et al. (1996) were used. Assuming a FS = 1.3 and *c* = 0, the back-calculated static friction angles now ranged from 25 to 41 degrees. Their back-calculated dynamic friction angles at three unlined landfills ranged from 27 to 45 degrees, which again indicates that the dynamic strength of MSW is higher than its static strength. The authors recommended that the mid-range dynamic friction angles of 35 to 38 degrees were most appropriate for use in engineering practice, with $\phi = 35^{\circ}$ as their best estimate recommendation.

Eid et al. (2000) estimated the shear strength using primarily large-scale DS test results available in the literature, but they also included back-calculated shear strengths from four failed waste slopes for which the quality of information was sufficient to estimate reliably the shear strength of MSW. Nine other landfill slope failures were not included due to uncertainties in the analysis, such as incomplete geometry, piezometric/leachate pressure, shear strength, or subsurface information. The strength estimates from the four failed waste slope back-calculations were in good agreement with the DS test results (Figure 23). The authors recommended a cohesion intercept of 25 kPa and a friction angle of 35 degrees.

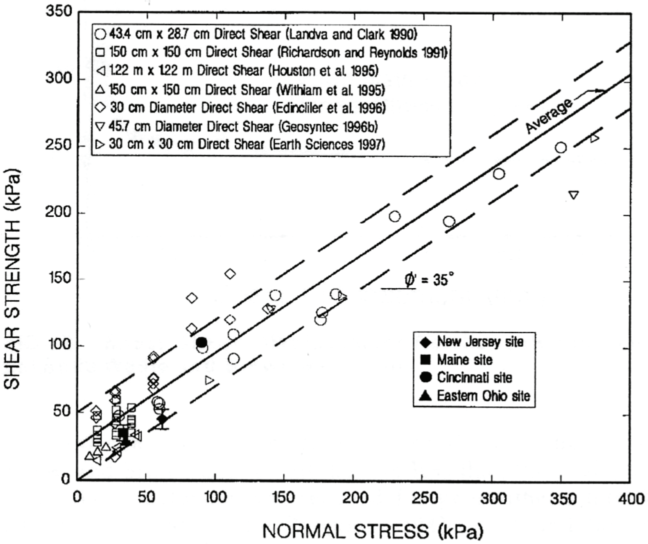


FIG. 23. Summary of measured and back-calculated data on shear strength of MSW (from Eid et al. 2000).

Bray et al. (2009) combined the results of more than 100 large-scale laboratory DS tests from several studies including their tests on the Tri-Cities landfill waste material. As shown in Figure 24, the DS static shear strength of MSW is slightly curved. The shear strength is best characterized by a friction angle of 36° at a normal stress of one atmosphere, with the friction angle decreasing by 5° for every log cycle increase in normal stress (i.e., using Eqs. 1 and 2: $c = 15$ kPa, $\phi_o = 36^{o}$, and $\Delta\phi = 5^{o}$). Other shearing modes that engage the fibrous materials within MSW (e.g., TX) produce higher friction angles. The $K_o = 0.3$ plus 5% additional strain criterion recommended by Bray et al. (2009) reduces the scatter in test results considerably compared to a criterion based upon strain measured from the isotropic consolidation stress state, and the use of $K_o = 0.3$ is more reasonable for most landfills. The $K_o = 0.3$ plus 5% criterion results in a TX compression test friction angles between 34° and 44°, with a mean value of 39°. Triaxial extension tests indicate that the peak strength of waste with fibrous inclusions can be greater than 50°, but peak strength is reached at relatively low strain levels (i.e., 1% to 4%). A relatively high friction angle could be employed to characterize the waste strength in TX extension but some conservatism is warranted, because some tests exhibited a post-peak strength reduction. The dynamic shear strength of was estimated to be 20% higher than its static shear strength; this estimate is believed to be conservative.

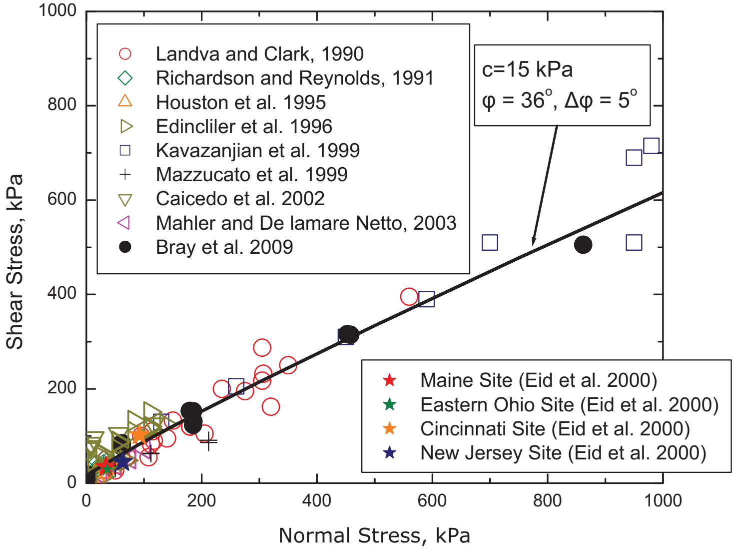


FIG. 24. Recommended static shear strength of MSW based primarily on DS tests and field observations of static slope stability, i.e., $c = 15$ kPa, $\phi_o = 36^{\circ}$, and $\Delta\phi = 5^{\circ}$ (after Bray et al. 2009).

2.4 PRIMARY FINDINGS AND RECOMMENDATIONS BASED ON PREVIOUS STUDIES

These previous studies of the shear strength of MSW that has a moisture content below its field capacity indicate:

- The Mohr-Coulomb strength criterion can be used to characterize the shear strength of MSW. Its static shear strength is primarily stress dependent (i.e., frictional), particularly at higher confining stresses, but it also has significant strength at low confining stresses (i.e., apparent cohesion). The shear strength at low confining stress appears to result primarily from the fibrous constituents of the waste.

- The friction angle of the MSW is stress dependent and can be characterized by the $\Delta\phi$ parameter (i.e., Eq. 2). The friction angle of MSW decreases as the normal stress increases.
- The shear strength used to characterize MSW depends on the specimen preparation procedures, testing conditions, and strength criterion used.
- Large-scale tests (at least 300 mm x 300 mm) provide reasonable estimates of MSW shear strength. "Undisturbed" and reconstituted large-scale DS tests on MSW performed indicate similar shear strengths. The shear strengths estimated from stable and failed waste slopes are similar to those estimated from DS tests performed on MSW. Small-scale specimens are of limited value in solid waste testing because they do not include the fibrous constituents that have been shown to play a significant role during shearing.
- Specimens with more fibrous waste materials are stronger than specimens with lower amounts of fibrous waste materials when the shearing of the test specimen cuts across the long-axis of the larger fibrous waste particles. The observed differences in the stress-strain response of MSW in TX compression tests and in DS tests can be explained by the "strain-hardening" influence of fibrous waste particles when shearing modes engage these larger particles. MSW in these cases responds as a reinforced material.
- Because of the upward curvature observed during the mobilization of the fibrous constituents, and the nonlinearity of the shear strength of MSW, authors should present representative stress-strain or stress-displacement responses as well as their interpreted strength parameters.
- Most studies that employed large-scale DS tests developed MSW static shear strength estimates of c and ϕ between 0 and 50 kPa and between 27^{o} and 41^{o}, respectively (typically, $c = 0$ to 25 kPa and $\phi = 33$ to 36 degrees). The most up to date strength recommendation by Bray et al. (2009) recommended that $c = 15$ kPa, $\phi_o = 36^{o}$ and $\Delta\phi = 5^{o}$. This MSW shear strength is appropriate for shearing that is parallel to the long axis of the fibrous material within the waste (i.e., largely horizontal sliding) and for waste having a moisture content below its field capacity.
- Utilizing TX compression test data to estimate the shear strength of MSW is complicated by the need to use strain level-based criteria of shear strength due to the lack of a well-defined peak strength. Additionally, the starting point of a strain-based criterion requires definition. Consequently, different TX test data interpretations provide different estimates of MSW shear strength. Static friction angles as high as 45^{o} to 53^{o} have been reported when using large strain levels (e.g., > 20%). However, when strength is evaluated at lower strain levels (e.g., 5%), which are typically considered appropriate for field characterization of MSW shear strength, TX compression test strength values are lower and more consistent with those derived by other means. A large set of TX compression test data compiled by Bray et al. (2009) indicates that the MSW shear strength mobilized at a limiting strain of 5% beyond an in situ stress state of $K_o = 0.3$ can be characterized by a secant friction angle between 34^{o} and 44^{o} (mean □ = 39^{o}) for confining stresses up to 400 kPa. This mode of shearing cuts across the fibrous waste particles, and thus, it is higher than developed in the DS tests when shearing

does not engage the fibrous waste particles. Triaxial shearing may be representative of the field shearing mode of waste in the case of the back-calculation of failed waste slopes

- TX extension tests indicate that the peak strength of waste with fibrous inclusions can be greater than 50^o. However, its peak strength is reached at relatively low strain levels (i.e., 1% to 4%), so stress-strain compatibility should be considered when selecting a friction angle, because a post-peak strength reduction was observed in some TX extension tests.
- There are relatively few large-scale SS tests reported on MSW. The shear strength interpreted from these large-scale SS tests was similar to the value interpreted from comparable large-scale DS tests only when the failure plane was assumed to be horizontal in the SS tests.
- Variations in the unit weight of MSW of 5% to 20% produced similar variations in the measured shear strength of similarly prepared MSW of similar composition. Strength increased as unit weight increased.
- The dynamic shear strength of MSW can be estimated conservatively to be 20% higher than its static shear strength, unless significant pore water pressure generation is anticipated during cyclic loading.

2.5 LIMITATIONS

There are several limitations to the profession's understanding of the shear strength of MSW, which include:

- The effects of the moisture content of MSW have not been explored fully, especially for cases in which the waste is saturated. Significant excess pore pressures could be produced during shear due to the highly compressible nature of MSW when the waste is saturated or nearly saturated. Additionally, the continual formation of landfill gas in saturated MSW can exacerbate the buildup of excess pore water pressures (Merry et al. 2006). These effects can lead to a significant drop in effective stress and a loss in shear strength. Potential strength loss due to excess pore pressure generation in saturated waste has not been investigated fully. However, when moisture contents are in the range of 10% to 25%, which is at or below the field capacity of most MSW materials, moisture content has not been found to be a key factor.
- The effects of waste degradation on its shear strength have not been addressed adequately. Some have speculated that significant degradation of MSW lowers its strength (e.g., Turczynski 1988). The level of degradation within waste is hard to quantify. Although age is an important factor, waste composition, climate, water content, and landfill construction and maintenance procedures are also likely to be important. Additional work is warranted in this area, and caution should be exercised when evaluating the long-term strength of MSW for landfills that are anticipated to undergo significant waste degradation.
- Advancements in the profession's understanding of the stress-strain response of MSW are hindered by the lack of a consistent specimen preparation and testing procedure for MSW testing. Researchers have used different specimen sizes with different maximum particle sizes and different specimen preparation techniques.

> In many cases, authors do not report all of the information that is required to interpret the test data. Consequently, there are significant inconsistencies among the findings of the many of the studies. Adoption of the waste characterization, specimen preparation, and testing procedures recommended in this waste symposium, or those described in Zekkos (2005), would eliminate many of the inconsistencies and uncertainties in waste strength characterization.

2.6 CONCLUDING REMARKS

Several large-scale testing programs have been conducted to evaluate the shear strength of MSW given a moisture content that is below its field capacity. Waste composition, unit weight, fibrous particle orientation, testing stress path, stress-strain compatibility, the interpretation of strength tests, confining stress, and rate of loading were found to be important issues to consider. For sliding parallel to the preferred orientation of the fibrous particles within MSW, the DS test appears to capture the load-displacement-strength response of MSW best. For this shearing mode, the stress-dependent Mohr-Coulomb strength criterion can be characterized with: c = 15 kPa, $\phi_o = 36^{\circ}$, and $\Delta\phi = 5^{\circ}$. Other shearing modes that engage the fibrous materials within MSW (e.g., TX) produce higher friction angles. The dynamic shear strength of MSW below its field capacity can be assumed to be 20% greater than its static strength. Issues such as the undrained response of saturated waste and the effects of waste degradation warrant further investigation.

The profession's understanding of the mechanical response of municipal solid waste (both monotonic and cyclic) has improved significantly over the last two decades. However, several important questions remain unanswered as our treatment of waste properties becomes more sophisticated. Standardized field characterization procedures, waste sampling protocols, specimen preparation methods, and laboratory testing techniques are required if significant advances in waste mechanics research are to be made. The waste mechanics discipline is at the point where standardized waste characterization procedures are required. Therefore, the development of a standardized, widely accepted and applied waste characterization framework is the top research need at this time. There is a myriad of other issues to investigate further, such as the use of advanced field and laboratory testing equipment and procedures, but the transfer of knowledge of waste property information is currently hindered by the lack of standardized, widely accepted methods for characterizing and testing waste.

2.7 ACKNOWLEDGMENTS

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Chapter 3

Settlement: the short and the long of it.

John McDougall[1]

[1]Reader, School of Engineering & Built Environment, Edinburgh Napier University, U.K.

3.1 INTRODUCTION

Total settlement in municipal solid waste (MSW) landfills can be considerable, from 25% to 50% of original fill thickness (Bjarngard and Edgers, 1990). Some occurs very quickly, i.e. during the filling phase (or short term), but there remains a significant amount of long-term settlement. Deformations of this magnitude and duration impact on the design, operation, closure and future use of landfills. Long-term settlement defines the pre-closure fill level and hence chargeable void space. If the eventual settlement is excessive or unforeseen, the integrity of the capping layer and any infrastructure for the collection of gas or recirculation of leachate may be compromised. Even if the capping layer remains intact it is necessary to avoid depressions on the upper surface where rainwater could pond. Finally, since settlement can continue for many years, it will pose a constraint on future development, including vertical expansion of the site. So, for engineers charged with the design of a landfill facility or site restoration, an understanding of, and ability to analyse, landfill settlement is required.

It is well known that landfill settlement is the product of a combination of processes, including load and biodegradation-related phenomena. Whilst existing geotechnical settlement models can handle load effects, they are limited in their ability to deal with biodegradation. There already exist a number of good reviews of the form and capability of these models, see for example, El-Fadel and Khoury (2000); Elagroudy et al. (2008). In this chapter conventional methods of geotechnical settlement analysis are reviewed as the background to recent work to develop a more fundamental approach to landfill settlement analysis. In addition to the review papers, there are a number of research papers that have contributed to the preparation of this chapter but which have not been expressly cited; these papers are collected in the bibliography.

It should also be noted that this chapter reports on a state of knowledge during and immediately following the International Symposium on Waste Mechanics, which was held in New Orleans following GeoCongress 2008. Papers published in 2009 and 2010 have not been included in this review.

3.2 GENERAL FEATURES

In general, landfill settlement is a combination of short-term load-related displacement and long-term displacement under constant load. The magnitude of short term settlement can be large but is adequately explained by conventional geotechnical techniques. The magnitude and nature of long-term landfill settlement were first elucidated nearly 50 years ago. Merz and Stone (1962) reported that test cells in which biodegradation had been enhanced showed settlement three times greater than that occurring in a control cell. Sowers (1973) concluded that the rate of long-term or secondary settlement is related to the organic content. He gave mathematical interpretations of load and long-term settlement. Yen and Scanlon (1975), from data extending over a 9 year period, observed a logarithmic relationship between rate of settlement and time. The influence of these early studies has been long-lasting, especially Sowers' model, probably due to its simplicity.

Some 15 years later the existence of two distinct phases of secondary settlement was recognised, first by Bjarngard and Edgers (1990) who investigated a large field data set, and later by König, et al. (1996), see Figs. 1 and 2. Explanations were given in terms of settlement mechanisms of the kind first put forward by Sowers. In the first phase settlement occurs at a relatively slow rate and is dominated by mechanical processes whereas in the second phase there is a higher rate of settlement attributed to decomposition.

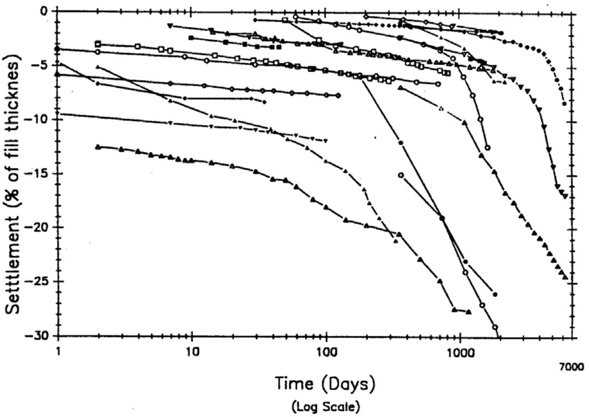

FIG 1. Landfill settlement vs. log time from field case histories (Bjarngard and Edgers (1990)

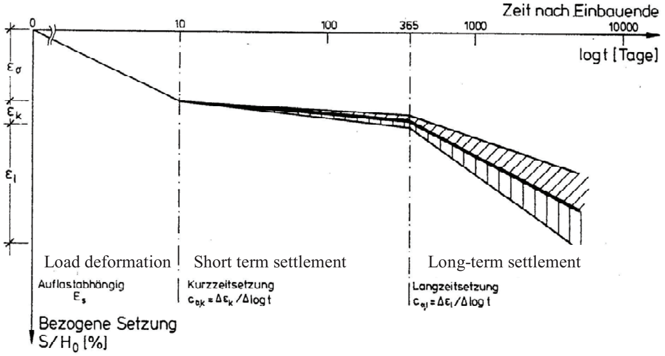

FIG. 2 Idealisation of settlement over time (from König et al, 1996)

3.2.1 Mechanisms of settlement & temporal classification

Settlement in landfilled waste is commonly described in terms of the five mechanisms identified by Sowers (1973):

- Mechanical: distortion, bending and crushing
- Ravelling: erosion, sifting of fines
- Physico-chemical: corrosion, oxidation and combustion
- Bio-chemical decay: fermentation & decay, aerobic and anaerobic
- Interactions, between the four other mechanisms.

Yen and Scanlon (1975) also identified five mechanisms of long-term settlement, which correspond closely to Sowers:

- Movement of fines into large voids
- Strength loss due to chemical & biological reactions
- Material loss due to biodegradation and methane production
- Creep processes
- Consolidation processes.

It is evident from these lists that there are mechanisms contributing to settlement in waste refuse that do not occur in engineering or inert soils. In fact only creep and consolidation would be recognised as conventional settlement mechanisms and the existence of consolidation in MSW has been questioned since (i) waste is less than fully saturated, especially at the time of placement, and (ii) even if saturated, has a permeability that is too high to allow any persistent build up of excess pore water pressure (Bjarngard and Edgers, 1990; Wall and Zeiss, 1995).

The likely incidence of settlement mechanisms during the life of a landfill site is shown in Fig. 3. Settlement following load, which may be due to self-weight or surcharge, e.g. capping, is generally regarded as complete within about a month of application. Mechanical creep is usually regarded as occurring at a gradually decreasing rate, *ceteris paribus*, throughout the life of the site although between one and 30 days creep effects are probably masked by load-related effects. According to Bjarngard and Edgers (1990) and König et al. (1996), biodegradation-related effects rise to prominence after about one year. Physico-chemical/corrosion effects and ravelling are probably the least well understood mechanisms. The former is shown as a rising then falling rate trend but of smaller magnitude than biodegradation; in the absence of better information, the latter is assumed to be constant throughout.

Not surprisingly, the variability of the waste stream, over time and between locations, means that the influence, if not the existence, of individual mechanisms will differ from site to site. A universal interpretation of landfill settlement behaviour has therefore proved elusive; however, there is some consensus on its temporal classification.

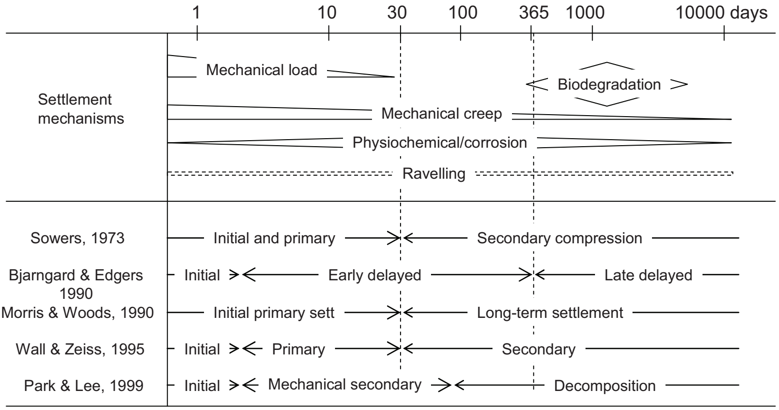

FIG. 3 Occurrence of settlement mechanisms and temporal classifications adopted by selected publications.

The bottom part of Fig. 3 shows the temporal classification of settlement as proposed by several researchers. There is consensus about the sequence of mechanisms. Load-related effects, commonly referred to as *Initial* and *Primary* settlement are thought to occur over the first month by Sowers (1973), Morris and Woods (1990) and Wall and Zeiss (1995). After one month, mechanical creep, physico-chemical/corrosion and biodegradation related effects dominate in what is collectively referred to as either the *Secondary* or *Long-term* phase. This phase can continue for 30 or more years. Bjarngard and Edgers (1990) and Park and Lee (1997), use different terminologies and time frames but their interpretations are consistent with others and the general sequence of settlement mechanisms.

Hence a combination of *primary* and *secondary* settlement conveniently classifies the mechanisms contributing to landfill settlement. Primary settlement occurs very quickly by comparison to the life of the landfill and can be adequately described by load-induced settlement models. Secondary settlement, driven by biodegradation effects, creep and physicochemical corrosion is a long-term phenomenon, which has for some time relied on time-dependent methods.

Before taking a closer look at existing and the newly developing more fundamental landfill settlement models, it is instructive to recognize the range of influencing factors that the input parameters of landfill settlement models strive to represent.

3.2.2 Influencing factors

Figure 4 shows a range of factors influencing landfill settlement feeding into a simplified suite of primary and secondary settlement mechanisms. Influencing factors can be viewed as (i) factors defining the condition of the waste within a landfill cell, i.e. internal to the landfill (the boxed factors), and (ii) factors or site operations and controls or initial conditions which influence the internal conditions. Some of the factors influencing biodegradation, namely moisture, leachate and gas composition, are not readily or explicitly incorporated into conventional settlement models. Moreover, during the period under investigation, the influence of these factors can change and in a way that is neither gradual nor predictable. Indeed, Landva et al. (1984) concluded that decomposition effects are too complex to predict.

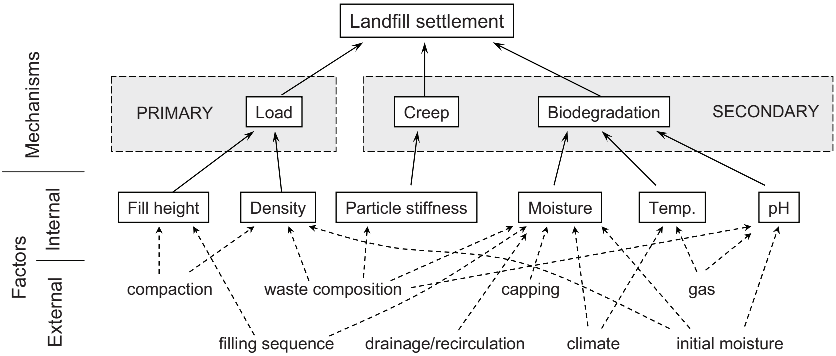

FIG. 4 Mechanisms and factors influencing landfill settlement.

Factors controlling the chemical and (micro)biological processes were considered in the very earliest investigations into landfill settlement. Watering and aerobic conditions were observed to be responsible for settlement some three times greater than that occurring in a dry anaerobic cell (Merz and Stone, 1962). Sowers (1973) noted that keeping a site dry may halt decomposition. He also recognised the complex role of moisture noting that flooding with no opportunity for water circulation may also halt decomposition because of (microbial) product inhibition. El-Fadel (1999) reported on factors such as moisture, sludge and buffer addition and their impact on biodegradation in a series of test cells at the Mountain View Controlled Landfill Project. Significant increases in the amount and rate of settlement were observed when biodegradation is enhanced (as indicated in the data presented in Fig. 5) and was shown by Benson et al. (2007). A fundamental understanding of the factors controlling waste decomposition elucidated by environmental engineers and others with expertise in microbiology is now well established, e.g. Farquhar and Rovers (1973); Leckie et al. (1979); Barlaz et al. (1989).

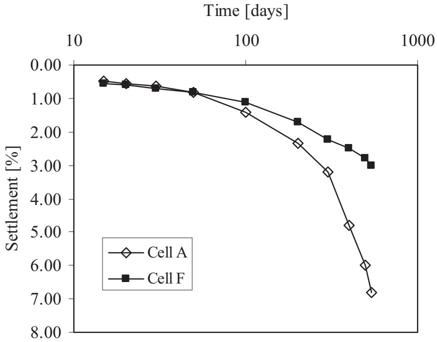

FIG 5. Effect of leachate recirculation on settlement magnitude [Cell A]; adapted from El Fadel (1999) [Cell F = control]

3.3 PRIMARY (LOAD-RELATED) COMPRESSION MODELS

Primary or load-related compression analysis and prediction has a long history in geotechnical analysis. The landfill settlement analysis described here is one dimensional, in the vertical direction, and occurs in response to changes in vertical stress. The relationship between stress and strain is assumed, for the purposes of monotonic loading, to be adequately described by a compression index, compression ratio, or one-dimensional (constrained) modulus.

3.3.1 Compression index

The compression index is the slope of the void ratio-log vertical stress relationship, i.e.

$$de = C_C \log\left(\frac{\sigma_{V0} + d\sigma_V}{\sigma_{V0}}\right) \tag{1}$$

where

e = void ratio
C_C = compression index [dimensionless]
σ_{V0} = the initial vertical stress
$d\sigma_V$ = change in vertical stress

Sowers (1973) and Morris and Woods (1990) proposed the use of a compression index, concluding that its value was related to initial void ratio. Sowers indicates that C_C is $0.15e_0$ for fills low in organic and $0.55e_0$ for fills high in organic content. Use of the compression index is hindered by the difficulty of determining the void ratio in waste.

3.3.2 Compression ratio

The compression ratio, also referred to as the modified compression index, is the slope of the vertical strain-log vertical stress. It avoids the need to determine the void ratio.

$$d\varepsilon = \frac{dH}{H_0} = C_R \log\left(\frac{\sigma_{V0} + d\sigma_V}{\sigma_{V0}}\right) \tag{2}$$

where

$d\varepsilon$ = vertical strain increment

dH = change in height

H_0 = initial height

C_R = compression ratio [dimensionless]

Oweis and Khera (1998) summarise C_R and C_C values for a range of waste types; for example C_R values range between 0.08 (for 15 to 20 year old waste) to 0.41 (waste with high organic content).

Kavazanjian et al. (1999) also reported compression ratio values for a number of waste samples tested in a large laboratory (460 mm diameter by 460 mm high) oedometer. Their results (Fig. 6) indicate virgin compression ratios of between 0.121 and 0.247; they also reveal irreversibility in the load-strain behaviour.

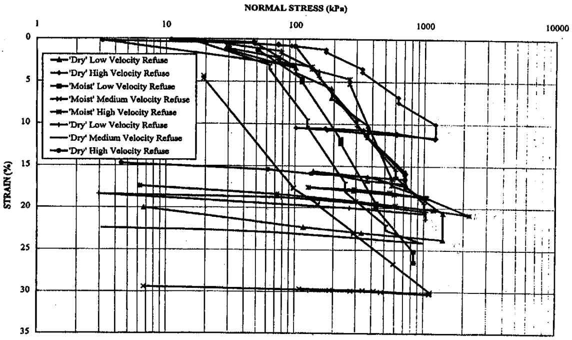

FIG. 6 Large scale laboratory compression data from Kavazanjian et al. (1999)

3.3.3 One-dimensional (Constrained) modulus

The one-dimensional (or constrained) modulus is defined as:

$$d\varepsilon = \frac{dH}{H_0} = \frac{d\sigma_V}{D} \tag{3}$$

where

D = one-dimensional modulus [kN/m^2]

The magnitude of the constrained modulus is dependent on the applied stress level, whereas the compression index and compression ratio values are constant with the logarithm of stress. Watts & Charles (1990, 1999) measured constrained modulus values for a range of waste types and sites finding values ranging between 550 and 6000 kN/m^2. Beaven and Powrie (1995) and Jessberger and Kockel (1995) also used the constrained modulus.

3.3.4 Compressibility: primary compression ratios and one dimensional moduli

Compression ratios can be converted to an equivalent constrained modulus by combining Eqs. 2 & 3,

$$C_R \log\left(\frac{\sigma_V + d\sigma_V}{\sigma_V}\right) = \frac{d\sigma_V}{D}$$

From which we can deduce that for a unit increment of vertical stress $d\sigma_V$ at stress level σ_V,

$$D = \frac{1}{C_R \log\left(1 + \frac{1}{\sigma_V}\right)} \tag{4}$$

Figure 7 shows a selection of measured compression ratio values (converted to constrained modulus values using Eq. 4) is presented together with directly measured constrained modulus values. Some of the outlying values, such as the high modulus values reported by Watts and Charles (1999), are known to be obtained from 40 year old refuse having a high bulk unit weight, i.e. 18 kN/m^3, with noted ash and rubble content. Notwithstanding the outliers, directly measured constrained modulus values, both in the laboratory and in the field, lie within the range of compression ratios reported by Oweis and Khera (1998), i.e. from 0.08 to 0.41. There is no clear influence of age on compressibility; the compressibility of the aged waste tested by Beaven (1999) reveals a compressibility closer to the high organic content waste in conditions favourable to decomposition reported by Oweis and Khera, rather than the 15-20 year old waste (also reported by Oweis and Khera).

It should be borne in mind however, that the physical condition of aged waste in the laboratory is usually different to that in the field. The decomposition process will produce a waste structure that is destroyed by sampling and subsequent placement in a laboratory cell. Compaction will probably produce a denser matrix with lower porosity in the laboratory compared to the in situ condition.

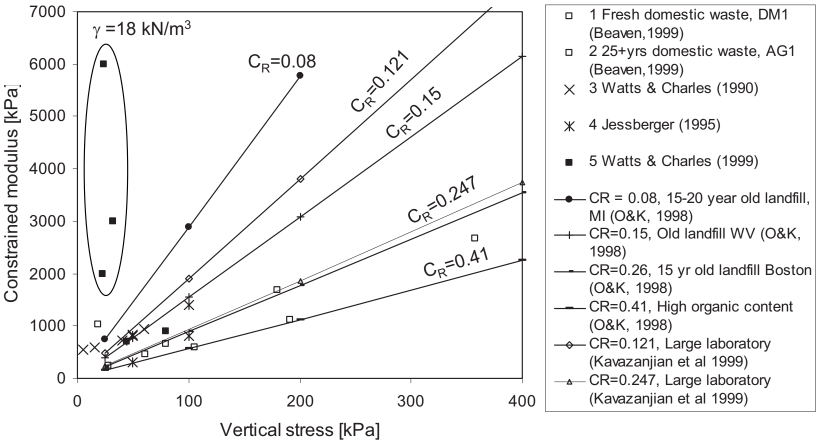

Fig. 7 Measured waste compressibility shown as constrained modulus values. Data points measured as constrained modulus; connected data calculated as constrained modulus from compression ratio values as denoted.

3.4 TIME-DEPENDENT SETTLEMENT MODELS

The complexity of the factors controlling the full range of secondary settlement mechanisms and the difficulty of their measurement, especially in the field, encouraged considerable interest in time-dependent methods. Simple in form, these models relate surface settlement to time and may be expeditious if the landfill milieu evolves in a gradual and predictable way. Several functions have been used:

3.4.1 Logarithmic (or 'soil mechanics')

Originally proposed by Sowers (1973), this form of settlement model is familiar as the soil mechanics secondary compression model,

$$de = C_\alpha \log\left(\frac{t_2}{t_1}\right) \tag{5}$$

where

C_α = secondary compression index [dimensionless]
t_1 = initial time of interest
t_2 = later time of interest

Morris and Woods (1990) and Wall and Zeiss (1995) avoid determination of void ratio by using a secondary compression ratio,

$$d\varepsilon = \frac{dH}{H_0} = C'_\alpha \log\left(\frac{t_2}{t_1}\right) \tag{6}$$

where C'$_\alpha$ is the modified secondary compression index or secondary compression ratio, i.e.

$$C'_\alpha = \frac{C_\alpha}{1+e_0} \tag{7}$$

3.4.2 Exponential (or Rheological)

Originally proposed by Gibson and Lo (1971) for long-term settlement of peat, the rheological model was first applied to waste refuse by Edil et al. (1990). It is a combination of a Hookean spring representing primary stiffness and a Kelvin element representing long-term settlement. This model can also account for primary settlement, although for the purposes of this review, only the time-dependent component is considered.

$$s(t) = H \cdot \Delta\sigma\left\{a + b\left(1 - \exp^{\left(-\frac{\lambda}{b}t\right)}\right)\right\} \tag{7}$$

where

s = settlement
$\Delta\sigma$ = vertical stress increment
a = primary stiffness parameter
b = secondary stiffness parameter
λ = compression rate parameter
H= initial height of refuse

3.4.3 Power creep

Also presented by Edil et al (1990), the power creep model is given by,

$$s(t) = H \cdot \Delta\sigma . m\left(\frac{t}{t_r}\right)^n \tag{8}$$

where

m = model parameter (compressibility)
n = model parameter (rate of compression)
t_r = reference time (taken to be 1 day)
H= initial height of refuse

3.4.4 Hyperbolic

The hyperbolic model was first applied to MSW by Ling et al.(1998). It utilises the ultimate settlement magnitude and initial rate of settlement as key parameters in its formulation.

$$s(t) = \frac{t}{1/\rho_0 + t/s_{ult}} \tag{9}$$

where

ρ_0 = initial rate of settlement
s_{ult} = ultimate settlement

3.4.5 Form and limitations of simple time-dependent functions

The performance of the time-dependent settlement functions depends on their ability to match data and the inherent shape of the function. Figure 8a shows the shape of the four functions over a two year period. Model parameters have been contrived to force the functions to follow similar paths. It would appear that any of the functions might be tuned to a field data set over the short period in question. Indeed, efforts to match these functions to field data have lead to the following observations:

- The combination of mechanical secondary compression, physico-chemical action and biochemical decay follows a linear settlement-log time relationship when there has been no drastic change in the [landfill] environment – Sowers (1973)

- Back calculation of parameters from field data shows better fit for the power creep model than the rheological model – Edil et al (1990)

- Hyperbolic model performed better than either power creep or logarithmic model, with correlation coefficients greater than 0.97, when fitted to three field scale data sets – Ling et al (1998)

Consider now the long-term predictive capability of the simple models, i.e. of the functions themselves. Figure 8b indicates final settlement magnitudes to a logarithmic time scale. The rheological and hyperbolic models become asymptotic to a final settlement value and would seem to offer some realistic long-term settlement prediction. In contrast, logarithmic and power models predict ongoing settlement. In the case of the power law model, deceleration in the rate of settlement is slow and settlement has fallen off the scale in less than 3 years. Clearly, the choice of model has a dramatic influence on the prediction of ultimate settlement.

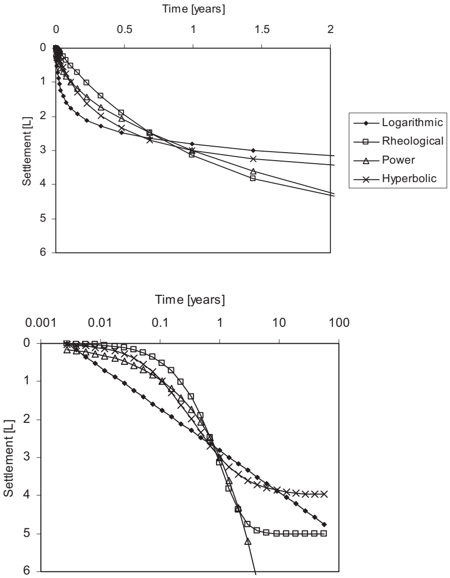

FIG. 8 Form of time-dependent functions over (a) two year period (a) and (b) much longer period (< 100 years)

Work to improve the long term fit of the time-dependent model functions has turned to two-stage secondary settlement models.

3.4.6 Two-stage secondary settlement models

Bjarngard and Edgers (1990) and König et al (1996) highlighted the existence of two identifiable stages of secondary settlement. The first is attributable to mechanical phenomena whereas the second is due to the onset of biodegradation and associated mass loss. Work by Hossain et al. (2003) on the settlement of degraded waste samples also points to a two-stage secondary process. However, care must be exercised in the interpretation of laboratory tests where degraded samples are remoulded into an oedometer as (already noted) the in situ fabric is inevitably lost. The simulation of secondary settlement including an accelerated phase of settlement improves the capability of time-dependent approaches. A number of models that expressly account for a second accelerated stage have been developed.

Edgers, Noble and Williams (1992)

Edgers et al. (1992) state that mass loss leads to a weakened matrix, increased compressibility and changed permeability. They also highlight the relevance of gas generation to secondary settlement. Indeed the kinetics of microbial growth is described as background to their two stage model but caution that the settlement mechanism is not at all clear. They idealised secondary settlement as a combination of (i) mechanical creep in the first stage described by a logarithmic model and (ii) bio-settlements in the second stage. In the first stage vertical strain is given by,

$$\varepsilon = \varepsilon_1 + \frac{A\exp^{(\alpha D)}t_1}{1-m}\left(\left(\frac{t}{t_1}\right)^{1-m} - 1\right) \quad \text{for m} \neq 1 \tag{10a}$$

$$\varepsilon = \varepsilon_1 + A\exp^{(\alpha D)}t_1 \ln\left(\frac{t}{t_1}\right) \quad \text{for m} = 1 \tag{10b}$$

where

ε = strain
D = stress level
ε_1 and t_1 are known reference values
A, α and m are rate process parameters.

The combination of Eq. 10 allows for non-linear ε-log t relationships, i.e. m ≠ 1.

In the second stage,

$$\varepsilon_{bio} = B\left(\exp^{\beta(t-t_k)} - 1\right) \tag{11}$$

where

B = scale factor corresponding to decomposition settlement
β = parameter reflecting microbial activity
t_k = time at which bio-settlements begin.

Excellent agreement for the model is claimed with four field cases for which B, β, and t_k could be back calculated.

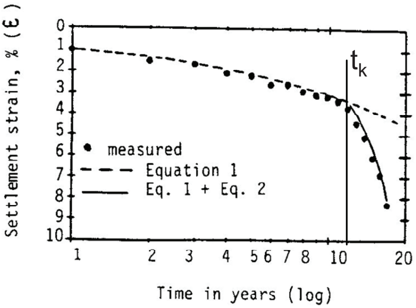

FIG. 9 Comparison of settlements including effects of decomposition using two stage secondary settlement model; modified from Edgers et al., 1992. Eqs. 1 & 2 in the figure refer to Eqs. 10a & 11 above.

Park and Lee (1997, 2002)

Park and Lee highlight the importance of biodegradation and the difficulty that soil mechanics has in accounting for biodegradation effects. They proposed a mechanical secondary compression stage using a combination of logarithmic and first order kinetic models. The logarithmic model is applied to the first stage,

$$\Delta\varepsilon(t)_{mec} = C_\alpha \log\left(\frac{t+\Delta t}{t}\right) \tag{12}$$

where C_α is the compression ratio (strictly C'_α according to the notation of Eqs. 5 & 6), followed by secondary compression due to decomposition depicted by first order kinetics,

$$\Delta\varepsilon(t)_{dec} = \varepsilon_{tot-dec}\left(1 - \exp^{(-kt_{bio})}\right) \tag{13}$$

where

$\varepsilon_{tot\text{-}dec}$ = total settlement due to decomposition
t_{bio} = time since decomposition settlement commenced.

Park and Lee are well aware of the microbial circumstances of the landfill environment, noting that the decomposition process is first methanogen-limited then, once methanogenesis is established, becomes hydrolysis-limited. Microbiological evolution and the associated decomposition can then be considered to reflect the progress of secondary settlement. They also highlight the importance of moisture availability in decomposition process.

El-Fadel, Shazbak, Saliby and Leckie (1999)

El-Fadel et al (1999) postulated an increase in void ratio and weakened structure due to biodegradation. They correlated settlement in six large field cells with three models, the power, Gibson & Lo (exponential) and 1-D consolidation (logarithmic) models, where the 1-D consolidation model is implemented as a two stage model.

The field cells, actually the Mountain View Controlled Landfill Project (Halvadakis et al. 1988), were configured to investigate a number of the factors controlling biodegradation, e.g. leachate recirculation and combinations of sludge, buffer and water addition. Secondary settlement in the logarithmic model was broken down into two separate stages defined by secondary compression ratios $C_{\alpha 1}$ and $C_{\alpha 2}$, where the ratio of $C_{\alpha 2}/C_{\alpha 1} \approx 10$ (strictly C'_{α} according to the notation of Eqs. 5 & 6). The distinction between the two stages is fixed by the time at which the slope of the stress-strain curve changes. Figure 10 shows the modelling and field results for cell B, which had sludge and buffer addition. Over the period and for all cells, it was noted that the two-stage 1-D consolidation model out-performed both the exponential (Gibson & Lo) and power models although the exponential model performed acceptably in all cases.

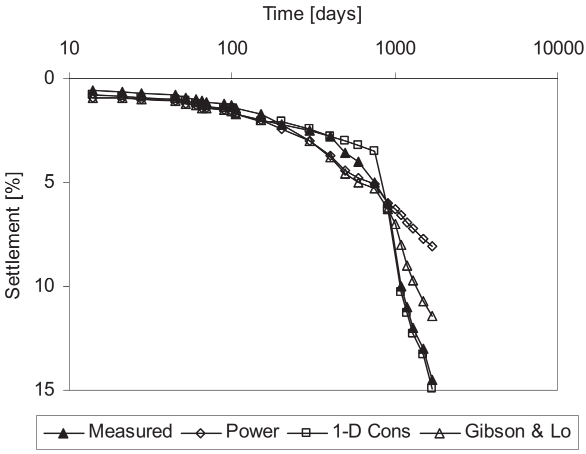

FIG. 10 Comparison of models with measured settlement data for cell B, Mountain View Controlled Landfill Project, after El Fadel et al. (1999)

Marques, Filz and Vilar (2003)

Marques et al. proposed a variant on Park and Lee's two stage model. They have first a mechanical creep stage (ε_C) followed by a biological decomposition (ε_B) stage. Mechanical creep is based on the exponential model,

$$\varepsilon = b\Delta\sigma\left(1 - \exp^{-ct'}\right) \tag{14}$$

where

b = creep coefficient
$\Delta\sigma$ = stress increment
c = compression rate parameter
t' = time since application of the stress increment.

Biological decomposition is also given by an exponential model,

$$\varepsilon = E_{DG}\left(1 - \exp^{-dt''}\right) \tag{15}$$

where

E_{DG} = total strain due to decomposition
d = decomposition rate parameter
t'' = time since placement of the waste in the landfill

In the models described so far, model parameters defined cell-averaged or site-wide conditions. Marques et al. point out that the implementation of their two stage model is on a layer basis, i.e. they model the filling phase. This is a matter which is addressed in more detail later in this chapter. Using model parameters obtained by regression analysis, surface settlements predicted by the model were found to be in good agreement with field data.

Hossain and Gabr (2005)

The model presented by Hossain and Gabr extends the two stage logarithmic model adopted by El Fadel et al. to three stages. An initial early stage of decomposition is proposed, when the landfill environment is predominantly acidogenic (or pre-methanogenic). Settlement is dominated by creep. In the next stage, biological decomposition is added. In the third stage, biological effects are exhausted but there remains some creep settlement.

Eq. 6 is used,

$$d\varepsilon = \frac{dH}{H_0} = C_R \log\left(\frac{t_2}{t_1}\right) \tag{6}$$

where three secondary compression ratios, corresponding to the early creep, biodegradation and final creep stages are $C_{\alpha i}$, C_β and $C_{\alpha f}$ respectively, are input into Eq. 6. There are four times, t_1 to t_4, corresponding to the start and end of the settlement stages as denoted in Fig. 11.

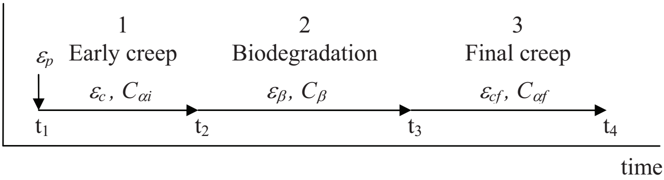

FIG. 11 Time dependent secondary settlement model extending to three stages as proposed by Hossain & Gabr (2005)

Small-scale laboratory compression tests provided values of $C_{\alpha i}$ and C_β ; the final creep stage was not considered so the comparison is of a two stage model only. A number of field projects, including the Mountain View Controlled Landfill Project (Halvadakis, 1988) and Yolo County landfill, were simulated. The test data was well matched by the model holding stage 1 and stage 2 compressibility ratios constant and manipulating only t_2 values, as can be seen in Fig. 12.

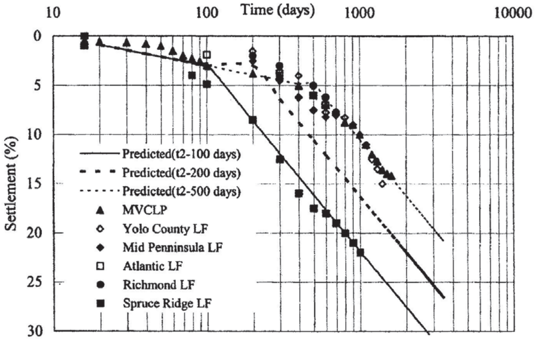

FIG. 12 Comparison of predicted and observed field settlement for bioreactor landfills, from Hossain and Gabr (2005)

3.4.7 Summary of two stage secondary settlement model and parameter values

The two stage models are a sequential combination of secondary settlement functions, as summarised in Table 1. Parameter value ranges, where provided, are also given.

3.4.8 Performance and limitations of time-dependent models

Time-dependent models appear to capture well the main landfill settlement features over sometimes considerable periods of time. However, in all cases model parameters have been tuned to fit model output to the data. The models have not yet been proven successful in the *a priori* prediction of either the magnitude or the timing of final settlement. Indeed, this may be an unrealistic expectation. It has been shown that different settlement models follow similar paths over short time frames but later diverge to quite different ultimate settlement magnitudes. Even if the choice of model is easy, the meaning of the model parameters and their determination is not. Biodegradation contributes significantly to total settlement and is a function of a complex set of conditions that extend beyond the normal geotechnical remit. Mapping both the biodegradation process and its manifestation as settlement onto a simple time-dependent function results in a highly empirical treatment of the phenomenon. The parameters in such a model lose physical meaning and can only be determined in an observational manner.

Nevertheless, some consistency has been found in secondary compression ratio values. Oweis and Khera (1998) reported secondary compression ratio values ranging between 0.001 for old landfills with high soil contents to 0.02 – 0.24 for old (15-20 yr) waste. Parameter values range over more than an order of magnitude. However, it is difficult to associate these data with particular wastes. Normal soil descriptions do not account for the state of decomposition and simple age descriptors may not give an adequate description. For example, a 1 or 2 year old waste at a site where decomposition has been allowed or even encouraged may be more degraded that 15 year old waste lying in a 'dry tomb' site. If biodegradation effects are to be accounted for in a predictive manner, a more fundamental treatment is required.

Table 1: Summary of functions used in two stage secondary settlement models and reported parameter values

	First stage	Second stage
Edgers, Noble and Williams (1992)	logarithmic	Exponential $\beta = 0.1622$ to $1.267\ \text{yr}^{-1}$
Park and Lee (1997, 2002)	logarithmic Fresh, field: $C_\alpha = 0.02$ Fresh, lab: $C_\alpha = 0.037$ 15 yrs, lab: $C_\alpha = 0.01$ 15~30 yrs, lab: $C_\alpha = 0.008$	Exponential Fresh, field: $\varepsilon_{tot\text{-}dec} = 10\text{-}25\%$; $k = 0.245 – 0.548\ \text{yr}^{-1}$ 8 yrs, field: $\varepsilon_{tot\text{-}dec} = <1\text{-}7\%$; $k = 0.584 – 2.19\ \text{yr}^{-1}$ 20 yrs, field: $\varepsilon_{tot\text{-}dec} = 1\text{-}3\%$; $k = 0.365 – 17.56\ \text{yr}^{-1}$
El-Fadel, Shazbak, Saliby and Leckie (1999)	logarithmic Field $C_{\alpha 1} = 0.015 – 0.035$	logarithmic Field $C_{\alpha 2} = 0.132 – 0.25$
Marques, Filz and Vilar (2003)	exponential 5 yrs, field $b = 4\times10^{-4}\ \text{m}^2/\text{kN}$ $c = 1\times10^{-3}\ \text{day}^{-1}$	exponential 5 yrs, field $E_{DG} = 0.15 – 0.21$ $d = 0.8\times10^{-3} – 2.5\times10^{-3}\ \text{day}^{-1}$
Hossain and Gabr[1] (2005)	logarithmic Field $C_{\alpha\iota} = 0.03$ $t_2 = 100 – 500$ days	logarithmic Field $C_\beta = 0.19$

[1] third stage not active

3.4.9 Time-dependent settlement with depth

Even if the issue of waste description can be avoided, say by conducting compression tests on a particular waste from the site under investigation, the state of decomposition may still affect settlement prediction. Working cells may be filled over a period of time extending two years. The measured surface settlement will therefore be a function of decomposition processes that may be considerably more advanced at the base of a site than in the upper layers.

With few exceptions, the time-dependent settlement models described so far have been applied to and/or obtained from a sample of waste or the full depth of a landfill cell. In other words, compression parameters have been cell- or depth-averaged. Compression ratios of this kind must be deployed judiciously. Alternatively, the settlement model may be deployed on a lift basis. Models presented by Morris and Woods (1990), Bleiker et al. (1995) and Marques et al. (2003) in the preceding section, offer such a capability. Both of these models apply the exponential model to individual layers of waste, summing the layer settlement predictions to obtain surface settlement.

Another model that exploits the time-dependent nature of the filling process is the Incremental Settlement Prediction Model (Olivier et al. 2003). In this model, the logarithmic function is applied to discrete layers of waste, the times of placement of which are used to determined the settlement of each lift. From a number of field scale validation exercises, Olivier et al found the compression ratio to vary relatively little around an average value of ($C'_\alpha =$) 0.11 when deployed in this way. Findings such as these indicate the benefit of implementing the settlement model on a spatial basis.

3.5 MORE FUNDAMENTAL SETTLEMENT MODELS

This section introduces a number of more fundamental landfill behaviour models that have emerged in recent years. The significance of biodegradation-related settlement has already been noted and the review of fundamental models begins with a review of the factors controlling biodegradation.

3.5.1 Biodegradation factors

The principal factors influencing the rate and extent of biodegradation in landfilled waste were outlined in Fig.4. It is not a definitive list but it does introduce a useful distinction between internal and external factors.

Internal factors

In Fig. 4, factors such as moisture content, temperature and pH are classified as internal. Internal factors define fundamental physical, chemical and (micro)biological phenomena that drive a predictable evolution of the landfill milieu. They give rise to process-based model parameters and may be derived from small scale or laboratory tests. Their influence can be regarded as universal from site to site and region to region. Factors that may be regarded as internal, including those identified in Fig. 4 are:

- moisture content: it is generally acknowledged that moisture is the main factor controlling biodegradation (Rees 1980; Reinhart and Townsend 1997); certainly it is the most easily controlled via external operations such as leachate recirculation.
- temperature: that microbiological activity is temperature-dependent can be clearly shown in the laboratory but the impact of temperature on decomposition in the field is less clearly defined. Test cells in the UK (Landfill 2000) showed very high rates of gas production achieved at temperatures below 15°C. At another UK test site, Brogborough, there was no correlation between gas production and temperature (Knox 1999).
- waste composition: the amount of degradable matter and its degradability. There have been a number of investigations of waste composition. See Grisolia et al. (1993) for one of the earlier three part classifications into inert, highly deformable and readily biodegradable fractions.
- leachate quality (pH): acid accumulation can inhibit microbial activity and thereby stall the decomposition process (van Meerten et al. 1995).
- gas and liquid conductivity: the ease with which required reactants and inhibiting products to the digestion process can diffuse through the waste (Bleiker et al. 1995)
- microbiology: the anaerobic digestion process requires a consortium of hydrolytic, acetogenic and methanogenic bacteria to become established; the growth rate of methanogens is relatively slow so accelerated methanogenesis takes time to become established (Barlaz et al. 1989).

External factors

Referring again to Fig. 4, factors that can be regarded as external include:

- site geometry: defines the lateral extent and depth of waste, and hence constrains stress- or depth-related properties such as density, porosity, gas and hydraulic conductivities.
- filling sequence: the state of a layer of waste is defined by its placement, i.e.
    - its position in relation to site geometry and hence overburden stress/in situ density
    - timing which defines the commencement of decomposition, climatic influence (rainfall/evaporation) and internal moisture redistribution
- climate: influences boundary moisture transfers
- operational controls: includes waste compaction and placement procedures, daily cover soils, time of capping, leachate management (recirculation and/or sludge addition).

External factors are effectively initial conditions or features of a particular site that define the biodegradation process both initially (geometry, filling sequence, compaction) and during the life of the site (climate, leachate management). They convey the spatial aspects of the problem and influence the biodegradation model accordingly. Waste type and external factors such as climate and operational practices may be similar at sites that are geographically close, but they are unlikely to be the same from region to region. Geometry and filling sequence are most likely to differ from site to site irrespective of their geographical proximity. External factors are largely site-specific; they influence the decomposition process through their impact on the internal factors referred to in the previous section.

So, biodegradation factors can be associated with the fundamental biodegradation processes or they define the circumstances in which those processes occur. Such a classification is instructive as it emphasises both the formulation of the fundamental model and its implementation at field scale.

3.5.2 Biodegradation consequences - mass loss and settlement

If a biodegradation model is to be used to control long-term settlement then some means of interpreting the volumetric consequences of mass loss is required. Conventional soil mechanics volume descriptors, such as the void ratio, are not unique indicators of overall volume in waste because of the changing solid phase volume. For example, the degradation of solid mass may be accompanied by an equivalent (to the solid volume lost) increase in void volume. There is then no change in overall volume although the void ratio has increased and the waste has become more skeletal. Settlement of this form can be seen in Fig. 13, which shows layer strain calculated from field measurements at depth in an Australian landfill (McDougall et al, 2004), where episodes of settlement showing zero settlement strain giving way to renewed movement can be seen.

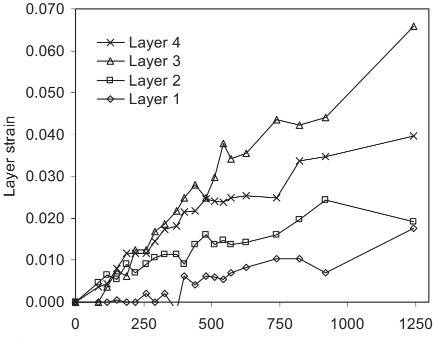

FIG. 13 Displacement of settlement monitoring stations at Lyndhurst Sanitary Landfill, stations in Control A shown as layer strain (adapted from Yuen, 1999).

Alternatively, decomposition may be accompanied by contemporaneous rearrangement of solids and overall settlement. In this case the associated change in void ratio is a function of changes in both void and solid phase volumes; void ratios may remain unchanged despite overall settlement. In fact, a constant void ratio condition is implicitly assumed by some of the fundamental landfill settlement models.

A general description of the relationship between decomposition of solid degradable matter, i.e. a change in solid phase volume V_S, and the induced change in void volume V_V, was presented by McDougall & Pyrah (2004), i.e.

$$dV_V = \Lambda \, dV_S \tag{16}$$

where Λ is the decomposition (or degradation)-induced void change parameter. Table 2 summarises changes in volumetric state variables and likely mechanical consequences associated with key values of Λ.

Coupling biodegradation with volume changes in this way offers three important benefits. Firstly, biodegradation settlement is not treated as a highly empirical time-dependent process. Time is communicated through solid organic matter depletion, which is controlled by the biodegradation model. There is a maximum rate of depletion but within that rate, under the influence of moisture deficit/addition or acid accumulation or changing crystallinity, for example, decomposition may slow down, accelerate, or stop completely. Secondly, there is no constraint on the form of biodegradation model selected; it can be as simple or as complex as necessary. Thirdly, this approach allows for a more fundamental treatment of changes in material properties such as stiffness, e.g. hardening with load and creep or (more likely) softening with decomposition.

Table 2: Decomposition induced void change parameter - reference values and associated phase composition changes where $dV_s < 0$.

Λ	**Void ratio**	**Overall volume**	**Phase composition and its expected strength**
-1	Maximum increase	No change	Much looser & possibly weaker
0	Increase	Reduction	Looser & possibly weaker
e (= void ratio)	No change	Large reduction	No change
>e	Decrease	Maximum reduction	More compact & possibly stronger

3.5.3 Model architecture – general ingredients

The classification of biodegradation factors presented in this chapter and the coupling of biodegradation with volumetric changes points to three main ingredients of a more fundamental approach to landfill settlement:

1. a model of the biodegradation process driven by parameters representing mainly internal factors
2. a means of implementation that communicates external factors as both initial and ongoing boundary conditions to the biodegradation model and,
3. an interpretation of the volumetric consequences of mass loss.

The models reviewed here are HBM (McDougall, 2007), LDAT (White et. al.2004), Moduelo (Lobo et al. 2008) and a model that has been developed at the University of Bahia, Brazil by Machado et al. (2008). Not all of these models have settlement analysis as their prime objective. The models also focus, to varying degrees, on hydrology or leachate quality and the strength of waste, so there is no common suite of factors upon which the models are founded. However, it is reasonable to say that they all recognise the importance of long-term volume change in the interpretation of landfill behaviour at field scale.

3.5.4 HBM, Edinburgh Napier University

The HBM model is a combination of three models each describing the hydraulic, biodegradation and mechanical behaviour of landfilled waste. The emphasis of this model is on settlement at field scale.

The hydraulic model is an unsaturated flow model. The biodegradation model is a two stage anaerobic digestion model and the mechanical model a visco-elasto-plastic deformation model. The three models are coupled as shown in Fig. 14, thereby enabling the integration and internal definition of system behaviour and variables that would otherwise be assumed constant or considered discretely. There is, for example, moisture control of biodegradation of solid degradable matter. The biodegradation model accounts for the enzymatic hydrolysis of solid cellulolytic matter. It is not a function of time but of the amount of moisture, volatile fatty acid (VFA) inhibition and the change in bioavailability. The hydrolysis function has the form:

$$r_g = \theta_E \, b \left[1 - \left[\frac{S_O - S}{S_O} \right]^n \right] \exp\left(-k_{VFA}(c)\right) \qquad (17)$$

where

r_g = rate of VFA accumulation [$g_{\mathrm{VFA}}/(m^3{}_{\mathrm{aqueous}}.\mathrm{day})$]
θ_E = effective moisture content
b = maximum hydrolysis rate [$g_{\mathrm{VFA}}/(m^3{}_{\mathrm{aqueous}}.\mathrm{day})$]
S = solid degradable fraction [kg/m^3]
n = bioavailability transformation parameter
k_{VFA} = product inhibition coefficient [$m^3{}_{\mathrm{aqueous}}/g_{\mathrm{VFA}}$]

c = VFA concentration [$g_{VFA}/m^3_{aqueous}$]

Equation 17 allows any of the controlling factors to affect the rate of hydrolysis/VFA accumulation, for example it may be stalled due to lack of moisture, excessive VFA accumulation (low pH) or reducing bioavailability. Equally, restoration of say a moisture deficit will accelerate the hydrolysis.

Moreover, biodegradation adjusts solid and void phase volumes, in other words the porosity, through the decomposition induced void change parameter Λ referred to above. This parameter can be evaluated from large scale laboratory tests, e.g. those by Olivier and Gourc (2007). Figure 15 shows the Olivier and Gourc test data together with HBM simulation output at selected Λ values.

The HBM model is implemented using the finite element method and can therefore simulate the filling phase by timed disclosure of individual elements. In this way, porosity and density changes due to load application and biodegradation can be handled; the saturated hydraulic conductivity can then be internally defined and automatically adjusted for overburden stress or biodegradation. The similitude of the hydraulic model is thereby considerably enhanced.

The HBM model does not account for gas migration and considers only a very simple leachate chemistry – a lumped volatile fatty acid concentration and a methanogenic biomass concentration.

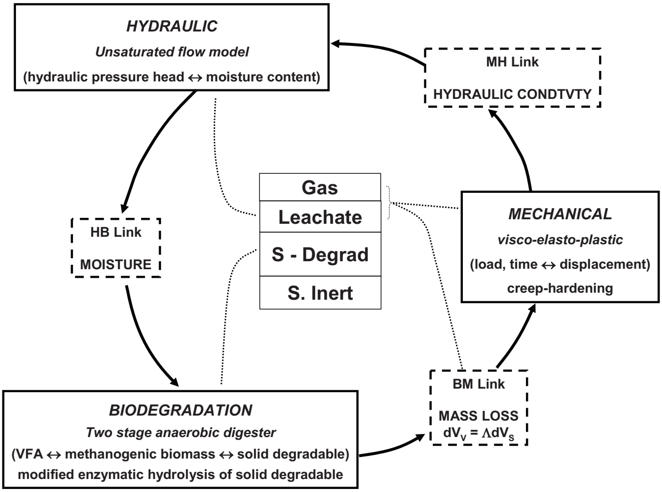

FIG. 14. Schematic diagram showing the constitutive formulation of the HBM model.

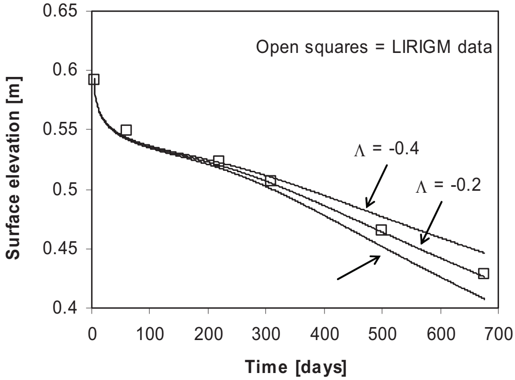

FIG. 15 Predicted (HBM) and measured secondary settlement behaviour during the experiment (LIRIGM, Olivier & Gourc, 2007) for selected values of decomposition-induced void change parameter, Λ.

3.5.5 LDAT, University of Southampton

LDAT has been developed at the University of Southampton (White et al. 2004), initially to interpret the long-term biodegradation of solid waste. It was designed to accommodate, in a spatially distributed context, a range of biochemical degradation pathways comprising the enzymatic hydrolysis, subsequent acetogenesis and methanogenesis. Biodegradation is treated as a three stage anaerobic digestion process, see Fig. 16. The degradation steps are handled using Monod kinetics, hence the depletion of the organic substrate by enzymatic hydrolysis is given by,

$$\frac{\partial C_S}{\partial t} = \left[\frac{\mu C_M}{K + C_M} C_S \right] \tag{18}$$

where

C_S = concentration of substrate [g/m^3]
C_M = concentration of hydrolytic enzymes [g/m^3]
μ = specific growth rate [g/m^3/day]
K = half saturation constant [g/m^3]

Physical properties such as density (and hydraulic conductivity) are determined from empirical relationships relating these properties to effective stress, i.e. to depth. In the case of dry density, a relationship of the form,

$$\rho'_S = A(\sigma - u)^a \tag{19}$$

where

ρ'_S = dry density
A, a = empirical coefficients
σ = total stress
u = pore water pressure

In this way a variation of density with depth is driven by empirical data and is not restricted to constant void ratio changes. With a similar expression controlling the hydraulic conductivity, LDAT offers an interpretation of degradation processes that allows for the kind of property variation with depth that will occur at field scale. A strength of the LDAT model is that the empirical relationships around which the model is built are obtained from the large-scale experimental facility at Pitsea.

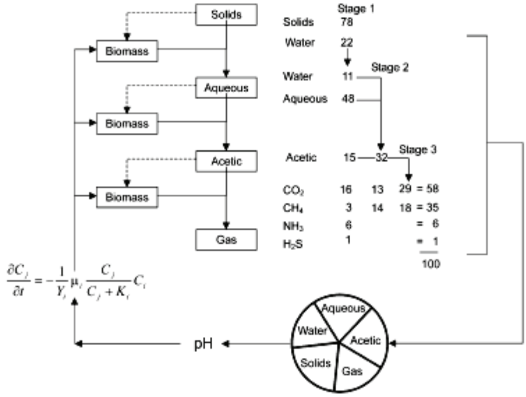

FIG. 16 Diagrammatic representation of the biodegradation process, from White et al (2004)

3.5.6 Moduelo, University of Cantabria

Moduelo is a landfill simulation tool that has been developed over a number of years at the University of Cantabria. It has available to it hydrological, biodegradation and settlement models. The biodegradation model uses a combination of first order kinetic functions to depict the conversion of readily and slowly hydrolysable solid matter into intermediate compounds and acetic acid, from which methane and carbon dioxide are produced. Lobo et al. (2008) indicate that biodegradation settlement is treated as a function of solid mass according to the 'Meruelo model'. In this case, the settlement to mass loss factor is taken to be 0.264 (no units given).

3.5.7 University of Bahia, Brazil

Machado et al. (2008) present an extension to the model they reported in 2002 (Machado et al. 2002). The earlier presentation deals with load and creep related compression and shear behaviour, idealising waste as a combination of paste-like and fibrous fractions. The fibrous fraction is made up of plastic or plastic-like components and allows for strain hardening under deviatoric stress. The paste-like fraction contains all other materials including a degradable part.

In the 2008 extension, degradation is handled by a first order decay function based on the USEPA gas generation model,

$$\frac{\Delta m_s}{m_{so}} = \frac{L_o(1+w)\{1-\exp^{-kt}\}}{C_m} \tag{20}$$

where

m_s = mass of solids [subscript *o* refers to initial conditions]
L_o = methane generation potential [m^3 CH_4/Mg of refuse]
k = methane generation rate constant [1/yr]
w = MSW water content on dry weight basis
C_m = MSW organic matter methane yield [m^3 CH_4/Mg of dry refuse]

Biodegradation volume changes are handled by α, a decomposition-induced volume change parameter like the Λ parameter. Importantly, they indicate that values of α are not constant but a function of the biodegradation stage and probably other variables such as stress and waste composition. In the absence of more information, Machado et al (2008) propose that α is linearly related to the progress of decomposition, i.e.

$$\alpha(t) = \frac{-\alpha^{*}\Delta m_s}{m_{so}} \tag{21}$$

where

$\alpha(t)$ = mass loss generated volume change parameter
α^* = maximum value of α

From Eq. 21, the Authors compute volumetric strains over time using,

$$d\varepsilon_v = -\left(\frac{\gamma_{so}}{\gamma_{sp}}\right)\left(\frac{1}{1+e_o}\right)(1-\alpha(t))\frac{\partial m_s}{\partial t}\frac{1}{m_{so}}dt \tag{22}$$

where

γ_s = specific weight of MSW
γ_{sp} = specific weight of paste

The dependence of Λ on the degradation process, actually dissolution, has been reported in another paper in this volume (McDougall 2010, this volume). The data are obtained from tests on sand-salt mixtures, so quite different to waste, but they do show a common trend in the evolution of the parameter Λ over a range of stress states.

Comparison of this data with the form implied by Eq. 21 suggests that this is a topic that warrants further investigation.

3.5.8 Summary of more fundamental model features

Table 3 is provided not as a complete and definitive statement of model capabilities but as a synopsis of the different emphases and varying degrees of complexity embodied by the more fundamental settlement models.

Table 3 Summary of general features and modelling capabilities included in the four fundamental settlement models.

	HBM	**Moduelo**	**LDAT**	**Brazil**
	McDougall (2007)	Lobo et al (2008)	White et al (2004)	Machado et al (2002, 2008)
Settlement	Yes load, creep & biodegradation	Yes, biodegradation	Yes load, biodegradation	Yes, load, creep & biodegradation
Biodegradation	2 stage: hydrolysis, methanogenesis	3 stage: hydrolysis, acetogenesis, gasification	3 stage: lytic, acidogenesis, methanogenesis	based on USEPA gas model
Control	1) modified hydrolysis; 2) Monod	All first order kinetics	All Monod	First order kinetic
Pathways	1: bioavailability transformation	2: readily & slowly hydrolysable	3: fast, medium & slow	
Moisture control	Yes	Yes	Yes	Yes
Leachate species	VFA, MB	Intermediates, HAc, NH_3, H_2S	VFA, HAc,	N/A
pH inhibition	Yes			
Gas species	LFG	CH_4, CO_2	CH_4, CO_2	CH4
Biodegradation-related volume change	Λ	e fixed	density function	α (= Λ)
Implementation	Finite Element	Finite element	Finite difference, constant volume	

3.6 LANDFILL MODELLING CHALLENGE

Despite their state of development, indeed as a means of encouraging more coherent development, the landfill models described above were all invited to enter the landfill modelling challenge. Prediction of long-term settlement was one of the three main objectives of the challenge. The challenge was devised by the Waste Management Research group at the University of Southampton. It is comprehensively reported in two special issues of Waste and Resource Management (2008), see in particular Beaven et al. (2008) and Beaven (2008).

The Challenge

The landfill modelling challenge was a blind prediction exercise. Two consolidating anaerobic reactors were run for a period of 919 days during which time leachate quality, gas production and settlement were monitored. Each reactor is 480 mm diameter by 900 mm high, filled with 27 kg of fresh shredded MSW, and subjected to a vertical load (50 kPa & 150 kPa). Leachate quality data for the first 77 days was made available. The modellers were then asked to predict leachate quality, gas production and settlement for the remaining period of the test.

Lesson learned from the Challenge

Figure 17 shows the settlement predictions for CAR1 made by each of the four models together with the measured data. Whilst two of the models match the measured settlement behaviour reasonably well, perhaps the most significant observation to be made from Fig. 17 is the ability of the models to delineate an acceleration in settlement strain. The measured data show a relatively distinct acceleration at about 70 days. The HBM and Brazilian models show a general acceleration rather than a pronounced change of strain rates in the two phases; LDAT produces the greatest contrast between strain rates.

Importantly, the settlement behaviour modelled in Fig. 17 has been produced without resorting to *a priori* input of a transition time. No gas production data was released to the modellers. However, modellers were given the initial VFA data from which an acceleration in settlement could be deduced. Figure 18 shows these data. Very low VFA concentrations at 60 days indicate the consumption of excess VFA and the onset of accelerated methanogenesis together with increased settlement rate.

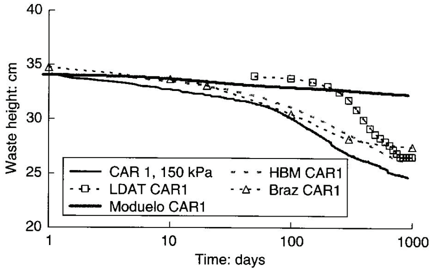

FIG. 17 Predicted waste settlements in CAR 1; from Beaven (2008)

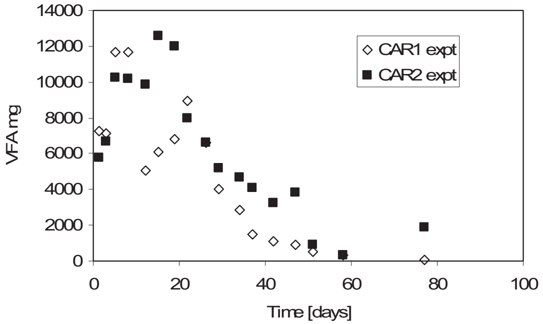

FIG. 18. Total VFA concentrations calculated from individual VFA concentrations measured in CARs 1 & 2 in the Landfill Modelling Challenge (Beaven et al. 2008)

Whilst the predicted settlement behaviour may be encouraging, if it is being modelled as a fundamental consequence of biodegradation-related mass loss, then it should be possible to match model and measured gas production curves. These are shown in Fig. 19, from which it is apparent that model predictions of gas production are mostly significantly lower than the actual gas production.

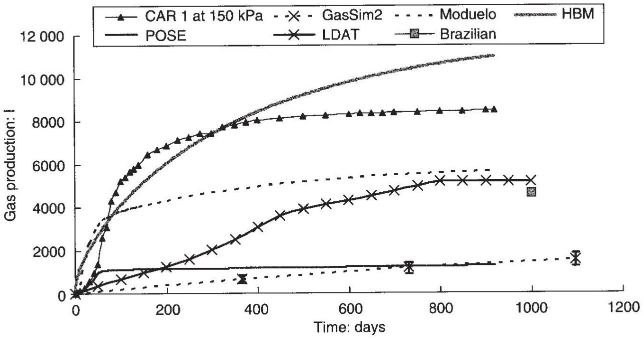

FIG. 19. Measured and predicted total [LFG] gas production for CAR1, from Beaven (2008)

The fit appears disappointing but is not necessarily indicative of a fundamental flaw in the biodegradation models. Rather, it emphasises the need to quantify the gas yield of the waste in question, i.e. the degradable content. Stoichiometric equations indicate precisely how much cellulolytic matter is required to produce a given quantity of landfill gas but the amount of gas produced by a given amount of organic matter depends on its degradability or bioavailability. Some organic matter is readily degradable, some shielded by lignin; when shielded, degradation proceeds slowly, if at all. So, whilst gas production curves reflect the current rate and progress of biodegradation, knowledge of a parameter like the methane yield coefficients in Eq. 20 is necessary to define the process end point, i.e. the gas volume evolved and mass degraded as a proportion of the total 'organic' content present. Consider Fig. 20, which shows relationships between degradation, gas production and settlement. The stoichiometric relationship between gas production and mass loss is shown as a linear function with the total amount of cellulolytic matter denoted by M_O. M_C is the mass loss associated with current gas production, G_C. M_F is the amount of this waste that will eventually be degraded. The ratio of M_F to M_O is directly related to the yield coefficient C_m in Eq. 20. With this information, and a knowledge of the way in which a volume change parameter such as Λ evolves, it is possible to estimate ultimate long-term settlement magnitudes, S_F. It is through the forensic analysis of challenges of this kind that the role of biodegradation, its evolution in field-scale landfill cells and impact on settlement will be revealed.

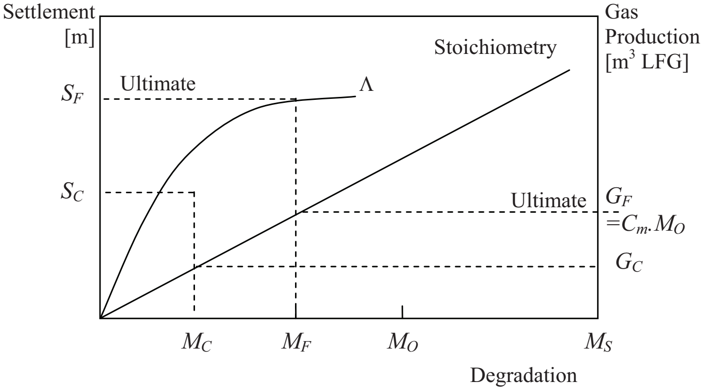

FIG. 20 Progress of settlement as a function of degradation, controlled by void volume change parameter Λ and gas production, via stoichiometric equation, showing limiting condition, i.e. ultimate settlement, defined by yield coefficient.

3.7 SUMMARY & CONCLUDING REMARKS

The analysis of landfill settlement is at a crossroads. Techniques for the analysis of short-term load-related primary compression and long-term settlement have been the subject of much research. For many years, one-dimensional compression and time-dependent analyses have been the main analytical tools. They have been shown to match well field observations over short periods of time and can be extended by the use of two settlement stages. However, the highly empirical nature of the analysis means that long-term settlement predictions will depend on the controlling conditions remaining constant for the life of the cell.

Recently there has been interest in more fundamental models. These models allow for the integration of mechanical, biodegradation and physico-chemical related phenomena. The latter phenomena are not part of the normal soil mechanics analytical toolkit. A number of models have emerged, four have been considered in this chapter, each with its own strength and emphasis. They do, however, all recognise the volumetric consequences of mass loss. Fundamental equations that link stress-related phenomena to microbial processes (and vice versa) are not known. Yet, we have seen here that mass loss is directly related to solid volume loss, which through a decomposition-induced volume change parameter, can be incorporated into settlement calculations. It therefore remains to understand and quantify the relationship between mass loss and the induced change in void volume. It is likely that this will be a function of (i) the stress state, (ii) particle stiffness, size distribution and shape, (iii) particle skeleton stiffness, and (iv) the rate and progress of degradation.

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Chapter 4

Dynamic Properties of Municipal Solid Waste

Dimitrios Zekkos[1], Neven Matasovic[2], Rami El-Sherbiny[3], Adda Athanasopoulos-Zekkos[1], Ikuo Towhata[4] and Michele Maugeri[5]

[1]Assistant Professor, Dept. of Civil and Environmental Engineering, University of Michigan, USA;
[2]Associate, Geosyntec Consultants, Huntington Beach, California, USA;
[3]Assistant Professor, Faculty of Engineering, Cairo University, Cairo, Egypt;
[4]Professor, Dept. of Civil Engineering, University of Tokyo, 7-3-1, Bunkyo, Tokyo 113-8656, Japan;
[5]Professor, Department of Civil and Environmental Engineering, University of Catania, Italy

4.1 INTRODUCTION

In areas of moderate to high seismicity, seismic loading typically controls the design of waste fills. In these areas, a reliable estimate of (strain-dependent) material properties of Municipal Solid Waste (MSW) is required for safe and economical design of waste fills. Our understanding of the dynamic properties of MSW has significantly improved since the promulgation of Federal (US) Subtitle D regulations in 1993. These landmark regulations mandated for the first time seismic design and analysis of landfills in areas of modest and high seismicity (PHGA in excess of 0.10 g; 2,475 years return period).

This chapter aims to review the state of the art of our understanding of the dynamic properties of MSW. These dynamic properties of MSW include:

- The shear wave velocity V_s and small-strain shear modulus G_{max} profile;
- The shear strain-dependent shear modulus reduction G/G_{max} and material damping (λ) curves; and
- The dynamic Poisson's ratio ν.

In addition, for the performance of dynamic analyses, the MSW unit weight γ profile at the landfill is needed. A procedure to measure the unit weight of MSW in situ and a framework for the selection of reasonable values of unit weight with depth is provided in Zekkos et al. (2006a). Athanasopoulos-Zekkos et al. (2008) demonstrated that the impact of the selected unit weight profile on the results of dynamic analyses is critical. Dynamic shear strength properties are briefly discussed in Chapter 2 of this publication.

It is important to recognize that MSW is a highly variable material. As such, some of the trends presented subsequently may not be applicable to all MSW. Waste composition, landfill operation practices, and climate will have an impact in the waste material. MSW variability is thus expected not only among countries that produce it, but also between different regions of the same country as well as within the same landfill. As more data is generated, our understanding of the various factors that affect the dynamic properties of MSW will improve.

4.2 MSW SHEAR WAVE VELOCITY

Whereas laboratory testing on reconstituted large-scale specimens of MSW are of interest to study the mechanics of waste mass response and to understand the various factors that affect the response, it is the in-situ measurement of V_s that is the preferred approach to establish design profiles for seismic analyses. An overview of in-situ methods for evaluation of V_s is presented in Chapter 6 of this publication. Relevant information required for conducting seismic analyses is presented herein.

The shear wave velocity V_s profile is used to estimate the small-strain shear modulus G_{max} of the MSW using the equation:

$$G_{max} = \rho * V_s^2 \tag{1}$$

Where ρ is the mass density of the material, which is equal to the ratio of the unit weight γ to the gravitational acceleration g.

4.2.1 MSW Shear Wave Velocity from In-Situ Testing

A large number of in situ methods have been used to estimate the shear wave velocity profile in the field. These include: the Downhole method; the Crosshole method; the OYO method; the Spectral Analysis of Surface Waves (SASW) method; and the Controlled Source Surface Wave (CSW) profiling method. These are described in more detail in Chapter 6.

Among the variety of available in-situ shear wave velocity measurement methods, surface methods (such as the SASW method) gained the widest acceptance because they are reliable, and non-intrusive (i.e., do not require boreholes). They are also efficient, allowing the performance of a large number of soundings at a landfill that can be used to evaluate the variability of the V_s of the MSW at the landfill.

Early studies include a study by Sharma et al. (1990) who performed Downhole testing at a MSW landfill in Richmond, California. The authors report an average value of V_s of about 198 m/s for a depth of 0 to 15.3 m and a compression wave velocity V_p of 717 m/s.

Singh and Murphy (1990) reference tests reported by Earth Technology Inc. using the Crosshole and Downhole method and reported an average V_s of 274 m/s. Singh and

Murphy further refer to a series of tests performed by EMCON that reported an average V_s of 213 m/s for West Richmond field, and 91 m/s for Redwood Refuse Fill. The authors state that values as low as 31 m/s have been reported for the Redwood Refuse Fill.

Kavazanjian et al. (1994) report V_s measurements at eight MSW landfills in southern California. These profiles were established using both the SASW and the CSW profiling techniques. Recorded shear wave velocities were as low as 80 m/s near the surface and increased to over 300 m/s at a depth of 30 m.

Kavazanjian et al. (1995) report additional V_s data generated by consultants at several landfills in the United States. At Puente Hills landfill in Los Angeles, Earth Technology Inc. measured V_s in waste buried by 6 m of fill that ranged from 240 m/s at a depth of 6 m to 270 m/s at a depth of 14 m. At the Brookhaven landfill in Long Island, New York, V_s ranging between 185 and 478 m/s was reported, but the representative depths at which these values were measured are not reported. Kavazanjian et al. (1995) estimated the these depths ranged between 24 and 37 m. Considering the above data, as well as some additional unpublished data, Kavazanjian et al. (1995) recommended a V_s profile for use in seismic analysis of MSW landfills. This V_s profile is shown in Figure 1 along with the background data used for its development.

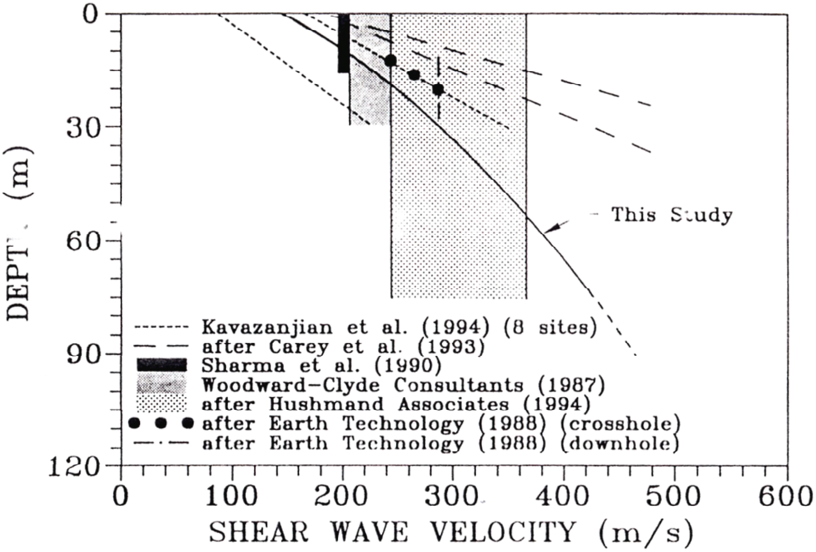

FIG. 1. Shear wave velocity profile recommended by Kavazanjian et al. (1995) and background data (Kavazanjian et al. 1995).

Houston et al. (1995) reported V_s and V_p profiles developed based upon surface wave profiling and Downhole soundings at the Northwest Regional Landfill Facility (NWRLF) in rural northwestern Maricopa County of Arizona. The authors reported that the landfill accepts MSW, inert construction debris, and landscaping debris. Groundwater was not encountered in any of the boreholes that reached depths varying from 15 to 50 m. The upper 1.5 m consisted of the stiffer soil cover and had a V_s of about 210 m/s and a V_p of about 355 m/s. The shear and compression wave velocity for the MSW was generally increasing linearly from a value of 124 m/s and 235 m/s, respectively, at a depth of 1.5 m to 229 m/s and 346 m/s respectively at a depth of 10 m.

A total of 27 SASW profiles were performed at the OII landfill by Geosyntec. The mean, mean plus one standard deviation and mean minus one standard deviation V_s profiles developed by Matasovic and Kavazanjian (1998) are shown in Figure 2. Values identified as Low Velocity (LV), High Velocity (HV), and Medium Velocity (MV) in Figure 2 were used to select representative MSW samples for laboratory testing. The authors also compared results from the SASW and the suspension logging method and concluded that the SASW results compare well (though on the lower bound) to their counterparts established by suspension logging.

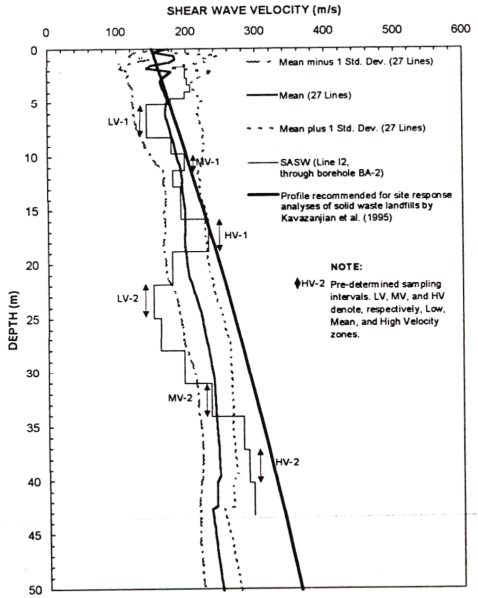

FIG. 2. Shear wave velocity profiles at the OII landfill (Matasovic and Kavazanjian 1998).

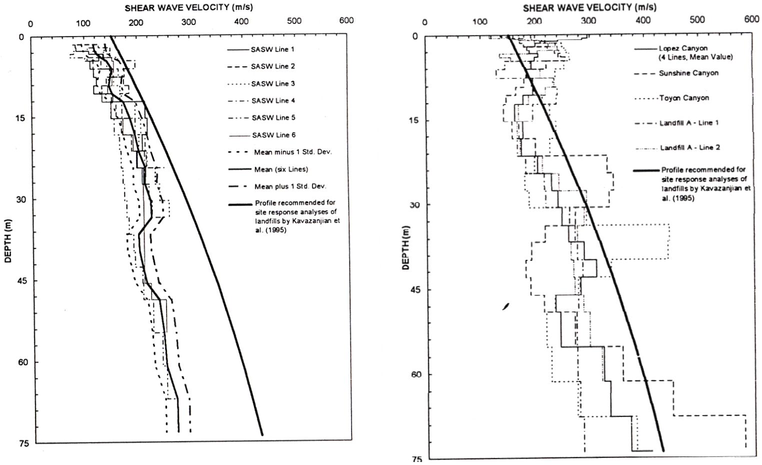

FIG. 3. Shear wave velocity profile at a) the Azusa landfill, b) at other landfills (from Kavazanjian et al. 1996).

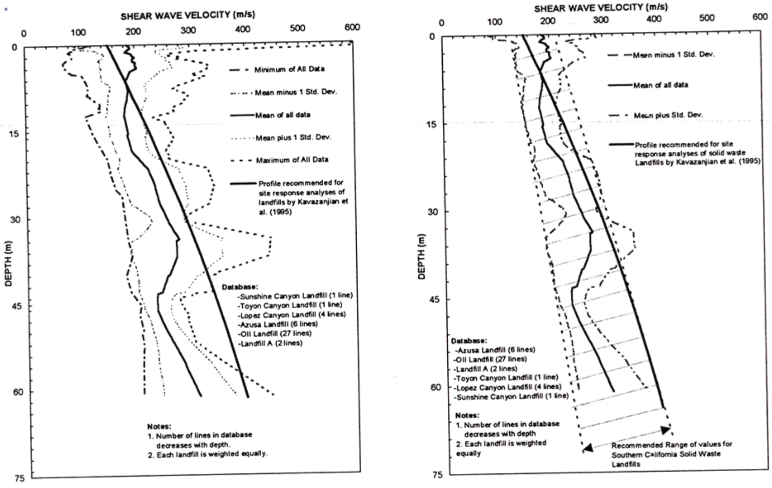

FIG. 4. Results from all landfills and recommended range of values for southern California solid waste landfills (from Kavazanjian et al. 1996).

Figure 3 shows the results of SASW measurements by Kavazanjian et al. (1996) at six landfills in southern California. These landfills are the Operation Industries Inc. landfill, the Azusa Land Reclamation Company landfill, the Sunshine Canyon landfill, the Lopez Canyon landfill, the Toyon Canyon landfill and an unidentified landfill named Landfill A. The results are dominated by the measurements at the Azusa landfill that is represented by 8 SASW lines. Based on the results of these investigations and measurements at the OII landfill that were in progress at the time, the authors recommended a range of V_s for seismic design of MSW landfills in southern California and other regions of similar MSW streams and relatively dry climate. This recommended range is indicated by shading in Figure 4.

Cuellar et al. (1998) performed the SASW method at the "Villalba waste dump" near Madrid, Spain. The developed V_s profile is shown in Figure 5. The Villalba waste had a low value of about 100 m/s near the surface and reached a value of about 210 m/s at a depth of 15 m.

Rix et al. (1998) performed the SASW method at the Sanifill and Bolton MSW landfills in Atlanta, Georgia. Using a simultaneous inversion of surface wave velocity and attenuation measurements, the authors were able to estimate both the shear wave velocity profiles as well as the small-strain damping profiles for both landfills. These shear wave velocity profiles are also shown in Figure 5. The results of the small-strain damping measurements are discussed later in this chapter.

Kavazanjian (1999), based on the data presented by Rix et al. (1998) and Manassero et al. (1996) as well as based upon other information cited in Kavazanjian et al. (1994; 1995; 1996) and Matasovic and Kavazanjian (1998), recommended that, in the absence of site-specific data, the southern California profile developed by Kavazanjian et al. (1996) and shown in Figure 4 may provide a good representation of shear wave velocity profiles of MSW landfills in temperate and arid climates.

Pereira et al. (2002) measured the V_s using the SASW method in Valdemingomez landfill near Madrid, Spain. In the upper meter, a crust with a V_s equal to 210 m/s was measured. At higher depths, V_s ranged from 100 m/s to 250 m/s as shown in Figure 5.

Lin et al. (2004) performed SASW soundings at the Tri-Cities, Altamont and Redwood landfills in the San Francisco Bay area of California. Soundings at 14 different locations at the three landfills were performed. The range of V_s is also shown in Figure 5. These authors measured relatively low shear wave velocities within the upper 10 m, lower than the lower bound of the range reported by Kavazanjian et al. (1996) for the southern California landfills.

The previously reported V_s profiles are summarized in Figure 5a. Figure 5b focuses on the upper 30 m. These Figures show that within the upper 30 m, V_s varies from less than 50 m/s to more than 200 m/s. A "crust" of stiffer material is typically observed at, and just below, the surface. In general, V_s increases with depth and reaches 200-300 m/s at a depth of approximately 30 m. Whereas the reported ranges are relatively large, the shear wave velocity profiles at any given landfill are generally more consistent and exhibit less variability (see for example V_s profiles for the OII landfill in Figure 2), highlighting the importance of site-specific shear wave velocity measurements and testing of waste.

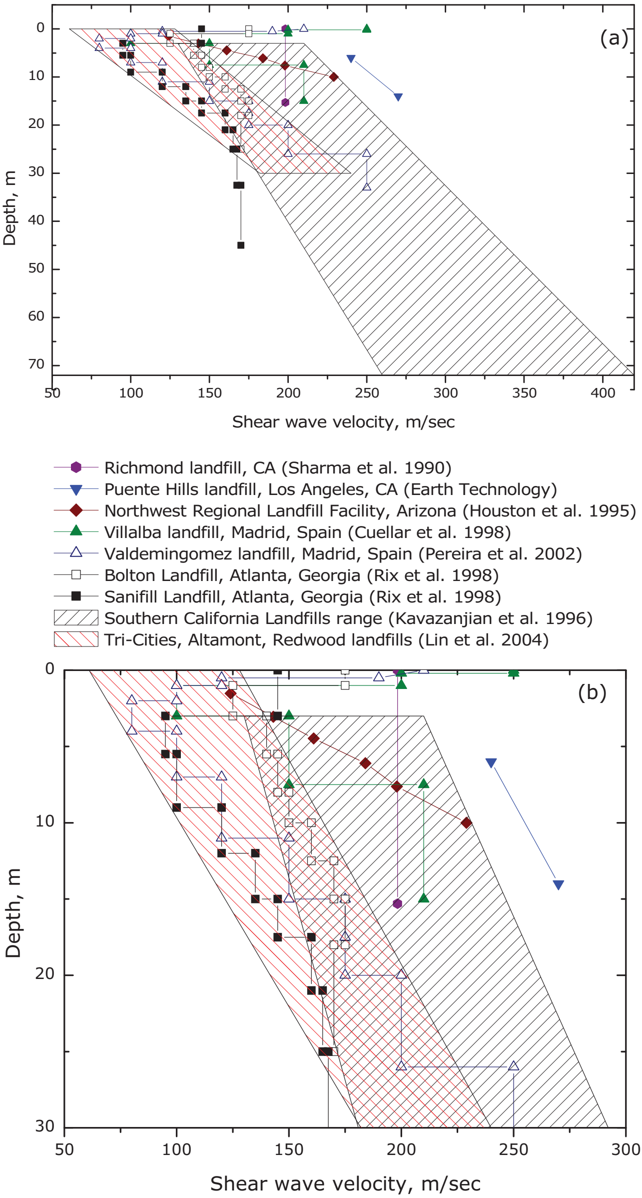

FIG. 5. MSW Vs profiles from the literature (a) to depth of 70 m; and (b) for the upper 30 m only.

4.2.2 MSW Shear Wave Velocity and Small-strain Shear Modulus from Laboratory Testing

Large-scale cyclic laboratory data are currently very limited. Matasovic et al. (1998) performed 9 large-diameter (450 mm) cyclic simple shear tests on OII landfill solid waste. Shear wave velocity of reconstituted waste specimens was measured using accelerometers.

Zekkos et al. (2008a) performed more than 90 cyclic triaxial test series on 25 large-scale (d=300 mm, h=630 mm) reconstituted MSW specimens from the Tri-Cities landfill in the San Francisco Bay Area of California. The effects of waste composition, confining stress, unit weight, time under confinement, and loading frequency on the dynamic properties were systematically investigated and are summarized in Table 1. Three different MSW samples, representative of older, deeper waste (15 yrs old at a depth of up to 25 m), younger and shallow waste (0-2 yrs old at depths of 3-9 m) as well as the most different waste encountered at the landfill, were tested. When the data were systematically studied, significant differences among samples were not encountered. Both the G_{max} and the V_s increased systematically with confining stress and unit weight. The effect of time under confinement was also studied via cyclic triaxial tests and V_s measurements using accelerometers mounted on the specimens. It was found that G_{max} increased significantly with time under confinement. Cyclic triaxial tests performed at loading frequencies of 0.01, 0.1, 1 and 10 Hz, indicated that G_{max} increases linearly with the logarithm of the loading frequency regardless of waste composition.

Additional small-scale (d=68 mm) cyclic triaxial testing of waste was performed. Small-scale specimens that included only the finer (i.e. <20 mm) material yielded identical G_{max} to the large-scale specimens that included the finer only fraction. Additional small-scale tests performed on specimens that included the same composition with large-scale triaxial specimens, but with the coarser (i.e., >20 mm material), fibrous fraction carefully processed to sizes <20 mm, so that they can be included in the specimen, yielded G_{max} values that were larger (by a factor of 2 approximately) than the values estimated from large-scale triaxial specimens with the same composition, indicating that small-scale testing of processed waste is not likely to be representative of the field behavior of MSW.

Lee (2007) performed cyclic testing using two devices: a small-scale (d=71 mm) fixed-free, resonant column and torsional shear (RCTS) device and a larger-scale (d=152 mm) free-free, resonant column device (LSRC). Typical results of the investigation were presented by Zekkos et al. (2008b) and are reproduced in Figure 6. The results of this investigation were largely consistent with the findings of the large-scale cyclic triaxial investigation (Zekkos 2005) on the same waste material when scale effects are considered. Resonant column testing allows the performance of high resolution tests in the small strain range. This investigation also revealed that G_{max} increases with confining stress and decreases as the percentage of >20 mm material increases. Small-strain damping was found to increase significantly with the excitation frequency, but varied only slightly with the percentage of <20 mm material. Also, small-strain damping was found to decrease slightly with increasing confining stress.

Table 1. Effect of different parameters on the MSW dynamic properties (after Zekkos et al. 2008).

Property **Effect of…**	**Small-strain shear modulus, G_{max}**	**Normalized shear modulus reduction curve, G/G_{max} vs. γ**	**Material damping curve, λ vs. γ**
Composition	Most important	Most important at larger strains	Most important at larger strains
Confining stress	Important	Important	Likely important
Unit weight	Important	Not important	Not important
Loading frequency	Important	Not important	Not important
Time under confinement	Important	Not Important	Not Important

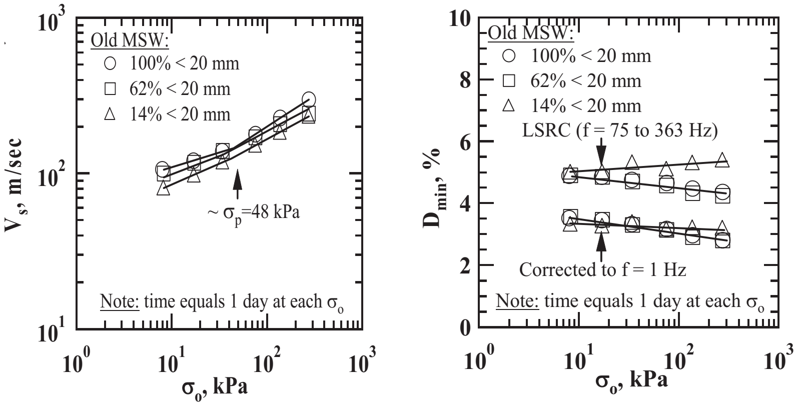

FIG. 6. Variation in Vs and small-strain material damping with confining stress for MSW with varying waste composition (Lee 2007).

4.3 NORMALIZED SHEAR MODULUS REDUCTION AND MATERIAL DAMPING CURVES

The first attempt to evaluate normalized modulus and damping of MSW was made by Singh and Murphy (1990). Based on the assumption that the strength properties of the refuse are more cohesive than frictional, the authors postulated that equivalent-linear characteristics of MSW must be between those of clayey soils and peat, and in the absence of better data, recommended curves developed by averaging clay and peat modulus reduction and damping curves. The majority of modulus reduction and damping curves that followed are based on the back-calculation of the response of the OII landfill to low-intensity motions using different analytical techniques. The Matasovic and Kavazanjian (2008) investigation also included large-scale cyclic simple shear test results on reconstituted specimens from the OII landfill at larger strains. Low intensity motions were recorded for 15 earthquakes at a base and crest stations of OII landfill (the highest PHGA recorded at the base of the landfill was on the order of 0.1 g). Different sets of ground motions have been used to back-calculate the properties of the waste material.

4.3.1 Normalized Shear Modulus Reduction and Material Damping Curves from Numerical Analyses

Studies by Matasovic et al. (1995), Idriss et al. (1995), Kavazanjian et al. (1995), Morochnik et al. (1998), Matasovic and Kavazanjian (1998), Augello et al (1998), and Elgamal et al. (2004) attempted to estimate the shear modulus reduction and material damping curves from the response of the OII landfill, located in Los Angeles California. A summary of the back-calculation studies by various researchers is presented in Table 2.

Table 2. Summary of numerical studies back-calculating the response of OII landfill.

Reference	Approach	# of cross-sections	Recordings
Matasovic et al. (1995)	1-D nonlinear and equivalent-linear	1	2 (largest-intensity)
Idriss et al. (1995)	1-D & 2-D equivalent-linear	1	5
Augello et al. (1998)	2-D equivalent-linear	2	10
Matasovic and Kavazanjian (1998)*	2-D equivalent-linear	2	10
Elgamal et al. (2004)	System identification	N/A	6

*Large-strain modulus and damping based upon site specific laboratory testing of OII Landfill MSW.

Matasovic et al. (1995) back-calculated the response of the OII landfill during the Northridge and the Landers earthquakes. The authors performed both equivalent-linear and non-linear site response analyses and developed a set of internally consistent (i.e., based upon the Masing rules) modulus reduction and damping curves. Idriss et al. (1995) performed a similar study using one–dimensional (1-D) and two-dimensional (2-D) equivalent-linear analyses of a single cross-section (Hudson et al., 1994) and time histories recorded in four earthquakes. Shapes of modulus reduction and damping curves were developed independently by these authors.

Augello et al. (1998) also back-calculated the response of the OII landfill using 5 different earthquake events (10 strong motion record pairs) using 2-D QUAD4M analysis. The authors evaluated the response in two orthogonal directions and considered a range of six G/G_{max} and λ curves, three V_s profiles and four values of Poisson's ratio. Comparisons between the observed and calculated motions were made using an "objective" statistical analysis. The best overall fit curve by Augello et al. (1998) falls between the clay PI=30 and PI=100 by Vucetic and Dobry (1991) at smaller strains and is closer to the clay PI=30 curves at larger strains. The maximum shear strain levels induced in the waste fill by the earthquake events considered by the authors listed above were on the order of 0.15%. The recommended curves are shown in Figure 7.

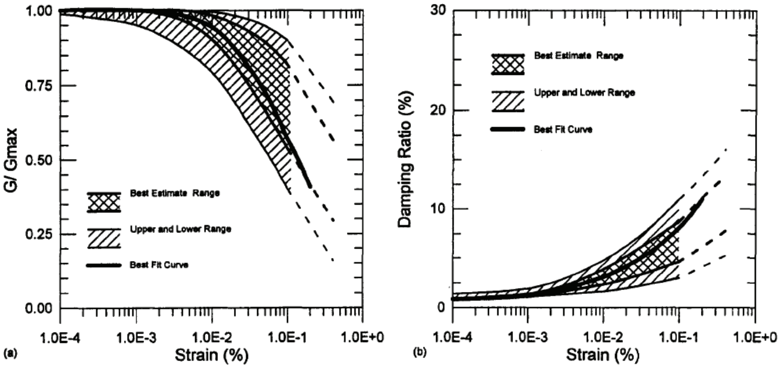

FIG. 7. Recommended best estimate range and upper and lower estimates for strain-dependent shear modulus reduction and material damping curves for soil waste (Augello et al. 1998).

Morochnik et al. (1998) used system identification techniques to estimate the dynamic properties of the OII landfill based upon 10 recorded earthquake events and considering only the longitudinal (East-West) components of the motion. Based upon results of their study, these authors postulated that the waste responded as a linear viscoelastic, not hysteretic material, with negligible reduction in shear modulus with shear strain (for strains up to 0.08%). The corresponding frequency-dependent viscous damping ratio was found to reach a value of 11% within the frequency range of 0.1 and 10 Hz.

Matasovic and Kavazanjian (1998) extended previous work by Matasovic et al. (1995) into the large-strain range by performing large-diameter (450-mm) cyclic simple shear testing on representative MSW samples. Using the 2-D equivalent-linear site response analyses program QUAD4M (Hudson et al. 1994), Matasovic and Kavazanjian (1998) back-calculated the East-West and North-South components of the 5 strongest earthquakes that were recorded at two stations. Similarly to the previous studies, the computed ground motion at the crest of the landfill was compared to its recorded counterpart for the same event. Site geometry developed from aerial photography and best estimate V_s (Figure 2), unit weight and Poisson's ratio profiles established by site-specific measurements were used in these analyses. Calculated maximum shear strains from these earthquakes were on the order of 0.1% (Figure 8). A family of best-fit, internally-consistent solid waste G/G_{max} vs. γ and λ vs. γ curves were established on the basis of qualitative examination of the observed and predicted acceleration response spectra at the top of the landfill and site-specific testing of MSW. This family of curves is shown in Figure 8. The "upper-bound" G/G_{max} vs. γ curve and corresponding "lower-bound" λ vs. γ curve were selected as the "recommended" curves for the following reasons: (1) The "upper bound" G/G_{max} vs. γ curve was more consistent with the back analysis results, (2) due to disturbance issues, the reconstituted specimens used in the laboratory testing were likely to yield increased shear modulus reduction and damping compared to in-situ, (3) the lower rate of energy dissipation and the reduced shear modulus reduction associated with the "upper bound" modulus reduction and "lower bound" damping curves was considered to be conservative with respect to the acceleration response at the landfill surface.

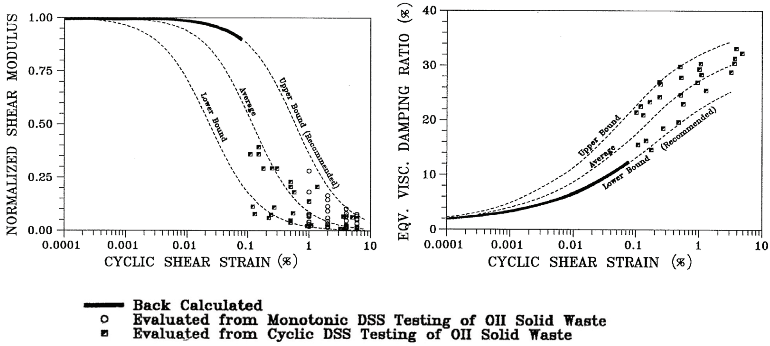

FIG. 8. Modulus reduction and damping from large-diameter laboratory testing and back analysis of OII landfill response (Matasovic and Kavazanjian 1998).

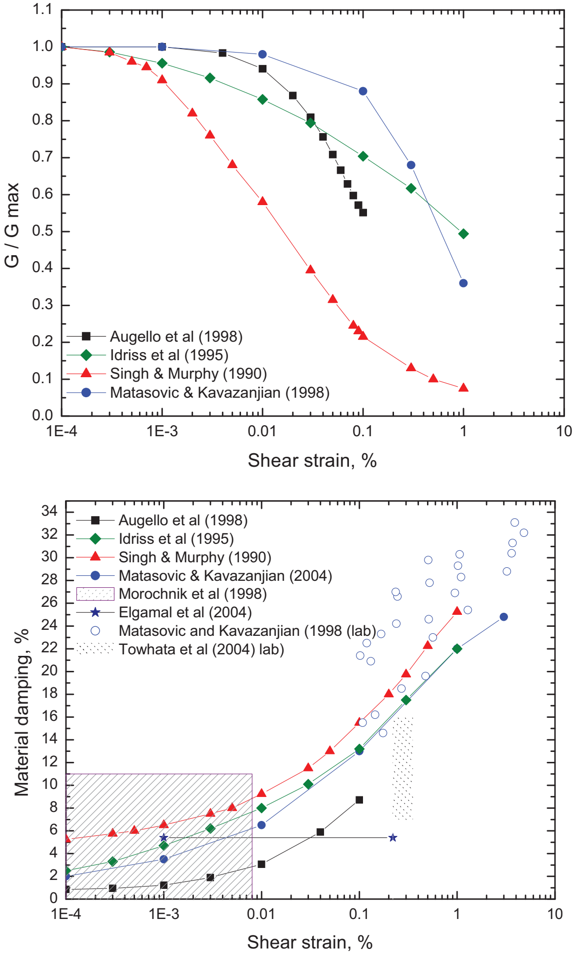

FIG. 9. G/Gmax and λ vs. γ curves and laboratory data from the literature (points on the curves are not actual data points; are used to discern between different curves).

Elgamal et al. (2004) used system identification techniques to estimate shear modulus reduction and material damping curves. The authors also used the ground motions recorded at the accelerometers of the OII landfill during six earthquakes. The results of the analyses suggest an average constant damping of about 5.4% (with values ranging between 3.6% and 8.8%) and no stiffness reduction for strains between 0.001% and 0.2%. Modulus reduction and damping curves by various authors are compared in Figure 9. A broad range of modulus reduction and damping curves of MSW can be observed in Figure 9.

4.3.2 Normalized Shear Modulus Reduction and Material Damping Curves from In-Situ Testing

The in-situ measurement of G/G_{max} and λ vs. γ presents many challenges and thus, there is currently no information available for waste. Rix et al. (1998) performed seismic in-situ tests using surface waves and developed small-strain material damping profiles along with shear wave velocity profiles that were discussed previously for two landfills, the Sanifill landfill and the Bolton landfill in Georgia. Small-strain material damping ranges from 1.5 to 7.5% for the Bolton landfill and from 5.5 to 10% for the Sanifill landfill, as shown in Figure 10. These relatively large material damping values are somewhat consistent and higher than the small strain damping values measured in the laboratory and back-calculated numerically.

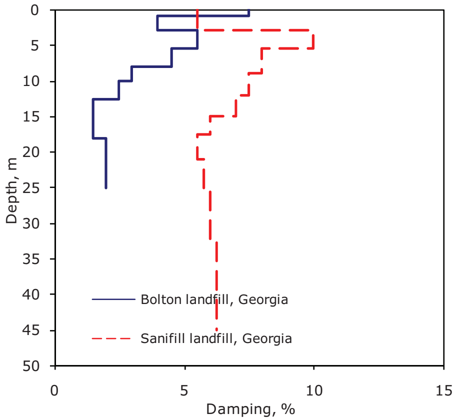

FIG. 10. In-situ measurements of small-strain material damping in two landfill in Georgia (after Rix et al. 1998).

4.3.3 Normalized Shear Modulus Reduction and Material Damping Curves from Laboratory Testing

Until recently, very limited laboratory data on the dynamic properties of MSW was available. Matasovic et al. (1998) performed 9 large-diameter (450 mm) cyclic simple shear tests on OII landfill solid waste. Results from that testing program are shown in Figure 8. Towhata et al. (2004) performed cyclic triaxial tests at a confining stress of 40 kPa and a loading frequency of 0.01 to 0.1 Hz on MSW specimens having a dry unit weight of about 0.75 gr/cm^3. Cyclic tests were performed only at a shear strain of 0.2-0.3% approximately. Thus comparisons could be made only at this level of strain.

Specimens with and without plastics were found to have similar secant Young's Modulus. Material damping appeared to increase with strain and higher values were estimated for specimens that did not include the plastic fibers. The authors also performed a series of shaking table tests using waste compacted by human foot. The results of these tests are shown in Figure 9.

Zekkos et al. (2006b, 2008a), as part of the study reported previously, investigated the effect of various parameters on the G/G_{max} vs. γ and λ vs. γ curves (Table 1). The study identified that waste composition and confining stress were the most critical factors affecting the dynamic curves. As the amount of fibrous (i.e. paper, plastic and wood) >20 mm material increases, the G/G_{max} curves shift to larger strains (i.e. a more linear response is observed), and the λ at large strains reduces significantly (Figure 11). As confining stress increases, a more linear response is observed. Also, λ reduces with increasing confining stress, albeit less systematically. The unit weight, loading frequency and time under confinement did not appear to have a significant effect on the G/G_{max} vs. γ, and λ vs. γ curves. Thus, a family of internally consistent shear modulus reduction and material damping curves as a function of composition and confining stress were recommended and are presented in Figure 12. Supplemental small-scale cyclic triaxial testing (d=68 mm) of waste indicated that testing of small-scale specimens with only the finer fraction or with processed coarser fraction cannot completely capture the dynamic properties of the original waste with larger sized particles. Thus, the dynamic properties of MSW are affected not only by the fibrous nature of the coarser fraction, but also by the relative size of the fibers with respect to the <20 mm material.

Lee (2007) using the RCTS and the LSRC devices also observed that the linearity in the normalized shear modulus reduction curve and material damping ratio increased with increasing composition of >20 mm material (Figure 13). However, this trend is not as pronounced as observed in the large-scale cyclic triaxial testing performed by Zekkos et al. (2008a), possibly due to the smaller size specimen used in the resonant column investigation.

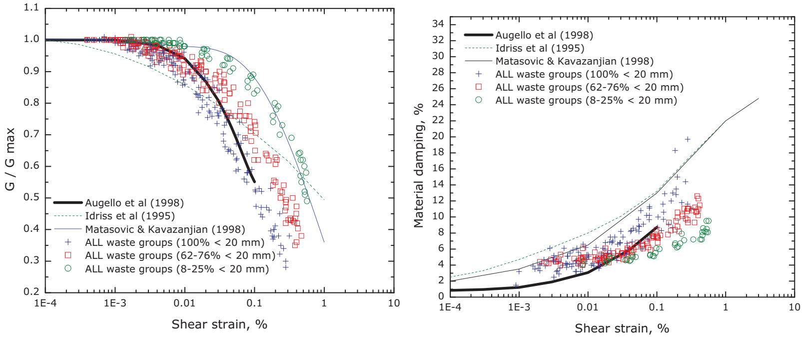

FIG. 11. G/G_{max} vs. γ and λ vs. γ curves from large triaxial specimens of all tested waste groups and varying compositions (Zekkos et al. 2006b).

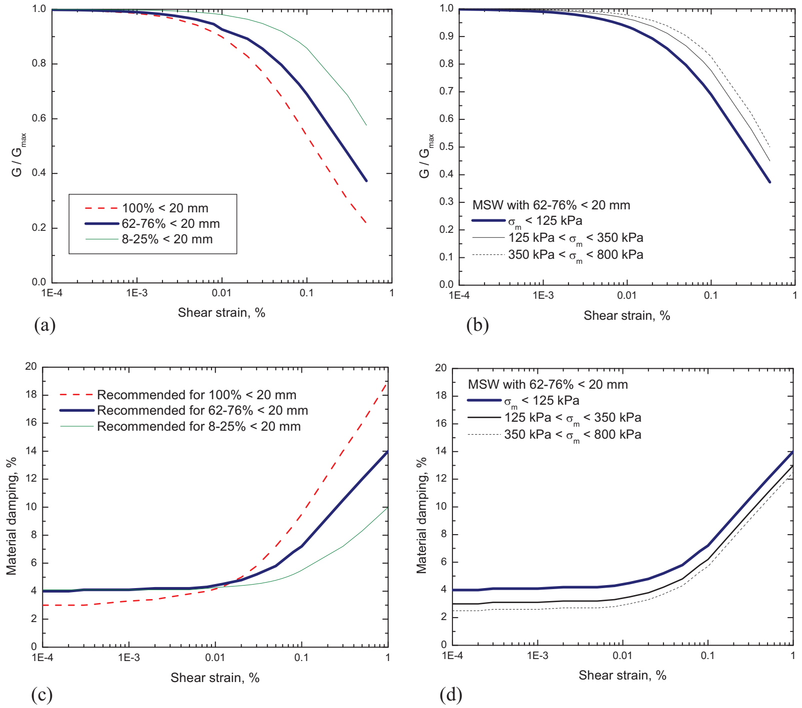

FIG. 12. Generalized G/G_{max} and λ curves for MSW as a function of composition for confining stress <125 kPa (a, c); and as a function of confining stress for waste with 62-76%<20 mm (b, c) (after Zekkos et al. 2008a).

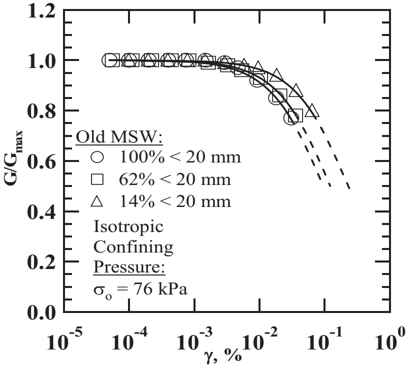

FIG. 13. Variation in G/G$_{max}$ and material damping with shear strain at a confining stress of 76 kPa for MSW with varying waste composition (Lee 2007).

Towhata and Uno (2008) performed large-scale (d=300 mm; h=600 mm) cyclic triaxial tests at low confining stresses. Tests performed under isotropic stress conditions (15 kPa, 30 kPa, and 45 kPa) suggest that the shear modulus increases with confining stresses, whereas material damping is not affected by confining stress. Significant variation of modulus and damping ratio was observed for strains less than 0.01% but the results were more systematic for larger strains. The results are shown in Figure 14.

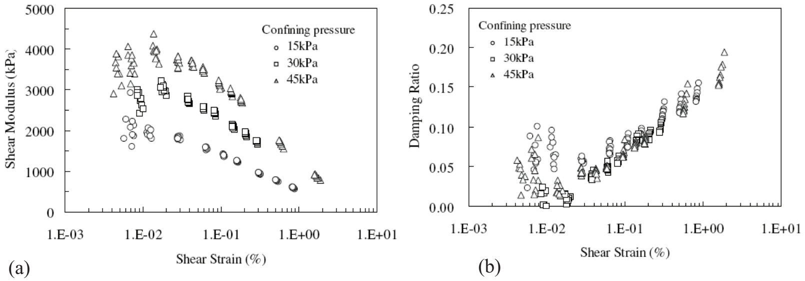

FIG. 14. Relationship between (a) shear modulus and strain amplitude; and (b) damping ratio and strain amplitude based upon cyclic triaxial testing (Towhata and Uno 2008).

4.4 POISSON'S RATIO

Poisson's ratio, ν, is a mandatory input parameter for the performance of 2-D and 3-D site response analyses. Relatively large scatter is observed in the measured values of Poisson's ratio reported in the literature. Whereas the laws of elasticity allow the estimation of Poisson's ratio from estimates of the at-rest earth pressure coefficient Ko, this review focuses only on direct measurements of Poisson's ratio in the field or the laboratory.

Laboratory testing has shown that inherent anisotropy and stress-induced anisotropy has a significant effect on Poisson's ratio. Different Poisson's ratio values will be measured in the field or the laboratory depending on the stress conditions and the structure of the material. MSW appears to be a highly anisotropic material (Athanasopoulos et al. 2008), but currently not much information is available on the effect of waste anisotropy on Poisson's ratio. All laboratory data reported subsequently were generated by measuring the horizontal deformation during the application of an increasing vertical load (and deformation). Different values of Poisson's ratio could be measured under other loading configurations or specimen waste structures.

In addition, wave velocity measurements in the field are also likely affected by the anisotropic nature of the material. Estimates of Poisson's ratio using Crosshole and Downhole velocity measurements could also be affected by differences in the compression and/or shear wave velocity of waste in different orientations. These topics require further studies, but as presented subsequently, the majority of the field and laboratory measurements indicate that Poisson's ratio values ranging from 0.05 to 0.35 are reasonable for MSW, with higher values being more appropriate for denser waste and/or waste with high soil composition.

4.4.1 Poisson's Ratio from In-Situ Testing

Sharma et al. (1990) performed in-situ Downhole velocity measurements in Richmond landfill in the San Francisco Bay area of California. Shear and compression waves were measured and the resulting Poisson's ratio was estimated to be 0.49.

Houston et al. (1995) performed Downhole testing in the Northwest Regional Landfill Facility (NWRLF) in Maricopa County, Arizona, USA, and evaluated the p- and s-wave velocity. Based on that evaluation, the authors estimated Poisson's ratio profile vs. depth (Figure 15). The top 2 m consisted of cover soil and Poisson's ratio was estimated to be about 0.3 at this depth. Poisson's ratio decreased with depth from a value of 0.3 to 0.11 at higher depths in the waste mass.

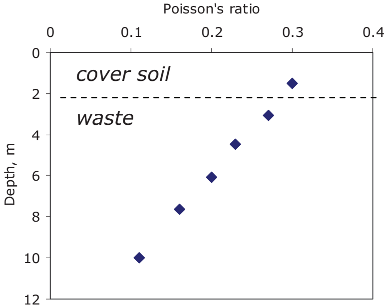

FIG. 15. Poisson's ratio profile at NWRLF landfill (after Houston et al. 1995).

Carvalho and Vilar (1998) performed the Cross-hole method and estimated the shear and compression wave velocities in Bandeirantes landfill in Brazil. With those measurements, the estimated in-situ Poisson's ratio ranged between 0.25-0.35 with a median value of 0.3.

Matasovic and Kavazanjian (1998) presented Poisson's ratio data estimated for the OII landfill using measured shear and compressional wave velocities. Values varied significantly, but the majority of the Poisson's ratio values ranged between 0.25 and 0.4. The data are shown in Figure 16.

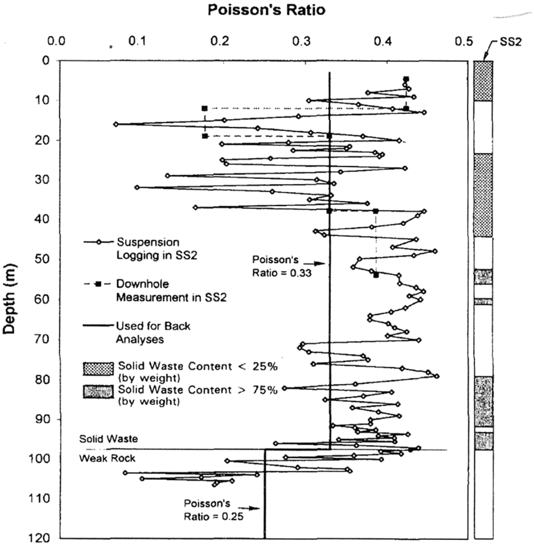

FIG. 16. Poisson's ratio profile of the OII landfill (Matasovic and Kavazanjian 1998).

4.4.2 Poisson's Ratio from Laboratory Testing

Jessberger and Kockel (1995), in a series of triaxial compression tests on waste under a range of confining stresses, found that the radial deformation at the initial levels of axial strain is about zero, yielding a Poisson's ratio that is practically zero. The authors found that Poisson's ratio increases with axial strain almost linearly until axial strain of about 20% (Figure 17). Poisson's ratio did not vary with confining pressure. The authors noted that the measurements for σ_3=100 kPa that appear to deviate from the remaining data are probably due to technical problems during the sample preparation and should, in fact, be in agreement with the rest of the data. The authors do not report how the radial strain deformation data were collected to estimate Poisson's ratio.

Zekkos (2005) measured Poisson's ratio during the performance of large-scale cyclic triaxial tests at confining stresses less than 100 kPa. Poisson's ratio was estimated by directly measuring the radial (horizontal) deformation using elastomer gauges, which provide local strain measurements. The data indicate that Poisson's ratio is generally constant for shear strains within the range of 0.01% to 1% even though in certain cases Poisson's ratio appeared to increase slightly with strain level. Poisson's ratio was measured to range from 0.05 to 0.4. Higher values were measured for specimens that were denser, and/or had higher composition of finer (<20 mm) material. A slight increase in Poisson's ratio was observed during the performance of a monotonic test from Poisson's ratio of 0.16-0.2 at small strains to 0.24 at axial strains of approximately 1%.

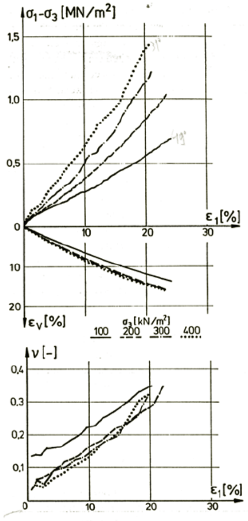

FIG. 17. Strain-dependent Poisson's ratio developed based upon triaxial compression testing of waste (Jessberger and Kockel 1995).

4.5 SUMMARY

The use of representative MSW properties is critical for the performance of reliable seismic analyses of landfills. Significant advances in our understanding of dynamic response of waste fills and cyclic characterization of MSW have been made in recent years. An attempt has been made to present a comprehensive, possibly not exhaustive, review of the Profession's understanding of the dynamic properties of Municipal Solid Waste. The goal of this review is to compile and summarize the current state-of-the-art on the dynamic properties of MSW. However, site-specific data are always preferable to general recommendations and past experience, since waste materials may differ due to a number of reasons including the sources of waste generation, landfill operation practices, climatic conditions as well as other factors.

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Chapter 5

Waste Characterization

Neil Dixon[1], Ulrich Langer[2], Krishna Reddy[3], Michele Maugeri[4], James Tinjum[5], Claudio Mahler[6] and Youngmin Cho[7]

[1]Professor, Department of Civil and Building Engineering, Loughborough University, Leicestershire, UK; n.dixon@lboro.ac.uk
[2]Dr.-Ing., ICP Ingenieurgesellschaft, Prof. Czurda & Partner mbH, Eisenbahnstr, 36 D-76229 Karlsruhe, Germany; langer@icp-ing.de
[3]Professor, Geotechnical and Geoenvironmental Engineering Laboratory, University of Illinois, Chicago, USA; kreddy@uic.edu
[4]Professor, Dipartimento di Ingegneria Civile e Ambientale, University of Catania, Italy; mmaugeri@dica.unict.it
[5]Department of Engineering Professional Development, University of Wisconsin-Madison, USA; tinjum@epd.engr.wisc.edu
[6]Department of Civil Engineering, COPPE/UFRJ, Brazil; cfmahler@usp.br
[7]Youngmin Cho, Environmental Engineering Sciences, University of Florida, USA; youngmcho@ufl.edu

5.1 INTRODUCTION: WHY IS ANOTHER WASTE CLASSIFICATION SYSTEM NEEDED?

To ensure stability of a construction, the physical properties of its components have to be known so that relevant analysis and design can be carried out. In a landfill, waste presents the largest structural element and influences stability and integrity of the lining system (Jones and Dixon, 2003) and operation of leachate and gas extraction systems. However, in spite of this critical role there is still a dearth of knowledge on behaviour of municipal solid waste (MSW) as an engineering material. To aid development of methodologies for measuring and reporting mechanical properties of waste materials, and to formalise analysis and design procedures, a universally accepted waste characterization framework is required. Waste characterization must provide sufficient information to enable designers and operators of waste containment facilities to appreciate the type and engineering properties of the waste mass and hence to anticipate likely behaviour and potential problems.

A waste characterization framework should have two elements, a classification system for waste components, and description of the structure/fabric of the waste mass. Classification of components can be related to material characteristics and parameters. Description of waste body structure can be related to mass characteristics and state parameters. Knowledge of both is required to understand mechanical behaviour of waste bodies (e.g. compressibility, shear strength and hydraulic properties), to group wastes with similar mechanical properties and to facilitate the exchange and interpretation of measured properties by both researchers and practitioners.

Although there are several waste classification systems in current use world-wide, none of these relate specifically to mechanical behaviour. Therefore, there is a need to both develop a waste characterization framework and to disseminate it to encourage use world-wide. This section summarises the state-of-the-art of waste characterization as reported at the Waste Mechanics Workshop, New Orleans, March 2008, and outlines a framework that was presented and discussed. Application of a component classification is demonstrated using data from the literature. The workshop defined the uses of a waste characterization procedure, it identified the key factors that should be included in a characterization system, and considered the methods that should be used to obtain measurements and the best approach to present characterization information. Consensus was achieved on the form of the characterization framework and it was agreed that it should be disseminated to those actively involved in waste mechanics research and practice, with the aim of promoting it’s use and to stimulate further development.

5.2 REQUIREMENTS OF A WASTE CHARACTERIZATION FRAMEWORK

Given the significant variation in waste materials, past, current and likely changes in the future, and the limited number of researchers and practitioners engaged in measuring mechanical properties of waste, a characterization procedure is crucial for development of a unified framework for waste mechanics. Past experience of waste behaviour is a potentially misleading guide to future behaviour. Life style changes lead to production of different wastes and the introduction of new legislation (e.g. reductions in biodegradable waste driven by the European Landfill Directive, European Council, 1999), recycling and pre-treatment activities that are resulting in significant continuing changes to waste composition. Knowledge of changes in waste types (i.e. through characterization) is required to evaluate future changes in mechanical properties of waste bodies and hence landfill behaviour.

Waste bodies are heterogeneous; they have anisotropic physical properties (due to placement in layers) and they are formed from components with a wide range of shapes, sizes, material type and degradation potential. To enable assessment of mechanical behaviour of waste bodies it is necessary to investigate the properties of its components and of the structures they form. A first step is to develop a classification system that groups components according to their physical and mechanical properties, including an assessment of their potential to influence mechanical behaviour of the waste body. The second step is to describe in situ waste body structures and hence to evaluate mechanical properties of these volumes of waste (e.g. compressibility, shear strength and stiffness). Structure of waste bodies relates to orientation and particle packing of components. For example, foil type components such as paper and plastic may have sub-horizontal orientations as a result of waste placement and compaction in layers. MSW materials can not be classified using approaches developed for use in soil mechanics. Key differences between soil and MSW components include waste components having the potential to be compressible and deformable, they can degrade (and hence change their properties over time) and foil shaped components can form structures not found in soils leading to development of tensile strength.

However, the need and principles for classification are comparable to those for soil. Whitlow (1983) justifies the need for a classification system and describes the principles for classifying soil as detailed below:

> "*The system adopted needs to be sufficiently comprehensive to include all […] deposits, while still being reasonable, systematic and concise. […]. Without the use of a classification system, published information or recommendations on design and construction based on the type of material are misleading, and it will be difficult to apply experience gained to future design. Furthermore, unless a system of conventional nomenclature is adopted, conflicting interpretations of the terms used may lead to confusion. […] A classification system must satisfy a number of conditions:*
> *a) It must incorporate definitive terms that are brief and yet meaningful […].*
> *b) Its classes and sub-classes must be defined by parameters that are reasonably easy to measure quantitatively.*
> *c) Its classes and sub-classes must group together soils having characteristics that will imply similar engineering properties.*"

The characterization framework must be of use for designers, site operators and researchers. Designers need to anticipate waste types to be placed in a landfill as part of the detailed design process, and they also require typical mechanical waste parameters to be associated with the expected waste to be landfilled. The framework must also be appropriate for use in studies of placed waste in order to check the validity of design assumptions and to identify critical changes in waste type that could impact on the performance of engineering controls. Researchers require the framework to record tested waste samples, thus facilitating the reporting and sharing of information on waste behaviour. The long-term aim is to relate classification to broad categories of engineering behaviour comparable to the way soil classification is related to types of engineering behaviour and properties (e.g. the way fine grained and coarse grained soils can be related to specific types of engineering properties and behaviour). However, this will require a significant body of research.

Key aspects of engineering behaviour that are required to be related to waste characterization include shear behaviour, volume change (i.e. compression, creep) and hydraulic properties (gas and liquid). It should be noted that these are all state properties. They are related to the density, stress level and structure of a waste body, in addition to the component classification.

MSW contains components that degrade with time and this means that the classification of a waste will change with time. Therefore, unlike soils, the characterization framework must include information on the degradation potential of components and the rate at which the process might occur. The characterization of a sample of waste is both time and state (i.e. stress level) dependent. The classification could change with time as particles either degrade or are subjected to changes in stress. For example, classification of a sample of waste material could change with time as follows:

- Initial classification of the waste delivered to landfill. Components will have been compressed in household storage containers, in the collection vehicle and possibly in a transfer container to site. Components could also be modified by treatment (e.g. sorting, composting, shredding).
- Short-term classification of the waste will be influenced by the stress state imposed during compaction and increasing overburden from subsequent lifts of waste. This will modify compressible and deformable components. The classification at this stage is related to engineering behaviour of the waste during staged construction of the landfill and will be relevant to assessment of interaction between the waste body and engineering controls.
- Intermediate classification of the waste will be related to the water content of waste components, creep deformation and component degradation. This will alter components, including softening and loss of mass, and it will also result in modification to the waste structure due to the loss of mass, and hence volume, and weakening of components, all of which will lead to component rearrangement. Classifications of the waste during this period are relevant to assessment of interaction between the waste body and engineering controls during the operational life of the landfill (e.g. leachate and gas collection infrastructure and the capping system).
- Long-term classification of the waste is related to completion of all degradation and creep. Classification of the 'inert' waste fill at the end of the operational life of the landfill facility is relevant to engineering behaviour of the fill material when the site is considered for re-development.

It is not currently possible to predict either the degree of change in a waste classification over time, or the rate of the change. However, information on the stress level the waste will experience, the percentage and type of degradable material present and the operational conditions in the landfill will enable likely trends in characterization with time to be identified. This will provide the opportunity to identify likely trends in key engineering parameters, and hence warn of potential changes that would be detrimental to performance of the landfill facility.

5.3 REVIEW OF EXISTING WASTE COMPONENT CLASSIFICATION SYSTEMS

A detailed review of reported waste classification systems developed as part of mechanical behaviour studies is provided by Dixon and Langer (2006) and Langer (2006). A summary of this information is provided and updated in this section. A number of the existing classification systems are simply based on material groups (e.g. paper, plastic, metal, etc., Siegel *et al.*, 1990) or on the distinction between soil-like and non soil-like, or fibrous, appearance (Manassero *et al.* 1997; Thomas *et al.* 1999). These existing classification systems do not fulfil the requirements of a rigorous classification framework as outlined in Section 5.2. Table 5.1 provides a summary of existing classification systems including the parameters used. Key elements of these classification systems are considered further.

Landva and Clark (1990) proposed a classification system that differentiates between organic and inorganic components. They subdivided these into putrescible and non-putrescible within the organic components, and degradable (corrodible) and non-degradable within the inorganic components (Figure 1). Additionally, void-forming constituents within each subdivision, excluding the putrescible group, are highlighted. This system provides detailed information on degradation and compressibility potential of components but does not consider component shape or material properties (e.g. tensile strength of components). Therefore this system could form part of a component classification framework but it is not comprehensive.

Table 5.1. Overview of Existing Classification Systems

Author	**Basis for Differentiation**	**Parameters Used for Differentiation**
Turczynski (1988)	Waste type	Density, shear parameters, liquid/plastic limit, permeability
Siegel *et al.* (1990)	Material groups	Part of composition
Landva and Clark (1990)	Organic, inorganic materials	Degradability (easily, slowly, non) Shape (hollow, platy, elongated, bulky)
ADEME (1993)	Particle size distribution and composition	Size, material groups, moisture content and degradability
Grisolia *et al.* (1995)	Degradable, inert, deformable material groups	Strength, deformability, degradability
Kölsch (1996)	Material groups	Size, dimension
Manassero *et al.* (1997)	Soil-like, other	Index properties
Thomas *et al.* (1999)	Soil-like, non soil-like	Material groups
Dixon & Langer (2006)	Shape-related subdivisions	Material groups, size, dimensions, shape related properties, degradation potential

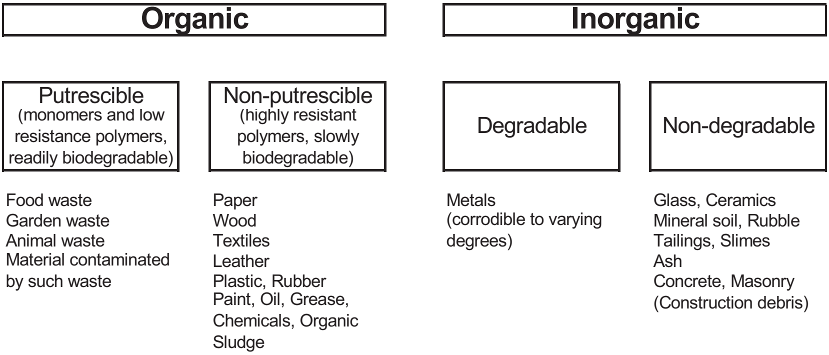

FIG. 1. Waste classification (after Landva and Clark, 1990)

The French Environmental Protection Agency produced the MODECOM^{TM} protocol (ADEME 1993) to characterize the particle size distribution and composition of both fresh and landfilled waste. Three sieve sizes (100, 50 and 20 mm) are used with each waste component retained on the sieves sorted into one of 18No. material categories. For each component the weight, moisture content and organic content are measured. The waste components are grouped based on biodegradability (i.e. easily, moderately, hardly, inert and residual fines). Application of the protocol is described by Grellier *et al.* (2007). This system is comparable to that of Landva and Clark (1990) regarding degradation potential but does not consider particle shape and compressibility.

Grisolia *et al.* (1995) defined degradable, inert and deformable component groups and classified wastes by plotting the percentages of each group in a ternary diagram. This allows comparison of the composition of different wastes. A strength of this system is that it provides information about compressibility and degradability of components. However, it is possible for a component to fit into more than one group (e.g. food residues are biodegradable and highly deformable). Particle shape is not considered, which means that the influence of foil type components reinforcing waste, that could increase shear strength, can not be identified.

Kölsch's (1996) classification system includes material groups, size and dimension of components. The advantage of this system is the possibility for a more detailed examination of component properties, which is consistent with the known large variability of waste component form and properties. The disadvantage is the large amount of data required and the omission of information on degradation potential. Such a detailed system is more appropriate for research purposes than regular practical use.

None of the above systems fulfil the requirements for a rigorous waste mechanics classification. However, they provide useful criteria. The information required to classify waste components can be summarised as:

- A distinction is required between the material groups (i.e. based on typical component material properties), with dominant groupings established. Information is then required on the proportion (e.g. by weight) of different size components in each material group.
- Knowledge of component shape is required to distinguish between soil-like (three-dimensional e.g. granular) and non soil-like (two-dimensional e.g. sheet) components. This allows classification of components in relation to their potential for influencing mechanical behaviour of the waste mass (e.g. compressibility, shear and tensile strength).
- Grading by size is required for each group of components (size assessment of each component).
- An assessment of component compressibility and hence the potential for components to change shape during placement and/or burial.
- An assessment of degradation potential for both organic and inorganic components.

The waste component classification system proposed by Dixon and Langer (2006) incorporates each of the above elements. At the current time it is the most rigorous of the systems proposed by researchers. It formed the basis of discussion at the Waste Mechanics Workshop and there was consensus that it should be the starting point for development of a universal characterization framework. A detailed description of the Dixon and Langer (2006) component classification system is provided below including explanation of the development process.

5.4 DIXON AND LANGER (2006) CLASSIFICATION SYSTEM

5.4.1 Material Groups

The starting point for a classification system is identification of the main waste components by material type. Due to the large variety of materials present in waste, a practical approach is to identify major groups of materials. For example, an American waste composition survey carried out by the Department of Environmental Quality (1998) used the following main groups: organic, paper, wood, polymer/plastics, metal (Fe/non-Fe), soil-like, ceramic, glass, inerts and rubber. Waste composition is defined by measuring the mass percentage of each material group present in a sample. A significant barrier to the sharing of information on waste behaviour is the use of different groups of materials by those classifying samples used in experimental programmes. In many instances the reasoning behind selection of specific groupings is not explained, and hence the factors influencing measured behaviour can not be fully understood.

Selection of appropriate groups requires consideration of component mechanical properties. It is proposed that components are considered in the condition they have on delivery to a landfill site. Definition of this initial state is required because mechanical properties, shape and size of components will change as a result of placement conditions (i.e. compaction) and stresses due to burial, as some particles will deform, and in the long-term due to degradation processes. The classification system must provide the possibility for components to change group as a result of these processes. Moreover, the groupings should be appropriate for every possible type of waste. The following mechanical properties can be considered as a basis for selecting component material groupings:

- Shear strength
- Tensile strength
- Compressive strength
- Elongation at break (at given strain)
- Modulus of elasticity

For each material group it is possible to obtain indicative shear and tensile strengths, elongation at break, compressive strength and modulus of elasticity. It can be shown (Dixon and Langer 2006) that large ranges of these values can be obtained, however it is not intended to use this information to define groups using specific material values, but to highlight the state of variability within groups, and stress similarities and differences between groups of components. This information can be used to identify those groups of materials that can be amalgamated to simplify the classification. In addition, it provides an indication of the groups that could influence specific aspects of waste body mechanical behaviour (e.g. compressibility, shear strength). However, it should be noted that waste body behaviour is also dependant on the overall composition of the waste body and on the in-situ density, structure and stress state.

This approach has been used to select the following material groups for use in the classification: Paper/Cardboard; Flexible plastics; Rigid plastics, rubber; Metals; Minerals, glass; Wood, leather, textiles; Organics; and Miscellaneous. The miscellaneous category is for components that are too small to practically sort. The maximum size of this material is discussed below. In a number of classifications this fraction is described as ‘soil like’ and although it may contain a significant organic content, there is potential to carryout standard soil mechanics index tests to provide additional classification information. This group of components is of particular importance in degraded waste materials.

5.4.2 Shape-related Subdivision of Components

The following distinction is based on observations of waste components and consideration of mechanical properties of components (e.g. how easily they can be compressed). Assessments have been made about the potential role specific material groups could play in mechanical behaviour of the waste body. Further research is required to validate these assessments. Dixon and Langer (2006) proposed that the shape of waste components could be characterised by one of two basic groups based on shape-related properties, in conjunction with associated subdivisions:

- Reinforcing components; one-, two-dimensional (e.g. plastic bags, sheets of paper)
- Three-dimensional components
  a) Compressible components
    - High compressibility (e.g. putrescible materials, plastic packaging)
    - Low compressibility (e.g. beverage cans)

  b) Incompressible components (e.g. bricks, pieces of metal)

The subdivision of compressible components is necessary for assessing changes resulting from placement activities (i.e. depositing and compacting the waste) and overburden stresses from additional waste layers. Stressing high compressibility components could lead to shearing and crushing of components, while low compressibility components could remain unaffected during deposition. The simplified distinction between high and low compressibility components provides a solution for consideration of short-term behaviour due to placement and compaction, and long-term behaviour of components in response to increasing overburden stress and creep. However, at present there is insufficient experimental data to enable such a subdivision to be quantified (i.e. to define the threshold stress between high and low compressibility). The threshold should be related to the maximum stress imposed during waste placement and compaction. Further work is required to develop an appropriate simple test for assessing the compressibility of components and to provide relevant threshold values. Incompressible components are those that will not compress if subjected to the maximum overburden stress in a specific landfill.

Definition of a component as reinforcing is based on an assessment of the size of reinforcing components (e.g. fibre or foil) in relation to the size of surrounding regular shaped 3-D components (i.e. those particles tending to spherical in shape). Theoretically, reinforcing can result when fibre/foil length exceeds the nominal diameter of the regularly shaped particles. If bonding of reinforcing components between regularly shaped 3-D particles does not occur, then tensile forces in the mixture cannot be generated. For example, Michalowski and Zhao (1996) suggest that the length of the reinforcement must be at least one order of magnitude larger than the diameter (d_{50}) of sand grains for fibre-reinforced soils. With a shape-related subdivision of waste constituents, a grouping of components with similar general mechanical behaviour (i.e. (in-)compressible and reinforcing properties) can be given and this meets the requirements of a geotechnical classification system.

5.4.3 Grading of Waste - Size of Components

A key element of a classification is information on grading. Each material group is sorted into one of the three shape-related subdivisions (i.e. compressible, incompressible and reinforcing components) and then the next step is to grade components into the following size ranges: <20mm, 20-40mm, 40-120mm, 120-500mm, 500-1000mm, >1000mm. It is considered to be impractical to sort components smaller than 20mm and as discussed above, this size fraction can be considered to be soil like in nature and hence investigated using traditional soil mechanics approaches (e.g. index tests). Grading of deformable and irregular components, such as plastic packaging and sheets, is challenging. It is proposed that the maximum dimension be obtained with the component in an unstressed state (i.e. not compressed, folded or deformed). Component sizes within the reinforcing shape-related subdivision should be reviewed considering the size ranges in the other two sub-divisions in order to assess their potential to act as reinforcing elements.

5.4.4 Degradation Potential

In order to be able to represent changes in classification that occur due to degradation, it is necessary to provide information on degradation potential of components. The subdivisions proposed by Landva and Clark (1990), and outlined in Figure 5.1, are considered to provide an appropriate framework. For assessment of degradation potential, it is important to distinguish between short-term, medium-term and long-term degradation rates. Paar (2000) specified the hierarchy of biodegradable substances (Table 5.2). As the largest degradation alteration of waste components occurs by bio-degradation, the framework currently only considers this. Other degradation processes like corrosion and dissolution or other chemical reactions depend on the surrounding milieu. For physical decay or weathering processes, temperature, water content and water and solids movement play important roles. There is inadequate information in the literature to develop this aspect of waste behaviour further at the present time.

Table 2. Degradation Hierarchy of Substances (after Paar 2000).

Substance	Degradability
Sugar, starch, protein, fat	Easy
Hemicelluloses, celluloses, wax, synthetic oil	Medium difficult
Lignin, resin	Difficult
Leather, rubber, plastics	Very difficult to non-degradable

The distinction of the different stages of degradation can be linked to different materials. For example, kitchen waste (for the most part vegetable residue or similar) degrades more rapidly than paper. A comprehensive classification system should include these factors. There are various methods available to assess the organic content. Methods such as the loss of ignition and the Total Organic Content (TOC) only provide information on the general organic fraction and the amount of organic carbon, respectively, and not on the degradable organic fraction and carbon, which is required if using the Paar (2000) subdivision. However, in conjunction with the Biological Oxygen Demand, conclusions can be made about the biological activity of components in specific material groups, shape-related subdivisions and size ranges. Selection of an appropriate approach will in part depend upon the size of the component.

5.4.5 Component Classification Procedure

The procedure of classifying waste components is presented in Figure 2. Figure 3 demonstrates an example application of the classification framework. The application considers the state of waste components at three stages during testing or landfilling: as delivered to laboratory/site, following placement in the test chamber or on site and in the long-term following degradation. Components that form a representative waste sample are examined to obtain information on: material type, shape and size. This would typically be achieved through a combination of visual assessment of material type and properties, measurement (e.g. size and shape) and estimation of degradation potential (i.e. related to material type). Based on the material property information, components are grouped in order to minimise the number of material categories. Information about material properties and shape of components is used to group them according to whether they are compressible, incompressible or reinforcing. An overall grading for each material group in each of the shape-related subdivisions is then obtained. The subdivisions are then reviewed and modified, if required, by taking into considering the relative size of reinforcing components to regular shaped components as discussed above. Finally, the degradation potential of components in each shape-related material group is defined either by testing or visual assessment.

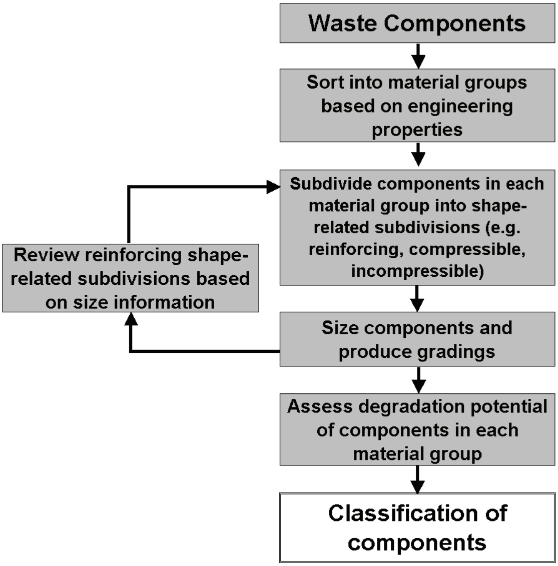

FIG. 2. Procedure of the proposed component classification framework (after Dixon and Langer 2006)

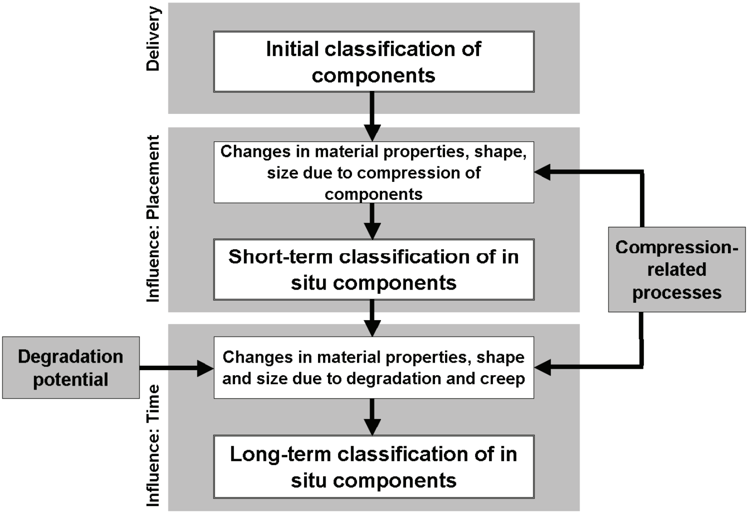

FIG. 3. Example application of the component classification framework (after Dixon and Langer 2006)

5.5 PRESENTATION OF INFORMATION

The comprehensive nature of the information required to classify waste components leads to the need to adopt a range of approaches for presenting the results of a classification. Information on the percentage by mass in each of the shape-related subdivisions, the proportion components in each material group, the size and grading for these components and the percentage of degradable material are all required. Figure 5.4 is an example of part of the data obtained from a waste classification exercise. It provides information on material groups and size ranges for the proportion of components classified as compressible.

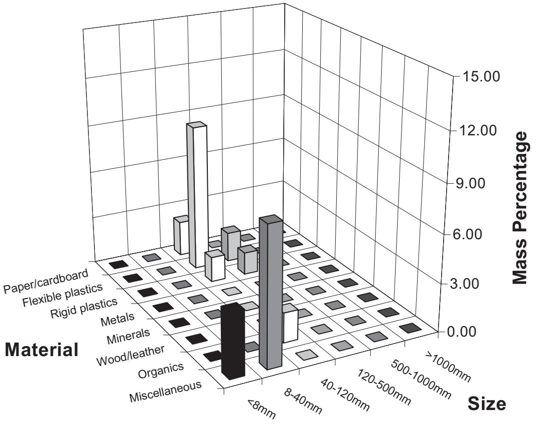

Fig. 4. Mass distribution for compressible components (after Langer 2006)

Figure 5.5 shows an example, fictitious, diagram for a shape-related subdivision of waste, to demonstrate a possible format for presenting information on size, grading and degradation potential for a specific shape related sub-division of the waste sample (i.e. compressible, incompressible or reinforcing). Figure 5.5 shows grading curves for three different material groups (materials 1, 2, and 3). The upper curve, denoted by a thick black line, gives the cumulative grading for the combined material groups forming the shape-related subdivision. The grading lines below this can be used to calculate the cumulative grading for each material group. For example, the size range of >120mm represents 73% of the overall material mass and is composed of 32.2% material 1, 24.3% (56.5% minus 32.2%) of material 2 and 16.5% (73% minus 56.5%) of material 3. The cumulative dry mass percentage of a material group for a given component size is simply the difference between the cumulative values of the material groups plotted immediately above and below. In this manner, computed values are related to the shape-related subdivision mass percentage of 100%.

Information on degradability potential is provided in the column on the right hand side of Figure 5.5, where the percentage of degradable and non-degradable content for each material group is related to the total mass of waste in this shape related subdivision. Sections of the column are used to represent each material group, with the height based on the percentage of that group as a proportion of the total sample (i.e. the three material groups in this example add up to 100% of the sample, with material 1 forming 41.1%, material 2 forming 33.9% and material 3 forming 25% of the total). If there is biologically degradable material present in a group, the information is represented by a grey section of the column with the percentage shown by the height (i.e. in relation to the overall mass of the shape-related sample), and the white section represents the inert percentage. The total percentage of degradable material present in a shape-related subdivision is obtained from the sum of the grey sections of the column. For example, the total degradable material in this subdivision is 43.3% (30.8% from material 1, 0% from material 2 and 12.5% from material 3). The information on degradation potential enables an assessment of possible mass reduction of materials due to degradation, and thus the reduction in proportion of the entire waste sample composed of the shape-related subgroups. This information can be used to predict the possible classification of the waste for the long-term condition when degradation is complete.

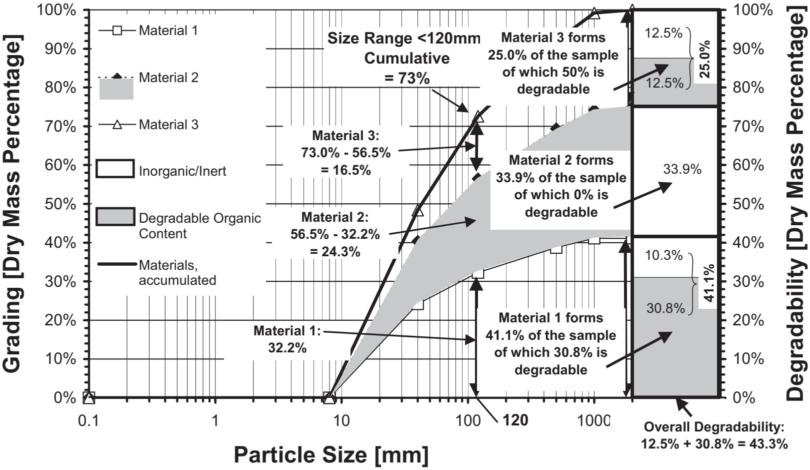

Fig. 5. Example graph demonstrating presentation of data relevant for component classification within a specific shape-related subdivision of the waste sample (after Dixon and Langer 2006)

An additional step in the characterization framework is to present an overall summary waste component classification based on percentages by mass of the shape-related subdivisions in a ternary diagram, as demonstrated in Figure 6. This diagram can be used to demonstrate changes in classification resulting from waste placement, which causes compression of some components, and in the long-term following degradation of some components. In Figure 6 information on the initial state is derived directly from the original shape and material properties data for components. For the potential state after placement, it can be assumed that the percentage of the reinforcing and incompressible components both increase due to the compression of highly compressible components such as paper, flexible plastic packaging and organic materials. In this example, degradation was not taken into account for the waste state following placement due to the fact that placement was considered to be a short-term event. The final state of the waste can be calculated based on the percentage of materials in each shape-related subdivision with potential to degrade. A loss of mass due to methane and carbon dioxide generation and the alteration of organic into mineral matter can be calculated using values for the degradation potential of components. The use of the ternary diagram requires the presentation of the shape-related subdivisions as percentages, which means that the loss of mass is not shown, due to the fact that the sum of the shape-related subgroups always has to equal 100%. In fact there will be a loss of mass in each of the three groups due to degradation. In wastes that do not contain compressible components the classification simplifies to the two shape related sub-divisions of incompressible and reinforcing.

A study using synthetic wastes is reported by Dixon *et al.* (2008) that attempts to relate waste component classification using the shape-related ternary diagram to broad trends in mechanical behaviour, such as one-dimensional compression and shear behaviour. Further research is required to continue this approach with the aim of associating ranges of mechanical behaviour to classification. This would be a useful tool for designers as they will only have preliminary information on the waste type to be placed in a given landfill, but they require engineering parameters for use in the design of the engineering controls. A comprehensive waste classification reflecting placement and long-term conditions requires a detailed investigation of potential changes in grading, shape and mechanical properties of the materials due to biodegradation, compression and creep.

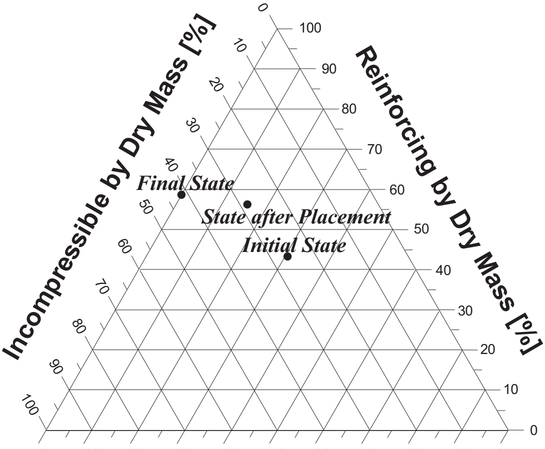

FIG. 6. Demonstration of the potential use of shape-related classification to aid evaluation of changes in mechanical behaviour of MSW bodies resulting from placement, and final state after long-term degradation (after Dixon and Langer 2006).

5.6 DESCRIPTION OF WASTE STRUCTURE

The main focus of international research to date has been development of waste classifications based on the components. However, as discussed in Section 5.1, a complete characterization also requires information on the waste body in addition to the components. The key engineering parameters required to design and assess waste containment systems, such as stiffness, shear strength and hydraulic properties, are all state parameters that depend upon in situ waste body conditions. Therefore it is essential that density, stress state, stress history, moisture content of components and structure are all recorded, whether in situ or for re-constituted samples used in element tests. There are well established procedures for measuring in situ density of waste (e.g. Zekkos *et al.* 2006), stress states can be calculated using these measurements in conjunction with depths of burial (although there is little current information on horizontal stress conditions), stress history can be obtained from site records of waste placement and compaction practice, and the moisture content of components can be measured. It should be noted that one of the fundamental differences between soil and waste is that many waste components can absorb liquid and this can lead to a changes in the compression and strength of the component.

There are currently no commonly accepted procedures or terminology for describing waste body structure, however it is possible to borrow from soil description practice. The following should be described:

- Thickness and spacing of layers of waste that are visually different, including temporary cover soil layers;
- General orientation of sheet like reinforcing components;
- Size and location of discrete pockets, lenses or layers of specific waste materials; and
- Location of zones of free liquid such as perched leachate above low permeability waste and/or temporary cover layers.

In addition, information on colour and odour can be used to provide information on the presence and stage of degradation.

5.7 SUMMARY AND THE FUTURE

This chapter reports the current state-of-the-art with respect to the development of a waste characterization framework. Discussion at the Waste Mechanics Workshop, New Orleans, March 2008, provided a level of consensus for basing further work on the component classification system presented in Section 5.4. In addition, the requirements of a full characterization framework were defined and areas that require further work identified. Key elements of the component classification are:

- Use of material groups: Paper/Cardboard; Flexible plastics; Rigid plastics, rubber; Metals; Minerals, glass; Wood, leather, textiles; Organics; and Miscellaneous;
- Definition of miscellaneous material as smaller than 20mm;
- Sub-division of all components to one of three shape-related groups: incompressible, compressible and reinforcing, with the compressible components further subdivided into high and low compressibility;
- Grading into size ranges: <20mm, 20-40mm, 40-120mm, 120-500mm, 500-1000mm, >1000mm;

- Assessment of degradation potential (e.g. using the framework proposed by Landva and Clark, 1990, or diagnostic laboratory tests); and
- The need to consider the time dependency of a classification, with stress state and degree of degradation resulting in changes to components.

Description of stress state and waste body structure should be carried out using approaches developed for soils.

It is proposed that researchers should commence using the framework as currently presented. It provides a common basis for the exchange of information on waste materials used in studies of mechanical behaviour. This will aid future efforts to develop our understanding of waste mechanics. However, there are a number of areas of further work that are required in order to strengthen the framework before it is likely to become widely used by practitioners. Areas requiring further study include:

- Confirmation of the relevance of the selected material groups for a range of waste types;
- Confirmation of the relevance of using a minimum component size of 20mm as the cut-off between components that are sub-divided into material groups and those that are grouped as miscellaneous, with soil like properties;
- Development of a generic method for assessing degradation potential of components;
- Selection of a procedure for sizing foil like reinforcing components;
- Development of a methodology for assessing compressibility potential of components; and
- Formalising description terminology for waste bodies.

A key requirement is for studies to be reported that trial the characterization framework so that it can be critically reviewed and revised as required. This includes the need for studies that relate mechanical behaviour to characterization of the tested waste as this will enable the relevance of the selected classification criteria to be examined.

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Chapter 6

In-Situ Measurements of MSW Properties

Neven Matasovic[1], M. ASCE, Rami El-Sherbiny[2], M. ASCE, and
Edward Kavazanjian, Jr.[3], M. ASCE

[1]Associate, Geosyntec Consultants, 2100 Main Street, Ste 150, Huntington Beach, California 92648; nmatasovic@geosyntec.com
[2]Assistant Professor, Faculty of Engineering, Cairo University, Cairo, Egypt; rsherbiny@eng.cu.edu.eg
[3]Associate Professor, Arizona State University, Dept. of Civil and Environmental Engineering, Tempe, Arizona, 85287; edkavy@asu.edu

6.1 INTRODUCTION

Recovery and testing of representative, undisturbed or intact samples of Municipal Solid Waste (MSW) is difficult, if possible. Therefore, in-situ testing is the most reliable method for evaluation of the material properties of MSW. However, in-situ testing techniques are also subject to limitations that may significantly affect their applicability and consequently reliability of evaluated MSW parameters. Furthermore, because these measurements can only be made after the waste is in place, they are only directly applicable to analysis of existing landfills while extrapolations are required for design of new landfills.

Material properties of interest to engineering community include unit weight and moisture content, shear strength, stiffness and compressibility, stress-strain behavior, hydraulic conductivity (saturated and unsaturated), and field capacity. These properties can roughly be categorized into mechanical and physical properties. Similarly, in-situ measurements may be divided into direct measurements of the behavior of MSW and indirect measurements that rely on correlations and/or back analyses to calculate properties of interest. It is generally difficult to categorize a certain in-situ test method as direct or indirect because each test method can directly measure certain properties and indirectly measures other properties. For example, wave propagation surveys are a direct measurement of wave velocity but an indirect measurement of stiffness; similarly, soundings with the Standard Penetration Test (SPT), Cone Penetration Test (CPT) and dilatometer (DMT) can be used to directly identify waste stratigraphy and indirectly to assess shear strength of MSW. Field measurements of MSW properties may also be divided into non-intrusive measurements that do not penetrate the waste mass and intrusive measurements that penetrate the waste mass. Classification of in-situ testing techniques into intrusive and non-intrusive is more distinct and will be used for categorizing in-situ test methods in the remainder of this Chapter.

Over the past years, significant improvements in field measurements became possible. These include rapid and inexpensive measurement of ambient vibrations (e.g., REMI), accurate measurement of small deformations with laser beams (e.g., LiDAR), and include abundance of relatively accurate digital terrain measurements generated by regulatory-mandated annual flyovers over landfills. This is in addition to more in-situ test methods being adopted from geotechnical engineering for testing and sounding at landfills, such as SPT and CPT sounding, and testing with devices such as dilatometer and (self boring) pressuremeter. This Chapter aims to provide a critical review of the state-of-the practice of these methods as applied to waste mechanics.

6.2 MATERIAL PROPERTIES OF ENGINEERING INTEREST

6.2.1 Mechanical Properties

Mechanical properties of MSW that are generally of interest to the engineering community include (strain-dependent) stiffness, damping, and Poisson's ratio, primary compressibility (compressibility under constant effective stress), secondary compressibility (compressibility under constant, long-lasting load), shear strength, and (strain-dependent) interface properties (e.g., p-y and t-z curves for pile foundation design). These mechanical properties are, to some degree, interrelated. For example, Young's modulus can be evaluated from shear modulus and Poisson's ratio, while both stiffness and strength are required to develop p-y and t-z curves. Furthermore, modulus of subgrade reaction can be evaluated as a ratio of contact pressure and settlement, whereas settlement is calculated from primary compressibility.

Secondary compressibility may be divided into mechanical secondary compressibility (compression of the waste mass under constant load without mass loss) and biological secondary compressibility (compression due to mass loss from bio-degradation). Both primary and secondary compressibility depend significantly on the state of decomposition of the waste. Primary compressibility of un-degraded MSW is of engineering interest, mainly for the purposes of calculating internal settlement of buried gas collection and liquid distribution pipes, evaluation of downdrag on risers and, to some extent, for landfill capacity and post-closure settlement evaluations. Primary compressibility of degraded MSW may be required for analysis of waste-on-waste ("piggy-back") liner systems and post-closure landfill development as well as for landfill capacity analysis. Secondary compressibility of MSW is important for evaluation of post-closure settlement of the landfill cover as well as for any structure constructed on top of the landfill. Secondary compressibility of MSW is generally governed by the biological component (Hossain et al., 2003).

MSW shear strength is required for both static and seismic stability evaluations. Traditionally, no distinction is made between the static and dynamic shear strength of MSW. More recent data indicate that the seismic shear strength of MSW is higher

(Augello et al. 1995, Zekkos et al. 2007). More information on the static and seismic shear strength is reviewed in Chapter 2. MSW shear strength may also be required for capacity and lateral resistance analysis of piles driven into waste during post-closure development of landfills. Shear strength may also be required for evaluation of bearing capacity of shallow foundations, though shear strength of landfill covers and settlement generally govern the foundation design in such cases.

6.2.2 Physical Properties

Physical properties of MSW that are generally of interest to engineering community include total unit weight, field capacity and in-situ moisture content, unsaturated and saturated hydraulic conductivity, and moisture retention properties (e.g., field capacity). The total unit weight of MSW is required for a variety of engineering analyses, including stability, settlement, site response, liner puncture potential, structural capacity evaluation of buried pipes, and hydraulic capacity evaluation of geonets. In-situ moisture content and field capacity are required for evaluation of leachate generation potential for MSW landfill design. Moisture content and field capacity are also essential parameters for design and operation of bioreactor landfills. Furthermore, as the in-situ moisture content of MSW increases beyond the field capacity, landfill gas pressure and water pressure within landfill mass may become factors that control waste mass stability (e.g., Merry et al., 2006).

6.3 FIELD MEASUREMENT TECHNIQUES

Field measurement techniques can be broadly grouped into intrusive and non-intrusive techniques. Non-intrusive techniques range from seismological and geophysical measurements of wave propagation velocities and electrical resistivity that require relatively sophisticated equipment to gross measurements of landfill surface deformation and observations of landfill stability (or instability). Intrusive measurements include measurements made in borings or soundings that include in-hole and down-hole geophysical measurements, various mechanical soundings such as the SPT, CPT, dilatometer and Pressuremeter, and internal measurements of landfill deformation. Table 1 lists the common types of field tests for MSW properties along with the properties that they measure.

Table 1. Applications of MSW Property In-Situ Measurement Techniques (Modified after Kavazanjian, 2003)

Technique	Applications
Wave Propagation Velocity Surveys	Elastic Wave Propagation Velocity (Direct) Small Strain Stiffness (Indirect) Small Strain Poisson's ratio (Direct) Small Strain Damping (Indirect) Stratigraphy (Indirect) Spatial / Temporal Variability (Direct)
Electrical and Nuclear Surveys	Moisture Content (Indirect) Waste Composition (Indirect)
Surface Deformations	
Vertical	Primary and Secondary Compressibility (Indirect)
Lateral	Shear Stiffness (Indirect)
Strong Ground Motions	Strain-Dependent Stiffness and Damping (Indirect) Predominant Period of Waste Mass (Indirect)
Ambient Vibrations	Predominant Period of Waste Mass (Indirect)
Waste Classification	Stratigraphy (Indirect) Strength, Stiffness, Compressibility (Indirect)
Internal Deformations	Stratigraphy, Variability (Direct) Compressibility (Direct, Indirect) Shear Stiffness (Indirect)
Borehole / Test Pit Density	Unit Weight (Direct)
Bulk Sample Moisture Content	Moisture Content, Field Capacity (Direct)
Pressuremeter	Strength, Stiffness, Lateral Earth Pressure (Direct)
In-Situ Direct Shear	Strength (Direct)
CPT Piezocone (CPTU) Electric Conductivity and Resistivity CPT (CPTU-EC/RCPTU)	Stratigraphy (Direct) Strength (Indirect) Hydraulic Properties (Indirect) Hydrogeologic and Geochemical Evaluation (Indirect)
SPT	Stratigraphy (Direct) Strength (Indirect)
Dilatometer	Stiffness, Lateral Earth Pressure (Direct)

Non-intrusive measurements are preferable to intrusive measurements from a health and safety perspective and are also generally simpler to implement due to their non-intrusive nature. However, non-intrusive measurements can be depth-limited with respect to resolution and generally only give an indirect measure of MSW material properties. Intrusive measurements are often limited with respect to the volume of material they represent and may also only provide an indirect measurement of the material property of interest. Despite their limitations, field tests are generally more reliable than laboratory testing for evaluating MSW properties, as laboratory tests are conducted on samples reconstituted to an assumed (and uncertain) in-situ unit weight and structure.

6.4 NON-INTRUSIVE FIELD MEASUREMENT TECHNIQUES

6.4.1 General

Common non-intrusive techniques for field measurement of MSW properties include wave propagation velocity measurements, electrical resistivity surveys, surface measurements of settlement and lateral deformation, records of earthquake strong ground motions, ambient vibration (microtremor) measurements, and load testing. Non-intrusive techniques are generally classified as indirect methods for evaluation of MSW properties, as they generally rely upon either correlation (e.g., electrical measurements for moisture content evaluation) or back analyses (e.g. settlement measurements for compressibility evaluation). Although non-intrusive wave propagation velocity measurements yield a direct measurement of wave propagation velocity, they still require "inversion" (back analysis) to develop a shear wave velocity profile and require knowledge of total unit weight in order to convert shear wave velocity to small strain shear stiffness (or shear modulus, or Poisson's ratio).

6.4.2 Wave Propagation Velocity Measurements

Non-intrusive wave propagation velocity measurement techniques include surface wave measurements, seismic refraction surveys, and measurement of ambient vibrations (e.g., REMI). The most common surface wave measurement technique currently in use the United States is Spectral Analysis of Surface Waves, or SASW (Stokoe et al., 1994). In this technique, two geophones are placed in-line with and at a known spacing from a source of surface wave energy. Measurements of the phase of the surface waves at the two geophones are processed mathematically to develop a plot of surface wave velocity versus wavelength. The calculated surface wave velocity is assumed, based upon analytical studies, to correspond to the average surface wave velocity of the subsurface material between the two geophones over a depth of one-half wavelength. Based upon an assumed value of Poisson's ratio, the plot of average surface wave velocity versus wave length is then converted to average shear wave velocity versus depth. By looking at progressively longer wavelengths, a plot of shear wave velocity versus depth is then developed from the data. Figure 1(a) provides a conceptual illustration of the SASW test set-up showing a signal source and a receiver (geophone) used for monitoring.

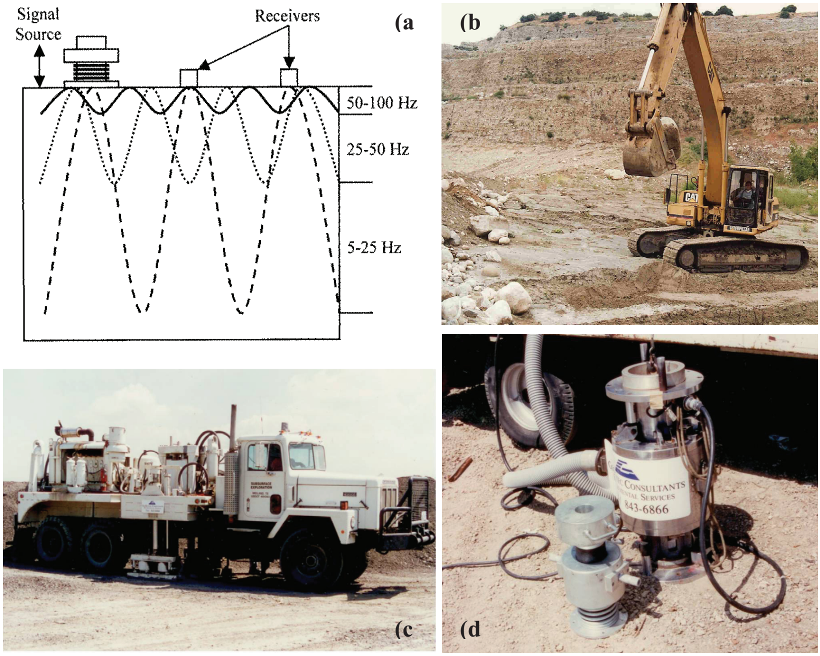


FIG. 1. Surface Wave Measurement Concept and Sample of Excitation Means: (a) Conceptual Illustration of SASW Test Set-Up, (b) Backhoe Dropping a Boulder as a Signal Source for SASW Measurements, (c) Vibroseis^{TM} Truck Generating Excitation for SASW Measurements, and (d) Electro-Mechanical Vibrator (Shaker) as a Signal Source for SASW Measurements.

The surface wave energy source may simply be a falling weight or a hammer striking a board or plate. However, to generate higher energy levels and thus achieve deeper penetration, heavy equipment such as a bulldozer or a backhoe can be used. Figure 1b shows a backhoe dropping a boulder as a signal source at the Azusa Landfill in southern California. At the Operating Industries, Inc. (OII) landfill, surface waves generated using a 30-ton Vibroseis^{TM} truck (Figure 1c) provided information on shear wave velocity to a depth of over 90 m (300 ft) (Matasovic and Kavazanjian, 1998). In more sophisticated (though not necessarily more accurate) applications of this technique, an electro-mechanical vibrator (shaker) can be used to generate surface waves of controlled frequency content (Figure 1d). Generally, a sinusoidal excitation is used and a sweep through the frequency range of interest is conducted, simplifying analysis of the data. This type of excitation has been referred to by some authors as Controlled Surface Wave or Continuous Surface Wave (CSW) sounding (Kavazanjian et al., 1994; Bouazza and Kavazanjian, 2000). Figure 2 compares shear wave velocity profile developed from surface wave measurements at six southern California MSW landfills using a combination of SASW and CSW techniques (thick solid line) with a range of SASW measurements at the OII Landfill.

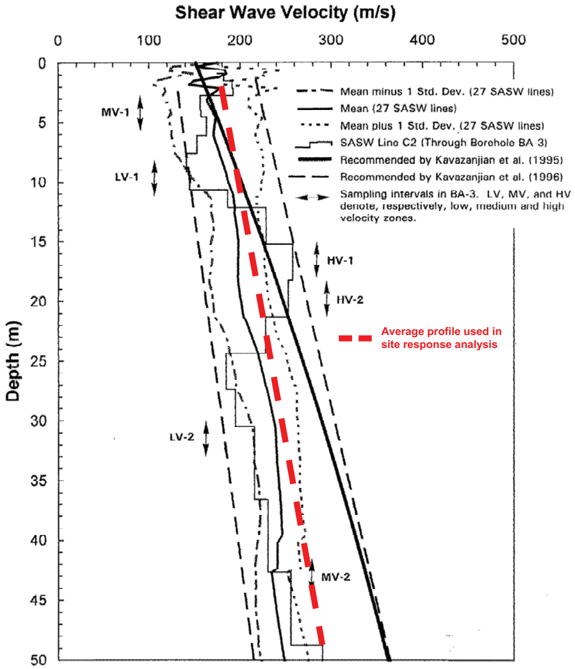


FIG. 2. Wave Velocity Profiles Established based upon Surface Wave (SASW) Measurements at the OII Landfill (Matasovic and Kavazanjian, 1998).

An important aspect of surface wave testing is that the "representative" volume to which the measurement applies increases with depth. In principle, the average surface wave velocity measured using this technique may be assumed to apply to a two-dimensional (2-D) slice along a plane passing though the geophones with a width of one wave length, i.e., approximately twice as long as the reference depth. Thus, the "deeper you go," the greater the "representative" volume. This may be advantageous if attempt is made to characterize the gross behavior of the waste mass, but may be disadvantageous when attempting to use the surface wave measurements to try to identify localized zones of anomalous stiffness within the waste mass (see, e.g., 15-m thick interim soil cover layer at a depth of 10 to 25 m in Figure 2).

Other limitations on evaluation of stiffness using the surface wave measurement technique include the need to assume a total unit weight for the waste material. A shear stiffness calculated from a shear wave velocity is directly proportional to the assumed mass density. Therefore, a 25 percent error in assumed unit weight would induce a 25 percent error in the calculated small strain stiffness. Poisson's ratio must also be assumed in order to convert surface wave velocity to shear wave velocity. However, uncertainty with respect to Poisson's ratio only becomes a factor when the value of Poisson's ratio exceeds 0.4 and approaches 0.5, and this only occurs when the waste approaches saturation. Thus, except for bioreactor landfills and unlined landfills where the waste is below the water table, assumption of a value for Poisson's ration should not introduce significant uncertainty into the derived values of shear wave velocity and shear stiffness.

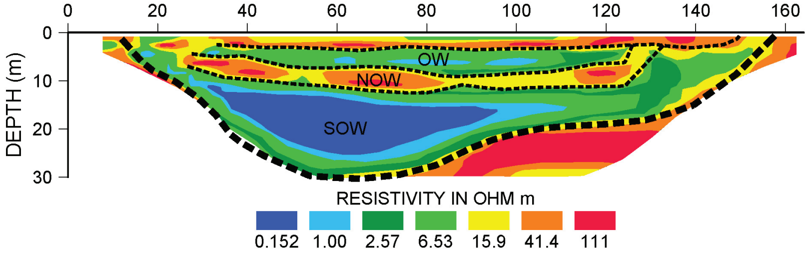
Attempts have also been made to evaluate small strain damping from results of surface wave velocity measurements by Lai et al. (2002). However, as damping evaluated in this manner is of limited use in engineering applications (can be used to calibrate strain-dependent damping within small-strain range), this technique in not widely used.

In principle, seismic refraction and reflection surveys can also be used to evaluate shear wave velocity in the field. WCC (1987) reports on a seismic refraction velocity survey performed at the OII landfill. Values derived from the seismic refraction survey at OII are consistent with values derived from surface wave measurements at the same landfill (Kavazanjian et al., 1996). However, the seismic refraction technique only gives an average velocity over the full depth of the waste mass (and requires knowledge of the depth of waste) unless there is distinct (and defined) layering with the waste mass (i.e., a distinct impedance contrast, where impedance is the mass density times shear wave velocity). Furthermore, seismic refraction surveys are generally more complex to set up and more expensive to conduct than surface wave measurements. For these reasons, seismic refraction and reflection measurements are not generally used at MSW landfill sites to evaluate shear wave velocity or shear stiffness.

6.4.3 Electrical Resistivity and Conductivity Surveys

Non-intrusive electrical property measurements, e.g., resistivity, conductivity, and/or inductance surveys, are sometimes employed to evaluate the homogeneity, consistency, and limits of a waste mass. While these techniques are more commonly used at hazardous waste sites, they can also be used at MSW landfills. The primary benefit of these techniques is to identify anomalous zones (i.e., wet zones or areas with buried drums or metallic objects) for further investigation, and not to evaluate material (mechanical) properties of waste. In principle, electrical property measurements can be correlated to moisture content and waste composition. Such correlations are interdependent on moisture content and composition (of both the waste and pore fluid) and thus are very site-specific. Furthermore, waste composition often changes spatially due to waste mass heterogeneity and temporally due to decomposition and deposition and/or dissolution of salts and metals within the waste mass and pore fluid (leachate). Therefore, these methods are best used to provide an indication of changes in waste composition (and hence properties) in time and/or space. Once a change of interest is identified, supplemental investigation using another measurement technique is generally required to evaluate the nature of the change and its impact on material properties.

Electrical resistively and conductivity surveys have been used in mapping numerous waste disposal sites. Soupios et al. (2007a) reported on the use of Electrical Resistance Tomography (ERT), and Electromagnetic Measurements (EM) at the Fodele MSW landfill in the island of Crete. The measurements were used to define the depth and extent of the landfill as well as to monitor spatial distribution of leachate plumes within the landfill. ERT measurements were also used to identify waste composition and layering as shown in Figure 3. Mondelli et al. (2007) used ERT in conjunction with Resistivity Piezocone (RCPTU) to identify contamination plumes and contaminant saturated zones at an MSW landfill in Bauru, Brazil. Guerin et al. (2004) tracked leachate recirculation at two sites by studying resistivity variations versus time using electrical surveys. Similar use of electrical resistivity and conductivity methods at landfill sites has also been reported by Bernstone and Dahlin (1996), Aristodemou and Thomas-Betts (2000), Stanton and Schrader (2001), Batayneh and Barjous (2005), Chambers et al. (2006), and Soupios et al. (2007b), among others.



Thick dashed line indicates boundary between bedrock and waste and thin dashed lines indicate waste layering by composition (SOW = Saturated Organic Waste, NOW = Non-Organic Waste, OW = Organic Waste).

FIG. 3. Waste Boundary and Layering of the Fodele Landfill evaluated based upon ERT Profiling (modified after Soupios et al., 2007a).

6.4.4 Surface Deformation Measurements

Surface (and near-surface) deformation measurements can be conducted on a macro and micro scales. The micro-scale deformation measurements are performed with a measurement tape. The macro-scale deformation measurement techniques include survey of settlement monuments and settlement plates, LiDAR imaging, and interpretation of aerial photography. The LiDAR imaging conducted by computer-controlled laser beam over preset time intervals is the most accurate measurement applicable at the macro scale. This technique along with settlement surveys conducted with traditional methods (level) theoretically may be used to evaluate mechanical properties of MSW. Application of LiDAR is hampered by its relatively high cost. Accuracy of the digital terrain measurements by aerial photography is increasing, but at the present allows only for estimate of waste settlement on a large scale (e.g., for waste disposal volume calculation).

6.4.4.1 Surface Deformation Measurements - Primary Compressibility

Surface deformation measurements can be used in conjunction with back analysis to estimate the compressibility and, in some cases, the shear stiffness of MSW. Primary compressibility can be back calculated from measurements of settlement under applied surface loads. The resulting compressibility is an average value over the zone of influence of the surface load. Unless the load is applied over a large area, the compressibility will be heavily weighted towards properties of the waste closest to the surface. This may be a particularly significant limitation with respect to the use of plate load tests to estimate post-closure settlement of shallow foundation: unless the plate is of similar size to the anticipated foundation, the estimated compressibility is likely to be excessively biased towards the compressibility of near surface waste. Unless the load is applied "one-dimensionally" (i.e., a uniform load applied over an area that is large with respect to the waste thickness), the resulting settlement may include a component due to lateral spreading and thus depend somewhat upon shear stiffness.

Large "one-dimensional" surcharge loads can give a relatively robust average value for the primary compressibility of a waste mass. Large surcharge loads may also induce waste mass subgrade (alluvium) settlement that may affect back-calculation of waste compressibility. Geosyntec (1996b) describes the use of settlement data from a load test at the OII landfill to evaluate the primary compressibility of the waste. Because this test was conducted for the primary purpose of evaluating waste shear strength, the test was conducted near the edge of a slope. An attempt was made to account for 2- and 3-D effects with respect to the subsurface stress distribution by modeling of the test using finite element method. Upon evaluation of the results and comparison with results of other measurements, compressibility values evaluated in this manner were not considered "particularly reliable."

6.4.4.2 Surface Deformation Measurements - Secondary Compressibility

Surface deformation measurements can also be used to evaluate secondary compressibility of MSW. Again, the resulting compressibility is a gross value over the entire thickness of the waste mass and foundation soil. Furthermore, it is not possible to distinguish between biological and mechanical secondary compressibility data on the basis of surface settlement measurements alone. Ling et al. (1998) report on secondary settlement rates back calculated from observations from nine locations at three different landfills. The post-closure settlement rate varied widely, by over two orders of magnitude among the three sites. The large difference in secondary settlement rates among the three landfills is almost certainly attributable to variations in biological secondary compression rates. Even for separate monitoring points at the same landfill, the settlement rate varied by over an order of magnitude at long times (several hundred days). However, because the settlement rate at long times was relatively small, post-closure settlement among different points at the same landfill varied by no more than a factor of two after 500 days. This trend is illustrated by the data shown in Figure 4 from five settlement points at the Spadra Landfill in the greater Los Angeles area. Figure 4a shows that the settlement rate at 400 days varied by an order of magnitude among the five points at the Spadra Landfill, while Figure 4b shows that the integrated total settlement only varied by a factor of two among these five points. Figure 4b also illustrates the Ling et al. (1998) conclusion that a hyperbolic function provides the best fit to secondary settlement data. However, the Ling et al. (1998) data in Figure 4a suggests that a logarithmic function will also provide a good fit to post-closure settlement data as long as the data points used to fit the function are not chosen too soon after the end of waste disposal, i.e., the log function is fit to data from more than 50 to 100 days after waste disposal ends. This data indicates that reliable estimates of secondary settlement can be made by initiating a surface settlement monitoring program immediately after reaching final grade and extrapolating these site-specific measurements using a hyperbolic function or on a log time scale. Once sufficient site-specific baseline data is available, such extrapolations are likely to remain relatively reliable as long as environmental conditions within the landfill do not change.

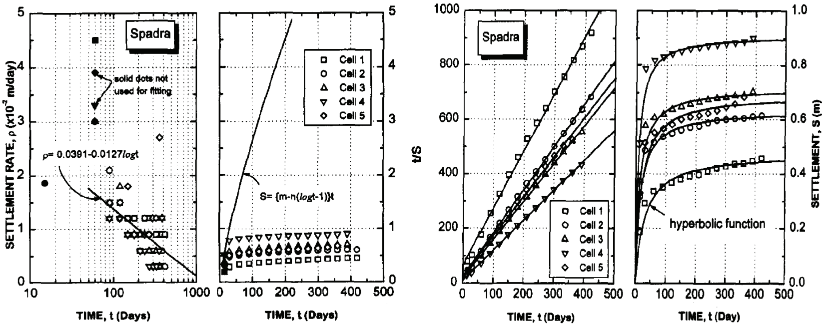


FIG. 4. Interpretation of Secondary Compression Data at Spadra Landfill (Ling et al., 1998).

Sharma and De (2007) measured secondary settlement at four landfill sites in California. At the "San Francisco Bay Area Landfill," average age of waste disposed of was 22 years. Settlement measurements conducted over a two-year period are presented in Figure 5. This waste settled under self weight. At the "Central Valley" Bioreactor Landfill, average age of waste was 10 months. Surface settlement under self weight was recorded over a six-year period. Secondary settlement was measured in two cells, in a bioreactor cell designed to re-circulate leachate, and in a conventional waste disposal cell. The back calculated c_α for the bioreactor cell and for the regular cell were 0.16 and 0.04, respectively. Sharma and De concluded that secondary compression of waste in bioreactor cells is within the range of values for 22-year old waste undergoing active composition, and that secondary compression of fresh waste, that is yet to begin secondary compression, is considerably lower.

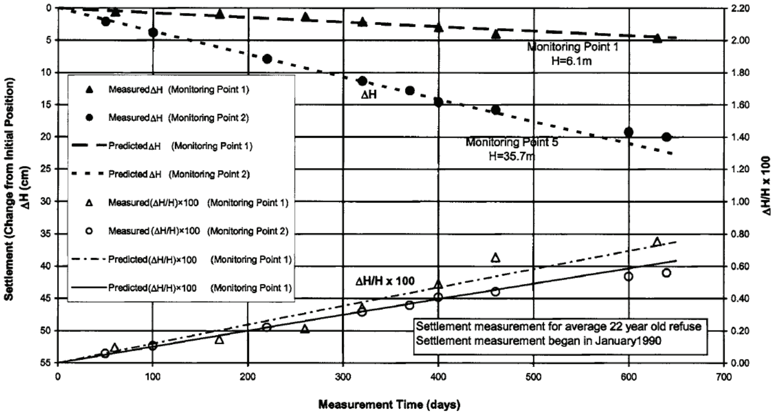


FIG. 5. Measured and Predicted Settlement at the San Francisco Bay Area Landfill (Sharma and De, 2007).

Geosyntec (1996b) describes the use of finite element method–based back calculations of surface measurements of post-closure vertical and lateral surface deformations to evaluate shear related creep strains at the OII landfill as well as secondary compression of MSW. Lateral spreading associated with shear-related (deviatoric creep) deformation contributes to the long-term settlement of embankment-like waste fills. The Geosyntec (1996b) back-calculations were made using a creep- and secondary compression-inclusive "Cam-Clay" plasticity model (Hsieh et al., 1990) as implemented in the finite element method computer program PISA (Chan and Morgenstern, 1992). Back calculations at four different cross sections yielded four widely different sets of material properties. Table 2 summarizes the range of compressibility values back calculated for the OII landfill in the Geosyntec (1996b) finite element analyses. The wide variability in back-calculated properties was attributed to the complex interrelationship of deformations induced by secondary biological and mechanical compression and by deviatoric creep combined with the heterogeneity of waste properties and biological decay processes within the waste mass.

Table 2. MSW Compressibility Values Evaluated by Back Analysis of OII Landfill Field Data (Geosyntec, 1996b).

Parameter	Range of Values	Notation
c_c	0.35 – 0.55	c_c = Primary Compression Ratio$^{(1)}$
c_r	0.035 – 0.055	c_r = Recompression / Rebound Ratio$^{(1)}$
Φ	32° – 35°	c_α = Secondary Compression Ratio$^{(1)}$
e_{cs}	2.6 – 3.0	Φ = Friction Angle
p_o	5,000 – 15,000 psf	e_{cs} = Void Ratio
c_α	0.10 – 0.18	p_o = Consolidation Stress

(1) Compression ratios are evaluated upon strain basis.

6.4.5 Strong Ground Motion Measurements

Site-specific measurement of earthquake-induced strong ground motions is a specialized type of non-intrusive field measurement. The results of such a measurement, when available, can be used to evaluate, by back analysis, the dynamic stiffness and damping of the waste mass. Generally, two strong motion stations are required: one on the waste mass and one on (level) ground far enough from the landfill not to be influenced by the presence of the waste mass but close enough to be representative of the ground motions that would have occurred at the site if the landfill wasn't there. Back analysis of low-intensity ground motions (from low-intensity nearby earthquakes or larger but distant earthquakes) recorded at the site will yield information on small strain shear wave velocity and stiffness (which can be compared to surface wave and other types of wave propagation velocity surveys) and, to some extent on layering within the landfill. Back analysis of high(er)-intensity ground motions will yield information on strain dependent modulus reduction, damping and Poisson's ratio within the waste mass, provided that waste thickness and unit weight profile are known.

While strong motion instruments have now been installed at several landfills in southern California, usable strong ground motion records are available only from the OII and Puente Hills Landfills. As reported by Matasovic and Kavazanjian (1998), back analysis of a series of small nearby earthquakes and a relatively large but distant earthquake (the 1992 Moment Magnitude M_w 7.3 Landers Earthquake) recorded at OII helped identify the presence of a continuous layer of interim soil cover at depth beneath the strong motion station located on the waste mass (see, e.g., 15-m thick interim soil cover layer at a depth of 10 to 25 m in Figure 2). Similar back analysis of OII landfill data by Matasovic et al. (1998a), partially presented in Figure 6, demonstrated that landfills can amplify earthquake ground motions in the same manner as earthen embankments do.

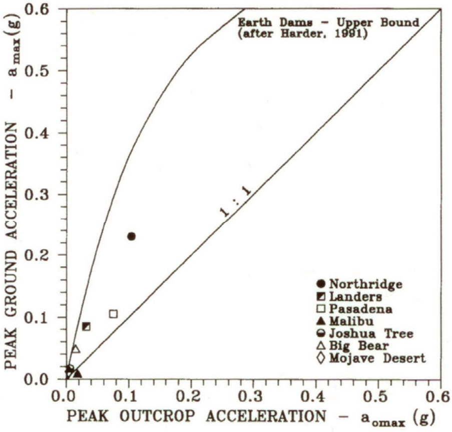


FIG. 6. Amplification of Earthquake Ground Motions at the OII Landfill, as Evaluated from On-Site Recordings (Matasovic et al., 1998a).

Back analysis of strong ground motion data recorded at top deck of OII landfill and listed in the inset of Figure 6 yielded invaluable data on strain dependent modulus reduction and damping of MSW. This back-calculated modulus reduction and damping data is indicated in Figure 7 by thick black line. Also shown in Figure 7 are results of large-diameter (457 mm) cyclic direct simple shear testing of reconstituted specimens of OII landfill MSW. This testing data was used by Matasovic and Kavazanjian to overcome limitation of relatively moderate intensity strong motion data recorded at OII landfill top deck and develop modulus reduction and damping curves for MSW.

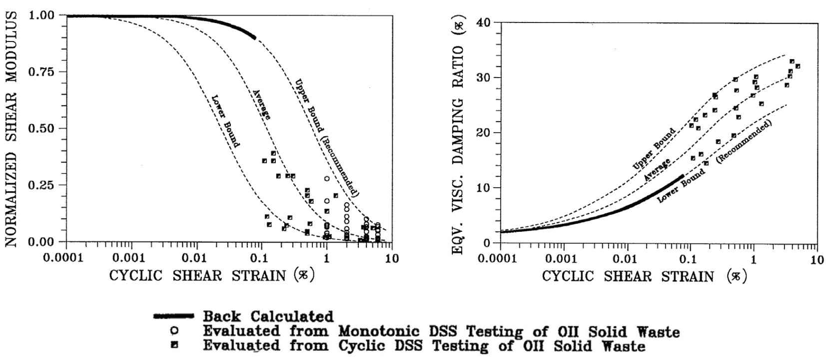


FIG. 7. Strain-Dependent Modulus Reduction and Damping from Back Analysis of OII Landfill Response and Large-Diameter Laboratory Testing (Matasovic and Kavazanjian, 1998).

6.4.6 Stability Observations

Observations of stable and unstable waste pile slopes and waste trenches have been used to back calculate MSW shear strength. Theoretically, back analysis of unstable (i.e., failed due to gravity loading) slope in modern landfill should be reliable as the Factor of Safety (FS = 1.0) and shape of failure surface are known therefore only assumptions on waste unit weight profile friction angle/cohesion ratio are required. On the other hand, back analysis of "stable" slopes, i.e., slopes with no visible signs instability such as bulging at the toe and/or cracking may be unreliable as it requires assessment of FS that may be significantly higher that 1.0. Verification of MSW shear strength parameters evaluated by back analysis of failed slopes is complicated by the fact that the only failures believed to be entirely in waste occurred at landfills in which excessive amounts of liquid had been introduced. Therefore, reliable back analysis of these and other failed landfill slopes may require, in addition to parameters listed above, information relative to the shear strength of an underlying (liner system and/or foundation) material, internal pore pressures within the waste mass, leachate elevation, landfill gas pressure, and other parameters discussed below.

Shear strength of MSW evaluated from back analysis of landfill slopes that failed under gravity (static) loading has been reported by Kavazanjian et al. (1995), Mitchell (1998), Hendron et al. (1999), Eid et al. (2000) and Koerner and Soong (2000). Kavazanjian et al. (1995) back analyzed relatively steep but stable landfill slopes listed in inset of Figure 8. Average inclination of these slopes was 1.4H: 1.0V (Horizontal: Vertical). Furthermore, for the OII landfill in-situ and laboratory testing data was available, and for the OII and Lopez Canyon landfills, seismic coefficients established by Matasovic et al. (1995) from acceleration time histories recorded in the 1994 Moment Magnitude M_w 6.7 Northridge, California earthquake were available. Based upon assumption on static and seismic FS of "stable" slopes (assumed to range between 1.1 to 1.3), Kavazanjian et al. (1995) established the low-bound MSW shear strength envelope for static and seismic design of MSW landfills. This low-bound envelope shown in Figure 8 is characterized by a cohesion of 24 kPa (500 psf) at low confining pressure (i.e. pressure equivalent to pressure of approximately 2 m or 7 ft of refuse or 1.5 m or 5 ft of cover soil) and by a friction angle of 33 degrees at higher confining pressures.

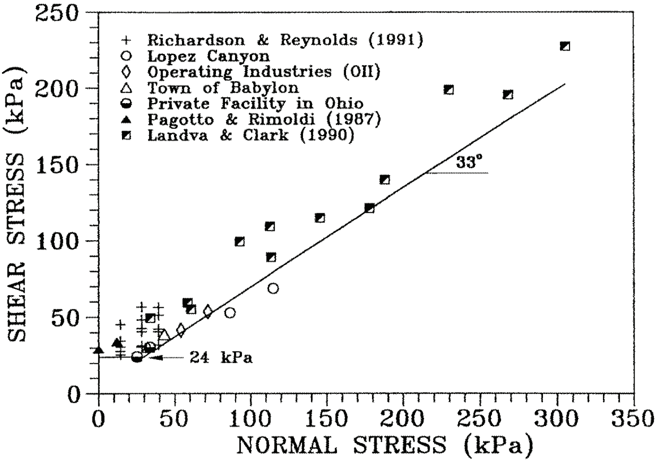


FIG. 8. Bi-Linear Lower-Bound Shear Strength Envelope of MSW from Back Analysis of Waste Slopes (Kavazanjian et al. 1995).

Values reported by Mitchell (1998) and Eid et al. (2000) are relatively similar to values reported by Kavazanjian et al. (1995). Koerner and Soong (2000) report a significantly lower value for the friction angle of MSW (on the order of 20 degrees). Based upon assumed values of pore pressure, Hendron et al. (1999) report a friction angle of 29 degrees for MSW at the Dona Juana landfill in Columbia, a landfill that failed due to leachate re-injection.

Singh and Murphy (1990) developed a family of possible MSW shear strength values from a load test performed at the OII landfill discussed previously. However, this load test was terminated due to excessive deformation of the load platform and thus never reached a state of global shear failure. Therefore, the values reported by Singh and Murphy (1990) should be considered conservative lower bound values for MSW shear strength.

Merry et al. (2005) reported on a slope failure at the Payatas Landfill in Philippines. The failure occurred following several rainfall cycles, including a storm that occurred just before the failure and generated 750-mm of rainfall. Using the U.S. EPA HELP model, Merry et al. (2005) estimated that, prior to failure, leachate depth was on the order of 15-m. As the back analysis of the failure with relatively low shear strength parameters (cohesion of 19 kPa and a friction angle of 28°) yielded FS = 1.2, these authors concluded that the failure might have been caused by elevated pore water pressures, beyond the hydrostatic pressure. These authors further postulated that accelerated anaerobic degradation of the waste and generated landfill gas were significant factors contributing to the failure.

Another example of complex back calculation of MSW shear strength parameters was presented by Koelsch et al. (2005). These authors back analyzed failure of the Leugajah landfill in Bandung, Indonesia in order to establish shear strength parameters of MSW modeled as fiber-reinforced soil. Failure was attributed to pore-pressure buildup in the subsoil and a smoldering landfill fire. A “fibrous” cohesion was assumed to represent the tensile stresses in the fibers as a function of normal stress, internal angle of tensile stress, a transmission factor, and a function considering anisotropy. The shear strength of the waste was represented by a friction angle of 20º in addition to the calculated fibrous cohesion. The slope stability analysis resulted in a FS = 1.13. To account for the landfill fire, the fiber reinforcement was assumed to be destroyed reducing the fibrous cohesion to zero. Based on this assumption, the FS dropped to one, indicating instability.

6.5 INTRUSIVE FIELD MEASUREMENTS

6.5.1 Intrusive Measurement Techniques

Intrusive techniques for field measurement of MSW properties include borehole (and test pit) sampling for compositional analysis and moisture content evaluation, borehole (and test pit) testing, including density (unit weight) testing, down-hole, cross-hole and in-hole wave propagation velocity surveys, pressuremeter, and SPT, CPT and DMT soundings, in-situ direct shear tests, various down-hole and/or internal electrical and nuclear measurements, and internal deformation measurements using inclinometers and extensometers. Compositional analysis, geophysical testing for electrical or nuclear properties, including electrical resistivity and capacitance, gamma radiation, and neutron absorption and scattering, and some types of internal deformation measurements are indirect tests in that the parameters they measure must be related back to the material properties of the representative volumes through either correlation or back analysis of large scale mass behavior. Moisture content evaluation, in-situ density testing, pressuremeter testing, SPT, CPT and DMT soundings, in-situ direct shear tests, and some types of internal deformation measurements may all be considered direct tests, as they directly measure the mechanical response of a relatively small “representative” volume of material.

6.5.2 Borehole Sampling and Testing

6.5.2.1 Types of Borehole Tests

A variety of different types of field measurements can be made on samples recovered from boreholes or within a borehole. Compositional classification of bulk samples recovered from a borehole is perhaps the simplest type of field property test. In-situ moisture content can also be evaluated on a recovered bulk sample. If the bulk sample is recovered from a relatively wet zone within the waste mass, the measured moisture content may be considered to be representative of the field capacity of the waste mass. In-situ tests that can be conducted within a borehole advanced into a waste mass include density (total unit weight), standard (and non-standard) SPT soundings, Becker Penetration Testing (BPT), plate load testing, (self boring) pressuremeter tests, and various geophysical measurements including down-hole and in-hole velocity measurements, electrical conductivity and capacitance measurements, and nuclear measurements of gamma radiation and neutron absorption and scattering. In addition to boreholes advanced for the purpose of sampling and in-situ testing, boreholes may also be required to install internal measurement devices such as inclinometers, tilt meters, extensometers, and/or specialty devices such as the Sondex® Device.

6.5.2.2 Complications Inherent to Borehole Sampling and Testing

Borehole sampling and testing and advancement of boreholes for installation of internal measurement devices is complicated by health and safety concerns over potentially hazardous and toxic substances and by the presence of obstructions and large pieces of some types of solid waste (e.g., building materials) within the waste mass. Due to the potential presence of methanogenic and non-methanogenic volatile organic compounds that pose explosion and health (inhalation) hazards, continuous air quality monitoring at the head of the borehole is generally required during boring and testing, at a minimum. If hazardous emissions are present, the borehole may require ventilation and workers in the vicinity of the borehole may require respiratory protection. Protective clothing may also be required due to hazards associated with dermal contact with waste materials. These protective measures can significantly increase the cost of borehole sampling and testing compared to “conventional” (non-environmental) geotechnical testing.

Obstructions and large pieces of solid waste may necessitate special drilling equipment and can, in the worst case, prevent drillers from reaching target drilling depth. If recovery of relatively intact pieces of solid waste is required, e.g., for compositional analysis or for reconstitution of specimens in the laboratory, a large diameter bucket auger (e.g., 750-mm diameter) may be required. In-situ density testing also requires a relatively large diameter boring to provide sufficient accuracy. However, a relatively small diameter hole (e.g., 100- to 150-mm diameter) may be required for down-hole pressuremeter or wave propagation velocity testing and for installation of inclinometers, tilt meters and extensometers. Drilling mud is rarely used when drilling in waste due to concerns about excessive fluid loss and introduction of additional liquids into the waste mass. Therefore, if borehole stability is a concern, methods such as Air Rotary Casing Hammer (ARCH) drilling may be required to advance a borehole in waste. All of these considerations can significantly increase the cost of borehole drilling and sampling and down-hole testing at a landfill site.

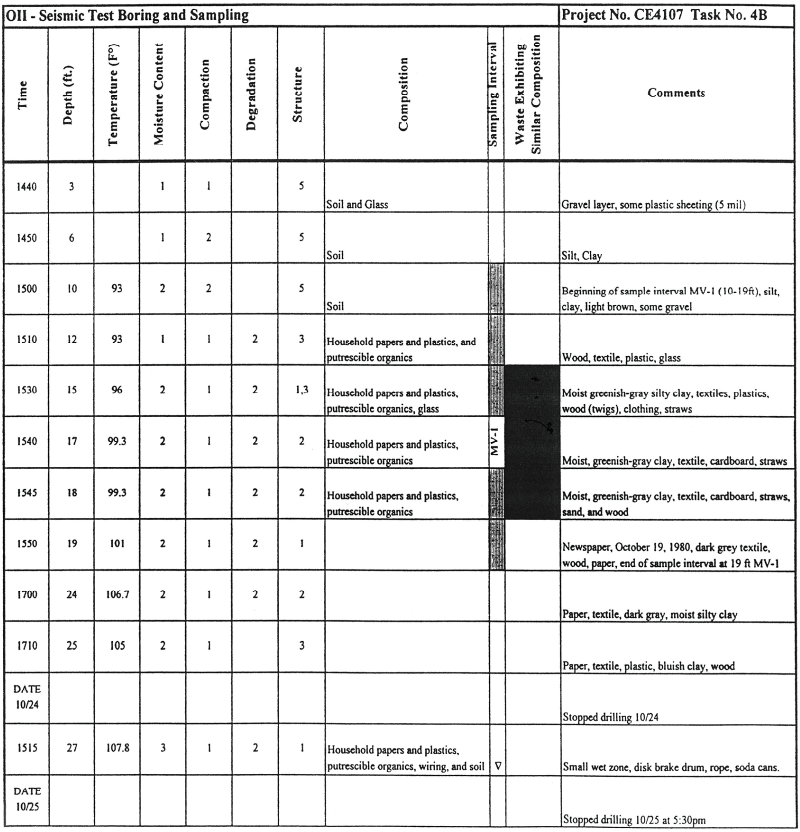
6.5.2.3 Borehole and Test Pit Sampling

Bulk samples of MSW recovered from boreholes and test pits are often visually classified and tested for moisture content in the field. While standard visual classification and correlation schemes do not exist for MSW, several firms have their own formal in-house classification systems while engineers and researchers sometimes employ their own informal correlations to relate waste (de)composition to material properties (see, e.g. Geosyntec, 1996a; and Matasovic et al., 1998b; Dixon and Langer, 2006; Dixon and Langer, 2008). The objective of waste classification, and thus the basis for development of a waste classification scheme, is to capture the characteristics of the waste that are expected to influence its behavior, e.g., its mechanical or physical properties. These characteristics are generally assumed to include the types of material present (e.g., paper, plastic, wood, fibers, soil and soil-like material), the state of decomposition of the material, and the moisture content (on a relative basis, from very dry to very wet). Table 3 presents the in-house system developed by Geosyntec Consultants for field classification of MSW.

Table 3. Geosyntec Field Classification System for MSW (Geosyntec, 1996a; Matasovic et al., 1998b).

Moisture Content	1 = Dry-damp moisture levels 2 = Wet moisture levels 3 = Standing water
Compaction	1 = Slight – Refuse easily falls out of bucket auger 2 = Moderate – Refuse falls out of bucket auger upon impact 3 = Heavy – Refuse falls out of bucket auger only after being struck multiple times
Degradation	1 = None – Newspapers very legible, no refuse discoloration 2 = Slight – Some newspapers still legible, discoloration 3 = Moderate – Newspapers partly legible, highly discolored 4 = High – Newspapers highly faded gray to black
Composition	1 = Household – paper and plastics 2 = Putrescible organics 3 = Concrete, bricks 4 = Wiring 5 = Metal 6 = Non ferrous metal 7 = Tires 8 = Asphalt 9 = Soil 10 = Medical 11 = Indistinguishable 12 = Glass 13 = Other (specify)
Structure	1 = Layered – Waste constituents oriented with long axis in a preferred direction (e.g., horizontal) (Note: direction in different column) 2 = Encapsulated – Waste constituents encapsulated in a soil matrix 3 = Fibrous – Waste constituents intertwined 4 = Interlocked – Waste constituents interlocked (“compacted”, “granular” type structure) 5 = Indistinguishable

Figure 9 presents a borehole log from an investigation at the OII landfill (Geosyntec, 1996a) that employed this classification scheme.



OII - Seismic Test Boring and Sampling | **Project No. CE4107 Task No. 4B**

Time	Depth (ft.)	Temperature (F°)	Moisture Content	Compaction	Degradation	Structure	Composition	Sampling Interval	Waste Exhibiting Similar Composition	Comments
1440	3		1	1		5	Soil and Glass			Gravel layer, some plastic sheeting (5 mil)
1450	6		1	2		5	Soil			Silt, Clay
1500	10	93	2	2		5	Soil	▨		Beginning of sample interval MV-1 (10-19ft), silt, clay, light brown, some gravel
1510	12	93	1	1	2	3	Household papers and plastics, and putrescible organics	▨		Wood, textile, plastic, glass
1530	15	96	2	1	2	1,3	Household papers and plastics, putrescible organics, glass	▨	■	Moist greenish-gray silty clay, textiles, plastics, wood (twigs), clothing, straws
1540	17	99.3	2	1	2	2	Household papers and plastics, putrescible organics	MV-1	■	Moist, greenish-gray clay, textile, cardboard, straws
1545	18	99.3	2	1	2	2	Household papers and plastics, putrescible organics	▨	■	Moist, greenish-gray clay, textile, cardboard, straws, sand, and wood
1550	19	101	2	1	2	1		▨		Newspaper, October 19, 1980, dark grey textile, wood, paper, end of sample interval at 19 ft MV-1
1700	24	106.7	2	1	2	2				Paper, textile, dark gray, moist silty clay
1710	25	105	2	1		3				Paper, textile, plastic, bluish clay, wood
DATE 10/24										Stopped drilling 10/24
1515	27	107.8	3	1	2	1	Household papers and plastics, putrescible organics, wiring, and soil	▽		Small wet zone, disk brake drum, rope, soda cans.
DATE 10/25										Stopped drilling 10/25 at 5:30pm

Note: see Table 3 for MSW Classification System used in Log Shown in this Figure.

FIG. 9. OII Landfill – MSW Field Classification Log (Geosyntec, 1996a).

Field and laboratory testing at OII subsequently determined that soil and soil-like material had lower shear strength than the un-degraded refuse. Therefore, continuous horizons of degraded waste and soil and soil-like materials, identified from borings and a review of the history of landfill development, were assigned lower shear strength in stability analysis than the body of refuse. Moisture content evaluation of bulk samples of MSW can be very sensitive to the drying temperature due to the presence of readily oxidized organic matter. Therefore, moisture content evaluations are generally made at as low a temperature as possible. At OII landfill, moisture content was determined by drying the specimen at 60^{o} C until the weight of the specimen (i.e., its moisture content) stabilized.

6.5.2.4 Borehole and Test Pit Unit Weight Testing

In order to measure in-situ unit weight at MSW landfill sites, Geosyntec (1996a) developed a borehole unit weight (density) test. This test was patterned after the sand cone density test (ASTM D 1556) that is commonly used in earthwork engineering. In this borehole density test, a bulk sample of waste is recovered from a borehole using a large diameter bucket auger. Upon removal, sample is carefully weighed and the corresponding borehole interval is backfilled with a calibrated gravel or rock. Gravel (or rock) are tremied through a pipe of fixed length into the bottom of the hole to minimize intrusion of waste from borehole sides. The gravel (or rock) is calibrated by tremieing it into a 227-litre (60-gallon) drum through the same fixed-length pipe used in the field. Several trials are used to establish the expected value and variability of the calibration factor. The weight of gravel tremied into the hole is monitored (by before and after measurements of the weight of the bin(s) from which the gravel is taken) and then divided by the calibration factor to determine the volume of the sampling interval. The weight of sample removed from the sampling interval is divided by the sampling interval volume to obtain the in-situ unit weight. Several investigators have used a similar procedure to obtain the unit weight of MSW from a test pit, except the test pit is generally lined with a plastic sheet and filled with a measured volume of water to determine test pit volume.

Geosyntec borehole density test has been developed based upon the gravel-replacement in-situ density measurement at 4 MSW landfills in California. When it was first used at the OII landfill, the test yielded unexpectedly large values for unit weight near the ground surface, on the order of 16 kN/m^3 (100 pcf). Therefore, an in-situ density test was conducted in a large test pit, on the order of 6 m in depth and 170 m^3 in volume, excavated at the landfill surface. The total unit weight of the test pit was approximately 15 kN/m^3 (95 pcf), within 5 percent of the value measured in the borehole, validating the borehole density test result.

6.5.2.5 Borehole Hydraulic Conductivity Testing

Several in-situ testing methods have been used to assess the hydraulic conductivity of waste utilizing boreholes, wells and/or temporary piezometers. These tests are generally carried out by monitored injection or pumping of fluids into or out of the borehole. The hydraulic conductivity of waste is then back calculated using measured hydraulic heads and flow rates. Hence, such tests are considered indirect measurement of hydraulic conductivity. In-situ permeability tests that have been used in measuring hydraulic conductivity of waste include slug tests, pumping tests, and “constant head” borehole permeameter tests.

Slug tests and pumping tests are generally used to evaluate hydraulic properties of aquifers. Therefore, these tests may be conducted on waste if the waste is submerged. This may be encountered in unlined landfills with sections below the ground water table. However, presence of standing water in a landfill is not an indication of the presence of a phreatic surface. In a slug test, water is rapidly added or removed from the screened well installed in a borehole, followed by monitoring of the change in hydraulic head with time. Results of slug tests are representative of the area within close proximity to the screened zone and are generally affected by the packing material in the well adjacent to the screen. Pumping tests are conducted at either a constant rate or at multiple-step rates. Draw down in the borehole and at surrounding observation wells at a given pumping rate are used to back calculate the hydraulic conductivity.

The borehole permeameter is generally used for in-situ measurement of the saturated hydraulic conductivity of soils above the groundwater table. Water is injected into the borehole and is maintained at a constant level. Steady state conditions are reached when the infiltration rate becomes constant. Analytical methods are used to back calculate the saturated hydraulic conductivity of the soil, or waste, based on the measured head and infiltration rate.

Shank (1993) reported results of slug addition and removal tests in gas wells of two unlined MSW sectors at the Alachua County Southwest Landfill in Florida. The slug addition tests were highly affected by the gravel pack in the gas wells. Oweis et al. (1990) and Wysocki et al., (2003) reported pumping tests at unlined MSW landfills assuming a phreatic water surface within the waste, as reported by Jain et al. (2006). Jain et al. (2006) reported borehole permeameter tests at the New River Regional Landfill, an MSW landfill in central Florida. The landfill contains mixed residential and commercial waste to a depth of 22 m (72 ft) placed between 1992 and 2000. Liquid was injected into 77 injection wells with screens at three different depths till a steady state condition was reached. Elapsed time to steady state condition varied widely with some wells not reaching steady state after 10 weeks of liquid addition. Jain et al. (2006) reported hydraulic conductivity results back calculated using three different analytical methods. The calculated hydraulic conductivity varied by factors of up to 2 based on the method of back analysis used.

A common limitation of the testing methods discussed above is that the methods used for back analysis of the hydraulic conductivity consider a homogeneous waste mass with equal vertical and horizontal hydraulic conductivities. Therefore, the back calculated hydraulic conductivity is considered an intermediate value. Benson and Wang (2000) used a Two Stage Borehole permeameter (TSB) in order to evaluate the in-situ hydraulic conductivity of paper sludge. The tests allow for back calculation of both vertical and horizontal hydraulic conductivities. However, TSB tests have not been reported on MSW.

6.5.2.6 Borehole Wave Propagation Velocity Testing

Wave propagation velocity testing can be conducted in a borehole using down-hole or in-hole methods. Cross hole testing can be conducted if there are two or more boreholes spaced close enough together for a down-hole hammer to generate a signal of sufficient strength to be detected in the adjacent borehole (typically, on the order of 5 to 10 meters). Down-hole testing is limited to the depth at which a surface excitation can be detected within the boring, generally on the order of 30 m. In-hole testing in not depth limited. ASTM and EUROCODE 7 standards are available for down-hole and cross-hole testing. In these methods, the distance between the signal generation point and the signal detection point is divided by the time interval between signal generation and signal detection to get the wave propagation velocity (in cross hole testing, three borings can be used and the measurement interval may then be between two different detection points). Down-hole testing is generally restricted to shear wave velocity testing while cross hole testing can yield both shear and compressional wave velocity.

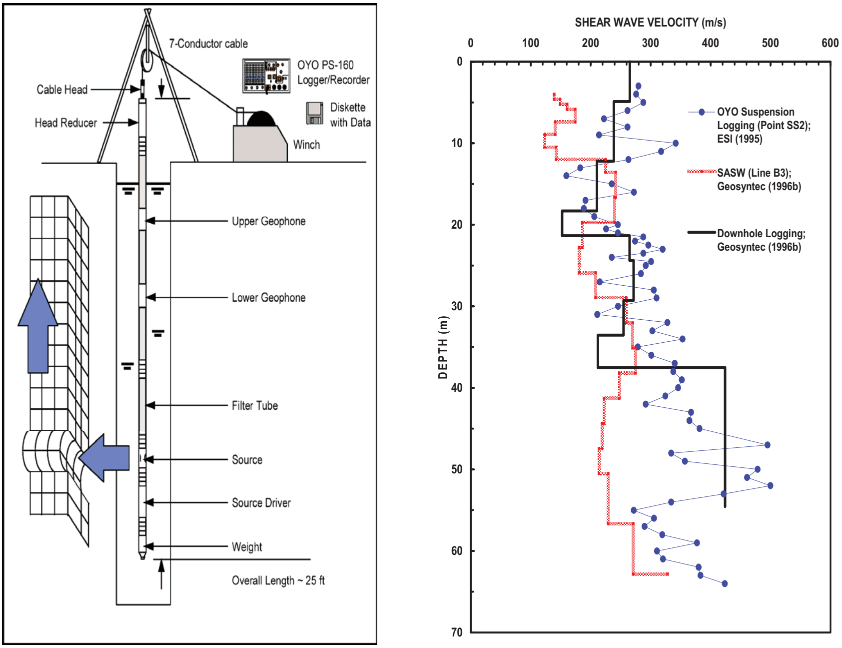


FIG. 10. (a) Typical OYO™ Suspension Logging Setup; and (b) Comparison of Shear Wave Velocity Profiles in OII Landfill MSW Established by SASW, Downhole, and OYO™ Suspension Logging.

In-hole testing is commonly referred to as the "OYO^{TM} Method," even though, strictly speaking, seismic Dilatometer testing can be conducted in-hole as well. The OYO^{TM} Method, also known as OYO^{TM} suspension logging, calls for a cased borehole to be filled with borehole fluid and an in-hole source applied as a rapid load against the casing. As schematically illustrated in Figure 10a, geophones suspended in the borehole fluid sense the casing deformations as the wave propagates upwards in the soil (waste) around the casing. Thus, by suspending two geophones at a known *distance apart, wave propagation velocity can be measured. This method can yield both shear and compressional wave velocity.

Down-hole, in-hole, and SASW measurements were conducted at the OII landfill. A compilation of these tests for a single location is shown in Figure 10b. Figure 10b shows that shear wave velocity profiles in MSW established by down-hole and in-hole geophysical techniques compare well, while profile established by SASW is lower. This discrepancy at particular location may be explained by point-sourec nature of down-hole and in-hole measurements, as opposed to SASW measurements that are representative of a relatively large body of waste mass.

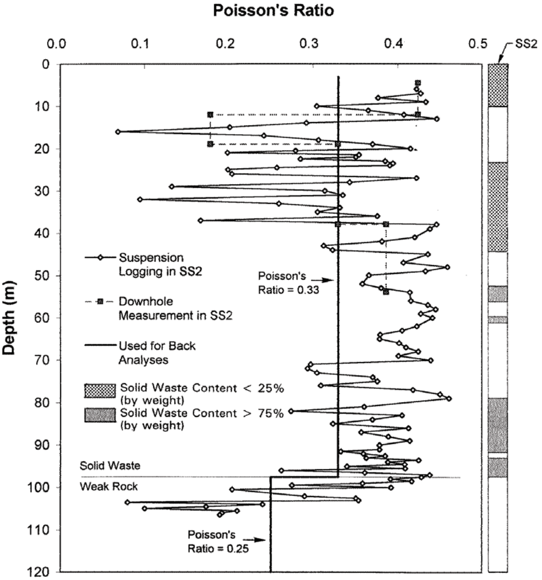


FIG. 11. Poisson's Ratio Profile of MSW (Matasovic and Kavazanjian, 1998).

As both shear and compressional wave velocities can be recorded by in-hole and downhole measurements, in-situ small-strain Poisson's ratio can be computed. The Poisson's ratio profile derived by Matasovic and Kavazanjian (1998) from the downhole and OYO^{TM} suspension logging velocity survey data at OII Landfill is shown in Figure 11.

6.5.2.7 Borehole Electrical and Nuclear Testing

A variety of electrical and nuclear measurements can be conducted in a borehole advanced through MSW, including “conventional” (i.e., used in the oil exploration industry) down-hole electrical resistivity logging, and gamma radiation and neutron probe logging. The advantages and disadvantages of these measurements when made down-hole are similar to those associated with non-intrusive surface measurements using the same or similar techniques: due to “calibration” issues, they are most reliable as an indicator that something is “different” (e.g., they may indicate that there is a change waste composition) or has changed over time (e.g., moisture content change) rather than as a means of measuring the absolute value of a parameter (i.e., of moisture content or waste composition). “One-time” measurements in a borehole or series of boreholes are generally used to indicate spatial differences in composition (i.e., as an index of stratigraphy) while measurements taken at the same location at separate times are generally used as an index of temporal change (e.g., an increase in moisture content). Yuen et al. (2000) report on the use of Neutron probes for monitoring moisture content changes with time in a bioreactor landfill. Based on a survey of available methods, they concluded that, despite calibration difficulties and other limitations of the method, neutron probe measurements through “permanent” access tubes installed in the waste was the best method to monitor moisture content changes over time within the waste mass. Figure 12 presents field data from an access tube installed by these investigators in a bioreactor test fill in Melbourne, Australia. The access tube was placed adjacent to a leachate infiltration trench and measurements were taken prior to leachate recirculation (labeled 23-Jul-96 in Figure 12), after a 32-hr leachate injection period (24-Jul-96 in Figure 12) and 7 days after leachate injection.

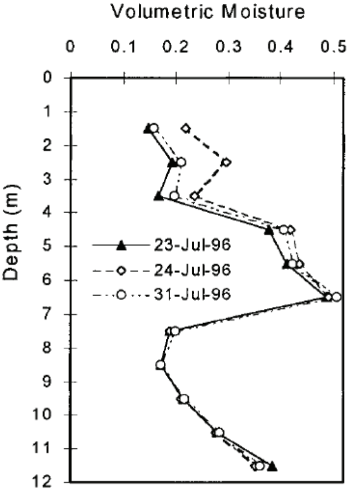


FIG. 12. Neutron Probe Measurements at a Bioreactor Landfill (Yuen, et al., 2000).

6.5.2.8 Borehole Pressuremeter Testing

Use of a pressuremeter to evaluate the mechanical properties of MSW was reported by Dixon et al. (1999; 2001; and 2006). These authors employed a 83-mm diameter, 1.2-m long self-boring pressuremeter in a “pre-drilled” borehole. A “Chinese lantern”, consisting of stainless steel strips bonded to a rubber membrane, was placed around the cylindrical probe to protect the 1.25-mm polyurethane inner membrane from damage during probe advancement in MSW. Once the probe fully penetrated the bottom of the borehole and reached the desired test depth, the inner membrane was expanded radially and radial deformation versus expansion pressure was measured and monitored. It should be noted that, in principle, this type of testing could be performed entirely in the self-boring mode, without the aid of a borehole. However, it seems unlikely that a small self-boring pressuremeter could penetrate any appreciable distance in a typical MSW landfill without reaching “refusal.”

The pressuremeter test calls for several cycles of unloading and reloading, as illustrated in Figure 13. Interpretation of the test results shown in Figure 13 typically yields values for the coefficient of lateral earth pressure at rest (K_o), the shear modulus at a reference cavity strain (typically 1%) and, an indication of shear strength. It should be noted that the modulus values reported in Figure 14 are evaluated at relatively high strain level and therefore generally lower then their counterparts evaluated from shear wave velocity (e.g., Figure 2) or by back calculation (e.g., Figure 7). The interpretation of MSW shear strength from pressuremeter testing is difficult, if possible, as radial strains induced in this test, even though relatively large, rarely approach failure strains.

Briaud et al. (1983) and Briaud (1997) used the pressuremeter test to evaluate p-y curves of waste.

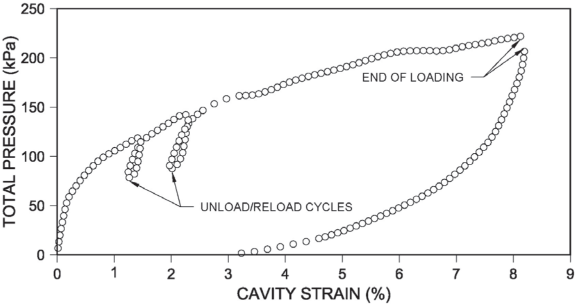


FIG. 13. Pressuremeter Test Results in MSW (modified after Dixon et al., 2001).

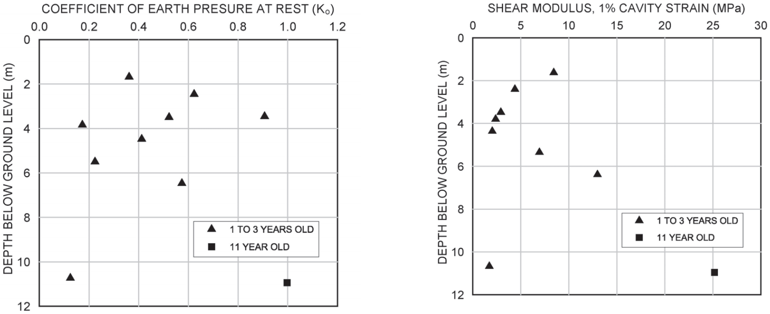


FIG. 14. Interpreted Pressuremeter Testing Results; MSW, Calvert Landfill (modified after Dixon et al., 2001).

6.5.3 In-situ Direct Shear Tests

Richardson and Reynolds (1991) and Houston et al. (1995) both conducted large-scale in-situ direct shear tests on MSW. The general procedure for these tests consisted of isolating a "pedestal" of waste by excavation and trenching, confining the pedestal in some type of rigid container split along a horizontal plane, fixing the bottom of the box against lateral deformation, loading the top of the box with the desired normal load, and then shearing the top of the box laterally while measuring both the shear force and lateral displacement. The advantage of an in-situ direct shear test is that a relatively large volume of MSW can be tested in its "natural" state (i.e., as deposited in the landfill). Main disadvantages of in-situ direct shear testing include relatively high cost (test requires excavation of pedestal of waste, either at the surface or in trench), the limitation on the normal pressure that can be applied on the waste pedestal, and restriction on testing relatively "shallow" waste. Other limitations include argument that the direct shear test may be of a relatively poor quality as failure is forced through pre-defined failure plane which is aligned with waste layering, non-uniform strain field throughout the sample, and that representative sample (waste pedestal) may be disturbed during preparation. However, despite these known and postulated limitations, the ability to test MSW in its in-situ state makes this type of field test potentially attractive and worth considering.

6.5.4 Cone, Standard and Becker Penetration Test Soundings

The CPT sounding can be used at MSW landfills awaiting closure to evaluate thickness of interim landfill covers. Figure 15 shows representative CPT sounding logs for a site in Los Angeles, California. Both tip and sleeve resistance logs show contrast at the cover-waste transition, even though the intensity of the contrast varies from location to location. Sharp excursions in both tip and sleeve resistance in waste are due to penetration through non-degradable components of the waste.

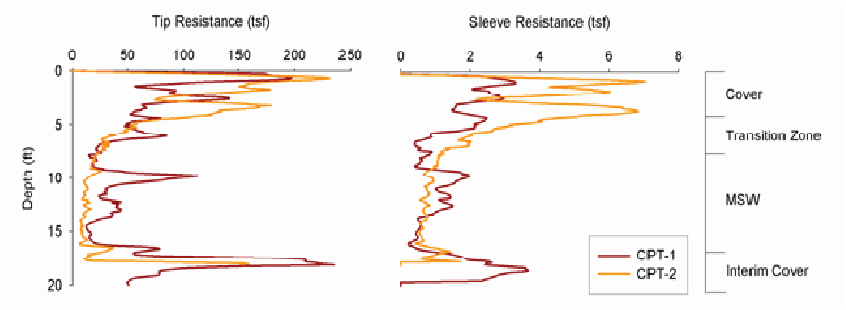


FIG. 15. Corrected Results of CPT Soundings through Landfill Cover at Lopez Canyon Landfill (Geosyntec, 2008).

The CPT, SPT, and BPT soundings have been conducted at MSW landfills with attempts made to interpret sounding logs based upon standard correlations. The success of these attempts in MSW is not known as no validation studies are available. The CPT sounding, coupled with SASW measurements and triaxial testing of cover soils from known borrow source was, however, successfully used to evaluate undrained shear strength of submerged waste at a hazardous waste landfill in southern California (Matasovic et al., 2006).

BPT (and to some extent SPT) soundings at MSW landfills may be promising as material sample can be recovered and visually classified either in the field or in the laboratory, opening a potential for development of correlations. Nevertheless, until more validation studies become available or appropriate charts are delivered, CPT, SPT, and BPT should be used as indicators of waste mass consistency and as means for evaluating the properties of buried soil layers (e.g., for evaluating properties of intermediate and interim covers within the waste mass) rather than for evaluation of MSW properties. For work at older landfills where large-particle waste was disposed of, it is recommended to plan for the possibility that multiple trials may be required in order to achieve target sounding depths.

Instrumentation can be added to the standard cone to provide additional measurements of waste properties. For example, the CPT with piezocone (CPTU) sounding, that provides for porewater pressure measurement through porewater pressure sensor can be used to evaluate hydraulic properties of waste. The seismic cone, i.e., CPT probe with embedded geophone and coupled with surface excitation can be used for down-hole measurement of wave propagation velocities. The electrical resistivity or conductivity cone (RCPT or CPT-EC, respectively) can measure the electrical resistivity or conductivity of the waste for monitoring moisture conditions, subject to the limitations previously mentioned for non-intrusive and borehole electrical testing methods. Mondelli et al. (2007) used ERT in conjunction with resistivity piezocone (RCPTU) to identify contaminant plumes and contaminant saturated zones at an MSW landfill in Bauru, Brazil. ERT provided an overall understanding of the shape and direction of the contaminant plume. The RCPTU results provided higher resolution and identified contaminant-saturated zones for groundwater sampling.

6.5.5 Dilatometer and Seismic Dilatometer Testing

The dilatometer (DMT) test, also known as the Marchetti Dilatometer test, has been widely used for in situ measurement of physical and mechanical soil properties, such as hydraulic conductivity, undrained shear strength, friction angle, coefficient of consolidation, and constrained modulus (e.g., Marchetti, 1997). The dilatometer blade is constructed of high-strength stainless steel and may be advanced into the ground using standard CPT rig or by hydraulic capability of a drill rig. Testing can also start from a bottom of a borehole.

The latest iteration of DMT, the seismic dilatometer (SDMT) is equipped with a seismic module for measuring wave propagation velocities. The small strain and large strain moduli back calculated from the SDMT measurements can be combined to identify the modulus degradation curve for a specific soil (Mayne et al., 1999). Despite its success in measuring soil properties, the use of DMT for in-situ measurement of MSW properties has not yet been reported in the literature.

6.5.6 Internal Deformation Measurements

Internal measurements of vertical and lateral deformation within a waste mass, described below, can provide both direct and indirect field measurements of waste properties. Internal deformation measurements made over a relatively small interval can provide elemental information on waste compressibility. Larger scale measurements of vertical deformation and internal measurements of lateral deformation can provide gross measures of MSW deformability that can be back analyzed to yield elemental property data. Oftentimes, the deformation measurement device can be installed as the waste is placed and accessed from outside of the waste mass, eliminating the need to drill into the waste, minimizing health and safety concerns, and making the measurement only semi-intrusive.

Internal deformations are commonly measured using settlement platforms (plates), inclinometers, tiltmeters, and/or extensometers, and occasionally by embedded crack gages and earth pressure cells and settlement profiler systems. Bowders et al. (2000) report on internal settlement measurements in a lined landfill in Columbia, Missouri. An internal settlement plate was constructed on top of the initial 2 m-thick lift of MSW and then monitored during and after placement of an additional 5 m of MSW at that location. The plot of settlement versus time from this settlement plate is presented in Figure 16, along with a plot of leachate generation. It appears from this plot that waste placement ceased after approximately 30 days and biological secondary compression commenced after about 70 days. On this basis, primary and secondary compression indices can be calculated from the field data (by dividing settlement by the waste thickness of 2 m).

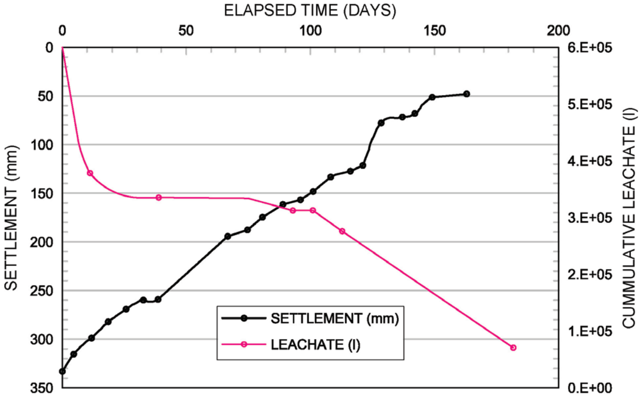


FIG. 16. Settlement Measurements at Columbia, Missouri Landfill (modified after Bowders, et al., 2000).

Sharma and De (2007) reported a case history of a landfill in southern California (Pomona, California) where internal measurements were taken for deformations due to secondary settlement of waste under self-weight. Internal deformations were measured using a Sondex device. The Sondex device is an extensiometer that consists of a corrugated pipe equipped with magnetic rings. The pipe is vertically installed in a borehole and grouted to the surrounding waste. The distances between the magnetic rings are measured using a magnetic probe lowered into the Sondex pipe as the pipe compresses with the surrounding waste. Measurements were taken on 10-year old waste over a period of two years. Sharma and De (2007) back calculated secondary compression indices (c_α) of 0.27 and 0.28 for the two monitoring locations presented in Figure 17. Sharma and De (2007) reported another case history of a landfill in northern California where internal deformations due to fill placement were measured using extensometers and surface measurements. The extensometer and surface measurements agreed well.

Internal lateral deformation measurements, generally made using inclinometers, can also provide information on MSW properties, i.e., shear modulus. Inclinometer measurements are gross behavior measurements that must be back analyzed to yield elemental properties. Geosyntec (1996a) included inclinometer measurements in their back analysis of observed deformations at the OII landfill. The inclinometer data was particularly useful is separating the landfill settlement due to secondary compression from settlement due to lateral spreading. The back analysis parameters reported in Table 2 are based upon both vertical and lateral deformation data from the OII landfill.

Bachus et al. (2006) described a “waste settlement profiler” for use in evaluating the settlement of liner systems for “piggy back” landfills, landfills where a liner system for a new waste unit is placed on top of an old unlined waste unit. This is a relatively common and an important problem in landfill engineering, as settlement of the old landfill may adversely affect the liner of the new landfill. As illustrated in Figure 18, the waste profiler consists of a horizontal guide tube through which a water-level indicator can be pulled. The guide tube is placed on top of the old waste unit prior to construction of the new waste unit liner system and extended out beyond the edge of the liner for access. By drawing the water-level indicator through the guide tube, the settlement profile of the guide tube, and thus of the underlying waste, is measured. Figure 19 shows data obtained using the settlement profiler beneath a test fill. The data from the settlement profiler represent the gross compressibility of the underlying waste subject to the load of the new waste unit. Monitoring during and after waste placement can provide information on both primary and secondary compressibility of the underlying waste.

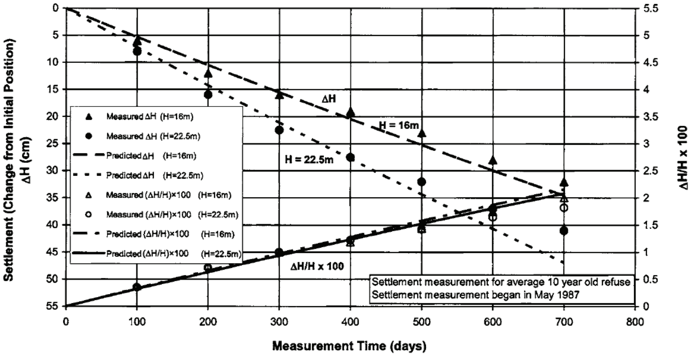


FIG. 17. Measured and Predicted Settlements at Two Monitoring Points of a Landfill in Southern California (Sharma and De, 2007).

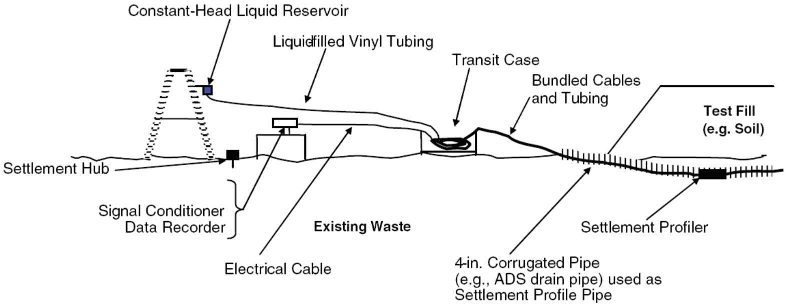
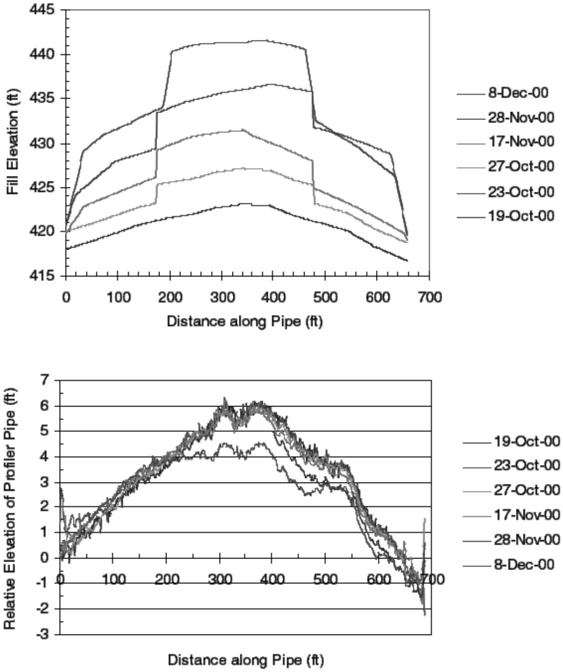


FIG. 18. MSW Settlement Profiler System (Bachus et al., 2006).



a. Fill elevation

b. Waste settlement

FIG. 19. MSW Settlement Profiler Test Fill Data (Bachus et al., 2006).

6.5.7 Internal Moisture Content Measurements

Internal moisture content measurements can provide information on moisture distribution and moisture flow, which can be very useful in leachate recirculation and bioreactor landfill applications. Such measurements may also be used to back calculate hydraulic properties of the waste mass. Oftentimes, the measurement device can be placed as the waste is placed and accessed from outside of the waste mass, eliminating the need to drill in to the waste, minimizing health and safety concerns, and making the measurement only semi-intrusive. Internal field measurements of moisture content within a waste mass are generally indirect measurements and are generally indicative of changes in water content rather than absolute measurements.

Internal measurement of moisture content can be carried out using borehole electrical and nuclear measurements, as previously discussed. Similarly, electrical resistance and impedance sensors can be embedded in arrays within the waste mass for measurement of moisture content changes. Electromagnetic sensors, such as Time Domain Reflectometry (TDR) and transmissivity (TDT) sensors, can also be used in measuring moisture content changes. Sensors used for measuring moisture content need to be calibrated on samples of the waste mass. Sensor calibrations need to be site specific due to the wide variability in waste content. Masbruch and Ferre (2003) reported on calibration of TDT sensors for measuring moisture content of MSW waste. They concluded that large errors may result from use of a calibration based on a single waste sample. Masbruch and Ferre (2003) calculated a root mean square error in volumetric water content on the order of 4% based on TDR calibration using nine oven dried samples. However, Masbruch and Ferre (2003) suggested that a simplified two-point calibration can be performed on each sample due to the highly linear relationship between the volumetric moisture content and the square root of the dielectric permittivity.

Khire and Haydar (2007) used TDR and electrical impedance sensors for monitoring moisture content changes within a bioreactor landfill in Jackson, Michigan. The array of sensors was used to monitor the progress of the wetting front from leachate injected into a geocomposite drainage blanket. The blanket was used for leachate recirculation within the waste mass. The impedance and TDR measurements responded to leachate arrival at the sensor location as shown in Figure 20. A constant measurement value was reached during reflection. The constant value was interpreted to correspond to a 100% degree of saturation based on laboratory calibration tests. Khire and Haydar (2007) performed numerical modeling of the leachate flow and back-calculated a waste hydraulic conductivity on the order of 10^{-4} to 10^{-5} cm/s.

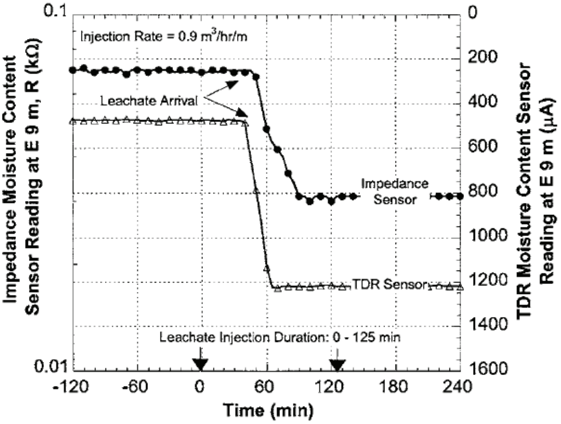


FIG. 20. Response of Impedance and TDR Sensors to Moisture Content Changes due to Leachate Injection (Khire and Haydar, 2007).

Another intrusive field method that can be used to measure moisture content of MSW is Partitioning Gas Tracers Tests (PGTT). PGTT involve injection and extraction of two tracers within the soil mass under steady gas flow. The arrival time of the tracers, measured using chromatography, can be related to the degree of saturation. Imhoff et al. (2007) reported good agreement between measured moisture contents using the PGTT and gravimetric measurements at two landfills based on tests conducted by Han et al. (2004) and Han et al. (2006).

Moisture content can also be monitored in-situ by measuring changes in temperature. In addition to moisture monitoring, temperature sensors can be used to measure the in-situ heat transfer properties and heat generation characteristics of MSW (Oettle, 2008). Temperature data can also be used to analyze frost depths, liner and cover desiccation, and geosynthetic aging (Yesillet et al., 2008). Thermocouples are the most popular way of measuring in situ landfill temperatures due to their chemical resistance, but vibrating wire piezometers with thermistors and fiber optic sensors have also been used (Oettle, 2008 and Imhoff et al., 2007). Temperature sensors can be placed in liners, covers, and in waste as landfill construction progresses, or they can be installed after waste placement by drilling. Long vertical and horizontal arrays of sensors can be installed to measure the spatial and temporal variation of temperatures at discrete locations (Hanson et al., 2008). In the case of fiber optic sensors, nearly continuous data can be obtained along the length of the cable (Imhoff et al., 2007).

Figure 21 illustrates how leakage through sealing materials, side seeps, and abnormal liquid flow can be detected from abnormalities in temperature measurements. Temperature sensors combined with an integrated heating cable can also be used to measure temperature changes due to induced heating. The change in temperature can be correlated, using site specific calibrations, to changes in the moisture content of the waste (Imhoff et al, 2007).

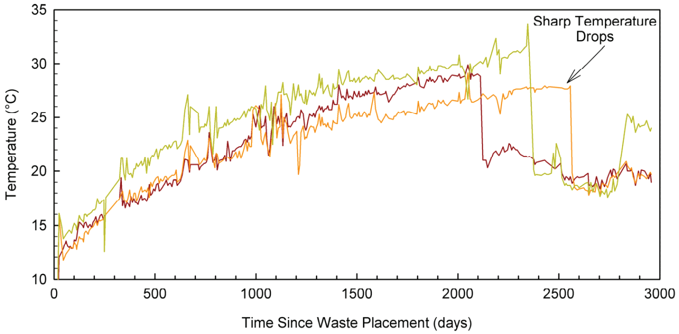


FIG. 21. Temperature Measurements from Three Thermocouple Sensors in an MSW Landfill Liner in Michigan. The Sharp Temperature Drops Indicated were Likely the Results of Leachate Arrival (adapted from Oettle, 2008).

Similar to electrical, electromagnetic, and nuclear measurements, PGTT and thermal measurements may only be indicative of changes in moisture content rather than absolute values. The advantages and disadvantages of the techniques discussed herein for field measurement of moisture content were summarized by Imhoff et al. (2007) as presented in Table 4.

Table 4. Advantages and Disadvantages of Various In-Situ Moisture Measurement Devices and Techniques (adapted from Imhoff et al., 2007).

Measurement technique	Advantages	Disadvantages
Neutron probe	• Moisture content can be measured regardless of its physical state in soils or waste • Offers large radius of influence, between 150 mm in wet soil and 700 mm in dry soil	• Measurement of absolute moisture content is difficult • Presence of non-water bound hydrogen interferes with the measurement • Some elements other than hydrogen have a propensity to absorb high-energy neutrons • Changes in density affect the results • The radioactive source of neutron probe is a highly regulated material • Automation is not possible
Electrical resistance/impedance sensors	• Sensors are relatively inexpensive • Sensor installation is easy • Automated measurement is possible • Can be produced inexpensively • Density does not affect readings • Fast response to leachate front arrival	• Sensors suffer from hysteresis at low moisture contents • Results affected by changes in electrical conductivity and temperature • Once wet the sensors do not drain quickly • Sensor must be calibrated using extracted waste
Electromagnetic techniques (Time domain reflectometry/transmissivity)	• Sensors are relatively inexpensive • Results are reproducible • Automated measurement is possible • Fast response to leachate front arrival	• Results affected by changes in electrical conductivity • Local heterogeneity of material properties affects the results • Sensor must be calibrated using extracted waste
Electrical resistivity tomography	• Non-intrusive technique • A two-dimensional evolution of a leachate injection plume can be obtained • Fast response to leachate front arrival	• Requires the knowledge of leachate electrical conductivity • Needs measurement of in situ temperatures from additional temperature sensors • Expensive instrumentation costs • Technique not evaluated for moisture content measurement
PGTT	• Provides reasonably accurate assessment of moisture content • Measurement accuracy is unaffected by the measurement volume • Relatively inexpensive field setup is required • Tracer gases can be injected through existing injection wells of a landfill	• Gas sample collection and laboratory analysis pose difficulty for automation • Needs measurement of in situ temperatures from additional temperature sensors • On larger scale provides assessment of average conditions and may not identify relatively wet spots
Optical fiber	• Provides data measurements at high spatial resolution • Ease of installation and automation • Fast response to leachate front arrival	• Technique not evaluated for moisture content measurement • Interference from preferential high gas flows in measurements

6.6 SUMMARY AND CONCLUSIONS

As recovery and testing of representative samples of MSW is difficult, if possible, in-situ testing is the most reliable method for evaluation of the material properties of MSW. However, in-situ testing and sounding techniques are also subject to limitations that may significantly affect their applicability and consequently reliability of evaluated MSW parameters. Furthermore, because these measurements can only be made after the waste is in place, they are only directly applicable to analysis of existing landfills.

Table 5. Summary of In-Situ Measurement Techniques for Evaluation of MSW Properties.

MATERIAL PROPERTY **IN SITU MEASUREMENT TECHNIQUE**		**Shear Strength Parameters**	**Unit Weight**	**Shear / Compressional Wave Velocity**	**Modulus Reduction and Damping**	**Hydraulic Conductivity**	**Moisture Retention**	**Young's Modulus**	**Modulus of Subgrade Reaction**	**Deformations/Settlement**
SASW	Non Intrusive		░	█				░		
REMI				█						
Back Analysis		░			░			░	░	
Plate Load Test (Surface)									█	
Surface Settlement Observation										█
ERT							░			
TSB	Intrusive					█				
Extensiometers/Sondex® Device										█
Settlement Plate										█
OYO™ Suspension Logging			░	█						
Cross-Hole / Down-Hole			░	█						
In-Hole Density			█							
Plate Load test (In-Borehole)									█	
SPT and BPT		░	░							
CPT/CPTU/RCPTU/CPTU-EC /SCPTU		░	░	█		░	░	░		
Pressuremeter								█		
Dilatometers (DMT/SDMT)			░	█				█		
Plate Load Test (In-Trench)									█	
Borehole/Test Pit Sampling			█				█			
Borehole Permeability Tests						░				
TDT/TDR/PGTT/Fiber Optic Sensors							░			
In-Situ Direct Shear Test		█								
Gamma Radiation/Neutron Probe							░			

█ = Direct Measurement; ░ = Indirect Measurement.

A variety of non-intrusive and intrusive techniques for field measurement of MSW properties are available to the design engineer. These techniques, as indicated in Table 5, include both direct methods for measurement of MSW properties of interest and indirect measurements that rely upon correlation with the properties of interest. Further categorization of these techniques with respect to tests nature (intrusive vs. non intrusive) is provided in Table 5 with symbols. Advantages and limitations for each of these tests were discussed throughout this Chapter.

It is not possible to single out a particular technique or test as a "recommended" procedure. Non-intrusive techniques are generally preferred from a health and safety perspective, and are generally cheaper, faster and easier to conduct than their intrusive counterparts. However, non-intrusive tests rarely yield direct measurements of key waste properties required for stability evaluation, such as shear strength, unit weight, and modulus reduction and damping ratio. Therefore, for stability evaluation applications, direct measurements are preferable to indirect measurements. Direct measurements generally require intrusion to the waste mass, require implementation of health and safety measures, and are generally more expensive than indirect measurements. On the other hand, several of these techniques can be used to directly evaluate shear strength, unit weight, and several other engineering parameters.

All field measurement methods, as applied to evaluation of MSW properties are subject to some limitations. One of the most significant limitations is the need for site specific calibrations and correlations. This is due not only to the lack of sufficient test data in MSW required for calibration of testing and sounding discussed herein, but also due to the high variability of waste deposits and hence related material properties. However, despite these limitations, field methods for measurement of MSW properties are, in general, considered more reliable than their laboratory counterparts.

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Chapter 7

Laboratory Testing of Municipal Solid Waste

George A. Athanasopoulos[1]

[1] M. ASCE, Professor, Dept. of Civil Engineering, University of Patras, Greece

7.1 INTRODUCTION

The evaluation of static and dynamic properties of MSW is a prerequisite for the performance of any type of meaningful landfill stability calculations, but also in many aspects of landfill design, operation and post-closure development. Field testing techniques can provide valuable data on the in-situ behavior of MSW properties under the specific conditions of the testing configuration. However, the constitutive behavior of MSW can only be studied in depth by systematic laboratory testing under carefully controlled confining stresses, and composition of waste samples. Although the collection of undisturbed samples of waste remains essentially impossible, sample disturbance may not be a major issue in laboratory testing of MSW due to the lack of "geologic history". On the other hand, the preparation of MSW samples in the laboratory, with conditions duplicating the field deposition and compaction, involves many critical issues that need to be carefully addressed. Presently, no standards or guidelines exist on the performance and documentation of laboratory testing of MSW and as a consequence different approaches are used. In some cases, complete documentation on various aspects of the testing is not presented limiting the value of the presented test results. The intention of this chapter is to examine these critical issues and provide some systematic guidance on laboratory testing of Municipal Solid Waste.

7.1.1 Reconstituted vs. "Undisturbed" Specimens

It was mentioned above that the in-situ condition of MSW is not characterized by a particular "geologic history" and is a function primarily of the waste placement and field compaction process as well as any degradation that has taken place. It seems therefore rational that the most important issue in preparing laboratory MSW samples is how to reproduce the field compaction mechanism and effort.

Mazzucato et al. (1999) performed large-scale direct shear testing of "undisturbed" solid waste and subsequently used the same device and waste material to reconstitute specimens and compare their stress-displacement response. The experimental data indicate that in terms of peak shear strength there is no significant differentiation between reconstituted and "undisturbed" specimens. However, there is a difference in the post-peak stress-displacement response (Fig.1): the shearing resistance of reconstituted specimens remains constant upon further increase of shear displacement whereas their "undisturbed" counterparts show a decrease in shear resistance. This difference in response may need to be taken into account in applications involving large deformations. In comparing a total of 103 large-scale direct shear tests performed on MSW, Zekkos (2005) did not find a systematic bias in the peak shear resistance of the in situ direct shear tests on "undisturbed" waste compared to its counterpart from reconstituted waste in the laboratory.

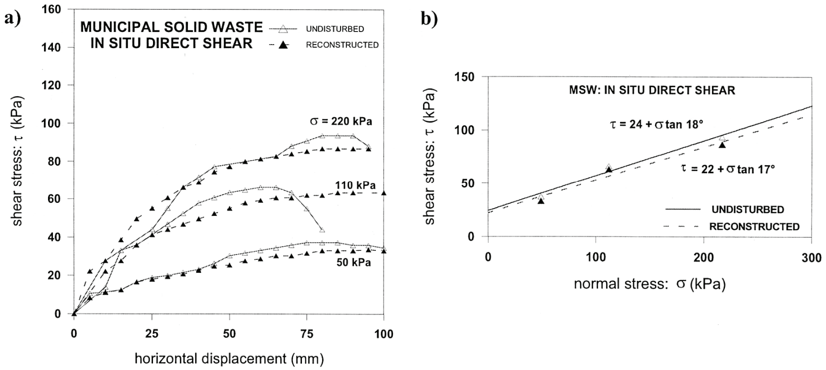

FIG. 1. Results of "undisturbed" and reconstituted specimens of MSW in a large direct shear device. (Mazzucato et al. 1999).

Methods used to compact and prepare reconstituted MSW specimens are the following:

1. Use of a drop weight like the one shown in Fig.2 (weight of drop mass ≈0.1kN) that is dropped repeatedly from varying heights to induce specific compaction energy. A drop pattern is used to uniformly compact the specimen. An example of such a pattern in a 300-mm diameter triaxial specimen is shown in Fig. 3. This method of preparation simulates well the field conditions in that the weight drop induces both a compressive and shearing stress component in the waste sample. This energy reasonably simulates the field "kneading" compaction induced in waste using sheepsfoot rollers. Also, the technique allows the compaction effort to be easily quantified. The contact area of the weight may be circular or square, depending on the specimen shape.

FIG. 2. View of the drop hammer used by Bray et al. (2009) for specimen preparation.

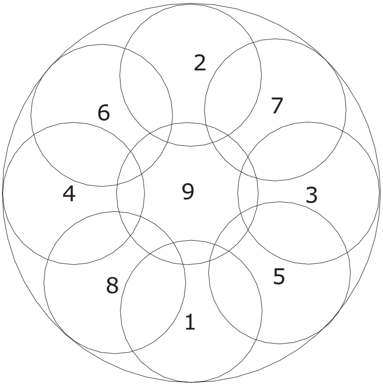

FIG. 3. Pattern of each cycle of drops (Bray et al. 2009).

2. Use of moist tamping as shown in Fig.4. This method of preparation may be difficult to apply in large-scale testing. Nevertheless, it has been found that moist tamping results in similar waste properties when the achieved material density is the same. Zekkos et al. (2008) used moist tamping to prepare small (d=71 mm) triaxial specimens using only the <20 mm fraction and the dynamic properties were essentially identical to large cyclic triaxial (d=300 mm) specimens that also

included only the <20 mm material and were prepared using the drop weight technique and to the same density. In preparing direct shear synthetic waste specimens with specific fibrous waste orientations, Athanasopoulos et al. (2008) used the moist tamping technique as shown in Fig. 4.

FIG. 4. A tamper being used for the preparation of synthetic waste direct shear specimen (from Athanasopoulos et al. 2008)

3. Other techniques for specimen preparation have been used, such as static compression and rodding. Static compression is not expected to be very representative of the field conditions and is likely to result in lower densities than the drop weight technique due to the absence of the shearing component of compaction. Rodding has also been used, but the technique is likely to cause damage to the various particles, particularly the fibrous constituents (e.g. paper, woods, plastic) and should generally be avoided.

It is emphasized that no matter what the method of MSW compaction will be, the lift size should be carefully selected. The lift size will determine the degree of compaction that can be achieved, and should also be large enough to accommodate the size of the larger particles included in each lift.

7.1.2 Size of MSW Specimen Used for Testing

Considering the large size of particles of different materials contained in the MSW it becomes evident that the size of test specimen would be expected to affect the results of laboratory testing. Small-scale testing of MSW has been performed and is available in the literature. This size of testing generally required either removing most waste constituents or trimming their size. Zekkos et al. (2008) has shown that small-scale triaxial (d=71 mm) testing of MSW produces different results compared to large-scale testing (d=300 mm) in terms of dynamic properties such as shear modulus and damping. More specifically, it was observed that test results on specimens containing either only the smaller fraction (<20mm) or also the larger fraction processed in smaller than 20 mm particles, were significantly different from the results on large-scale specimens containing the larger fraction. No systematic bias was observed among 103 test results obtained on direct shear boxes ranging from 300mm x 300 mm to 1400 x 1400 mm (Fig.5). Thus, it is recommended that testing of MSW be performed on specimens with size at least 300mm. It is also recommended to avoid testing on specimens with size 70 mm, as those are not expected to be representative of the waste material in the field. It is also important to note that scaling laws have not yet been adequately investigated, and more research is needed in that direction.

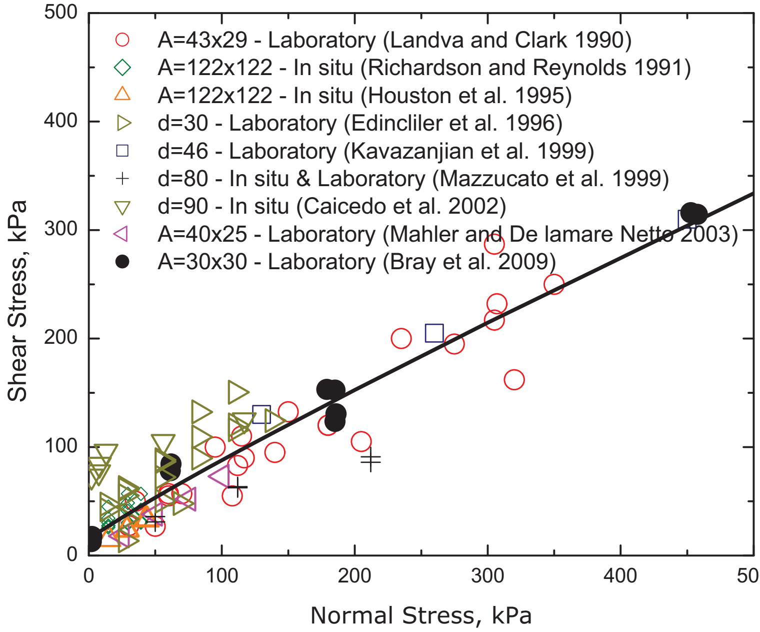

FIG. 5. Large-scale direct shear tests on Municipal Solid Waste. Legend indicates dimensions (d for diameter of circular specimen; A for area of square specimen) as well as whether the tests were in situ or laboratory. Also shown is the Bray et al. (2009) recommended strength envelope.

7.1.3 Maximum Particle Size of Waste in the Specimen

A number of rules and guidelines are in existence regarding the maximum allowed particle size in a soil specimen in order to obtain reliable results reflecting the global response characteristics of the material. In the case of MSW, based on experience obtained so far, the following recommendations are made:

1. The size of bulky constituents (e.g. wood, gravel, glass) should be less than 1/6 the size of specimen (diameter or side), consistently with our experience on soil testing.
2. The size of softer, easily folded, high-aspect ratio, constituents (e.g. paper, soft plastics) may be larger and possibly up to ¼ the size (diameter of side) of specimen.

Additional research work is needed to evaluate the effects of the size of the constituents compared to the specimen size. The size of waste particles that are present in a MSW sample may be reduced by the following methods: (a) scalping, i.e. removal of particles with a size greater than a specified size, (b) scaling (trimming) of particle size, (c) processing (particle size reduction). It must be noted that the impact of these modifications on the behavior of the material, are still not adequately investigated.

7.2 GUIDELINES FOR PERFORMING LABORATORY TESTS ON MSW

Based on the above general principles, the execution of the different types of laboratory tests should comply with the following guidelines:

7.2.1 Waste Characterization and Index Testing

Waste characterization (discussed in a separate chapter) is a critical task in order to adequately document the nature of the tested waste material. Characterization of the coarser (>20 mm material) and the finer (<20 mm material) fractions is critical. Index testing can be conducted either for the whole sample (globally or separately on the coarse and fine fractions) or for the fine fraction (<20mm) only. The <20 mm can be classified using the Unified Soil Classification System (USCS) according to ASTM D-2484.

Index testing of MSW may involve:

(a) sieve analysis: Sieve analysis is important to characterize the distribution of the various particle sizes, particularly for the <20 mm material. Both wet and dry sieve analyses have been performed in the literature, even though it is recognized that dry sieve analyses will tend to underestimate the composition in finer grained soils (Gabr and Valero 1995). The method used to establish the grain size distribution need to be reported.

(b) Size of larger waste constituents: The >20 mm material typically involves many fibrous constituents such as paper, plastic or even long constituents such as wood pieces, that are not amenable to sieving. It is expected that the size of the various constituents will have an impact in the behavior of the waste material (Dixon and Langer 2006) and thus measuring the distribution of the sizes is valuable for research purposes. In practice, and since the effect of the size of these constituents on the waste behavior is not yet adequately documented, this task becomes less critical.

(c) Atterberg Limits: When the <20 mm material includes significant amount of fines (>30% by weight greater than 0.075 mm), it is important to measure the

Atterberg limits. The Fall Cone may also be used for establishing the Liquid Limit.

(d) Moisture content: Moisture content is a critical parameter and always needs to be measured. To avoid volatilization of material at higher temperatures, moisture content has been measured at temperatures lower than 105 degrees C. A temperature of 55 degrees is recommended at a minimum and an additional measurement at 105 degrees would be desirable. It has been shown that moisture content is very sensitive to the specimen size and its composition (Zornberg et al. 1999, Zekkos 2005). Thus, both need to be reported. To ensure that each specimen is representative of the waste mass, it is recommended to test as large specimens as practically possible. It is also recommended to measure the moisture content of the <20 mm and the >20 mm material separately, as these values tend to be significantly different.

(e) Organic content: Similarly to the moisture content, the organic content is a function of the waste composition. It is recommended to measure the organic content separately for the <20 mm material and the >20 mm material. It would also be preferable to test separately the various constituents of the >20 mm material.

(f) Specific gravity (G_s); Measurement of the specific gravity of the <20 mm is recommended.

In addition, it is desirable to measure the cellulose (C), hemicellulose (H) and Lignin (L) concentrations of the waste material in order to evaluate the (C+H)/L ratio which has been shown to be indicative of the waste's state of degradation (Hossain et al. 2003).

Additional measurements of the pH, the electrical conductivity, the biochemical methane potential and the redox potential are also useful.

7.2.2 Strength and Cyclic Testing

The shear strength of MSW may be evaluated in the laboratory by direct shear, simple shear and triaxial loading testing. In the case of cyclic testing, the cyclic triaxial, cyclic simple shear, cyclic torsional shear and resonant column tests can be used. The size of the constituents and specimens should comply with the recommendations presented previously.

Other issues that need to be addressed are:

(i) The pertinent ASTM procedures for test execution need to be followed with a detailed description of any necessary deviations.

(ii) The consolidation procedure (including time under confinement) and the stress state need to be reported and taken into consideration in comparisons. Time under confinement has been shown to have an impact on the small strain stiffness of MSW (Zekkos et al. 2008). The stress state (isotropic vs. anisotropic) is also critical, particularly for anisotropic materials such as waste and thus needs to be reported.

(iii) The measurement of the unit weight at each stage of test (e.g. initial values, prior to testing and after testing, if feasible) is required, since the unit weight of MSW has been found to significantly affect all properties of waste and may also vary significantly at varying confining stresses and with time. When efforts are made to produce specimens representative of the field, it is important for the material density during shearing (not necessarily after compaction) to match the field density.

(iv) The measurement of the moisture content at least during specimen preparation and upon completion of the test is desirable. The moisture content may change for long test durations.

(v) If not during preparation, then upon completion of the test, a detailed evaluation of the specimen's composition is critical. This should include the % by weight of the <20 mm material and the >20 mm material and also the detailed characterization (preferably by weight) of the various constituents of the >20 mm material.

(vi) For saturated testing, back pressure should be used to saturate the material and the B value should be measured and reported. Experience suggests that B values on waste may be lower than other soils due to the greater potential for air or gas to be trapped within the waste specimen structure.

7.2.3 Compression / Consolidation Testing

Laboratory compression / consolidation testing should follow the same guidelines as for strength testing and follow the general guidelines of ASTM D-2435, with the following exceptions/additions:

1. The maximum particle restriction may be relaxed, based upon lift thickness e.g. the maximum particle size may be up to ½ of lift thickness, or less depending on compressibility.
2. The initial density of the sample should be equal to the as-placed (after compaction) density.
3. The fluid loss should be monitored.
4. In the case of reactor tests (and maybe for very long term conventional tests) the temperature and gas production should be monitored and the state of degradation at the end of test (through measurement of the biochemical methane potential or (C+H)/L) should be quantified.
5. The specimen size should be as large as possible (300mm minimum)
6. Full description of any mechanical waste processing should be provided.

7.2.4 Permeability Testing

Guidelines for permeability testing are the same as for compression testing. The ASTM D-5084 procedures should generally be followed, but the following remarks should be made:

1. The walls of the container should be flexible.
2. The test should be conducted at different stress states and the compression of specimen should be continuously measured.

3. Back pressure should be used to saturate the material in order to evaluate the saturated hydraulic conductivity.
4. The specimen temperature should be monitored.
5. Site-specific leachate should be used when possible. In all cases, the chemical composition of water or leachate used in the test should be reported.

7.3 MINIMUM REQUIREMENTS LABORATORY TEST DATA REPORTING

When reporting the results of laboratory tests on MSW, the following information should be included:

1. Detailed waste characterization and age
2. Quantitative description of waste composition (% <20mm and % constituents of the >20mm fraction)
3. The density / moisture content of the compacted specimen and organic content of tested material
4. Description of specimen preparation procedure (including the method used to mix the waste constituents, compaction method and effort as well as lift size)
5. Explanation of the basis for data interpretation (e.g. peak shear stress vs. stress at limit displacement of apparatus). It is preferable to provide complete stress-strain or stress-displacement plots than just a summary.
6. Comparison of test results with results reported in the literature.
7. Unit weight values upon compaction and immediately before testing to provide an estimate of the change in unit weight with increasing confining stress.
8. Description (statement) of testing conditions (i.e. drained vs. undrained) and confining stress.
9. Present laboratory test data, not just the results of interpretation. The experimental stress-strain plot should be presented and not just the values of cohesion and friction angle.

7.4 CONCLUDING REMARKS

Experience with testing of Municipal Solid Waste in the laboratory has grown significantly in recent years, however significant differences in testing are observed among researchers. Whereas more research is needed to address various issues associated with laboratory testing of MSW, some minimum requirements and recommended procedures for laboratory testing are presented to guide future testing investigations.

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Science and engineering of landfilled waste mechanics

John McDougall[1]

[1]School of Engineering & Built Environment, Edinburgh Napier University, EH10 5DT, UK

BACKGROUND

This statement of research needs assumes an ongoing need to deposit and contain waste in landfill. Further, that landfills are designed, operated and subsequently managed in as technically efficient and environmentally sustainable manner as possible.

There follows a need to understand better the internal processes that control the behaviour of the contained waste because it is these processes – a complex mix of hydraulic, biochemical and mechanical phenomena – that define the operational conditions and long-term performance of the engineered containment system.

This statement is the perspective of a researcher who happens to be working in UK; it is not the authorised statement of any UK authority, agency, or contractor, nor is it the agreed agenda of the UK landfill research community. Note that the perspective has international relevance. In fact, advances in landfill research may now be more beneficially exploited in countries outside the EU, since EU waste management policy has shifted away from landfill.

SCIENCE AND ENGINEERING IN LANDFILLED WASTE: MECHANICS

Interpreting the fundamental behaviour of landfilled waste is a unique engineering challenge. It requires the application of hydraulics, biochemistry and geomechanics to a porous particulate system that has been deposited in a remarkably short time period (at least by comparison to more conventional geologic media) and which undergoes hydraulic, biochemical and geomechanical change at an equally rapid rate.

For the purposes of design and construction, individual landfill behaviours, i.e. the hydraulic, biochemical and mechanical, are usually idealised as discrete systems. Leachate generation is a product of infiltration and a cell-averaged absorptive capacity, gas generation is a simple function of time and waste composition, as is long term landfill settlement. The discrete approach can be expedient, but a more fundamental interpretation of this complex system offers deeper insights into landfill behaviour and an enhanced predictive capability.

The form of the more fundamental, integrated framework is not difficult to imagine – the physical composition, especially density and its variation with depth, control void space and hydraulic and gas permeabilities. These physical conditions define the hydraulic domain. In turn, the amount and distribution of moisture control the progress of decomposition. Biodegradation models that respond to moisture content already exist (McDougall, 2007). The real challenge, however, is to understand the impact that mass loss (in landfill, the enzymatic hydrolysis of cellulolytic matter and ensuing subsequent methanogenesis) has on phase composition. It is this interaction of the hydraulic, biodegradation and mechanical systems, more specifically the mechanical consequences of decomposition, which is the focus of this statement of research needs.

A programme of laboratory tests and results is presented herein. The tests reveal how mass loss impacts on the volumetric state of a part soluble particulate medium. Obtaining this information at field scale in landfill is a huge challenge so the main aim of this programme is to establish an appropriate strategy and anticipate analytical procedures.

MECHANICS OF MASS LOSS IN A PARTLY-SOLUBLE SANDY SOIL

A series of inundation tests on a sandy soil containing 20% by mass of soluble salt was performed to reveal the effect of particle dissolution on volume change and phase composition. Vertical displacement and pore-fluid conductance data were collected and interpreted using a dissolution-induced void (DIV) change relation. The data obtained suggest that dissolution leads to a systematic and quantifiable change in phase composition.

Theoretical Background

The DIV change relation quantifies the relationship between solids volume loss V_S and an induced change in void volume V_V,

$$dV_V = \Lambda \, dV_S \tag{1}$$

Certain values of Λ can be associated with foreseeable mechanical consequences, as summarised in Table 1. It is important to note that in a decomposable soil, the conventional void ratio is not a unique indicator of the volumetric state. For example, when $\Lambda = e$ (the current void ratio), mass loss induces void volume changes that result in a constant void ratio, yet significant overall volume reduction occurs (see McDougall & Pyrah 2004 for more details).

Experiment: materials and equipment

Dry particles of Leighton Buzzard quartz sand (a poorly graded uniform sand with D_{60} = 0.92 mm, C_U = 1.5) and rock salt (all particles between 2.0 and 3.35 mm) were combined in proportions 80:20 by mass (see Figure 1). The samples were placed in an oedometer to an initial dry density of approximately 1600 kg/m^3, loaded, then subsequently inundated with distilled water. The soil was tested at five different vertical loads: 12, 25, 50, 112 and 237 kPa. Dissolution of all rock salt occurs within 60-90 minutes.

Table 1: Some key values and associated mechanical consequences of Λ

Λ	Void ratio	Overall volume	Phase composition and its expected strength
-1	Maximum increase	No change	Much looser & possibly weaker
0	Increase	Reduction	Looser & possibly weaker
e (= void ratio)	No change	Large reduction	No change
>e	Decrease	Maximum reduction	More compact & possibly stronger

Displacement and conductance with time

Figure 2 shows the vertical displacement and Figure 3 shows the conductance, both with time, during dissolution of the 50 kPa sample. Vertical displacement begins relatively slowly, accelerates to reach a maximum rate after about 15 minutes, then gradually slows to a negligible rate after about 60 minutes. The general pattern of conductance readings is consistent with the displacement time frame and emphasises the link between dissolution and vertical displacement. A more insightful interpretation is obtained if displacement is presented as a function of dissolution rather than time.

Displacement as a function of dissolution

Figure 4 shows vertical displacement with degree of decomposition for the 50 kPa sample. The degree of decomposition is a dimensionless measure of the progress of dissolution (Al-Khafaji & Andersland 1981), in this case calculated from the dissolved ion concentration.

FIG.1. Leighton Buzzard:rock salt (80:20) mix.

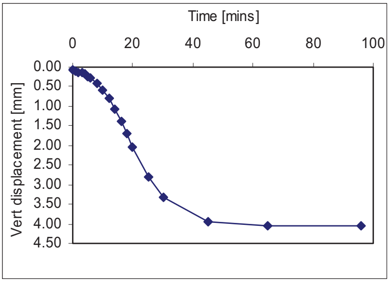

FIG. 2. Vertical displacement with time

From Figure 4, the relationship between vertical displacement and dissolution, independent of time, is observed. Little overall vertical displacement is evident during the early stages of dissolution. The relationship between displacement and dissolution then increases becoming linear in the second half of dissolution process.

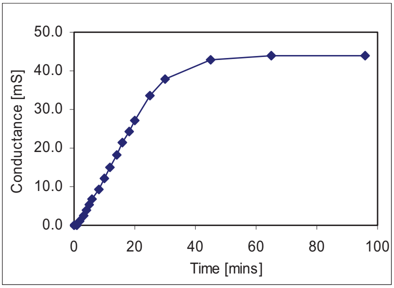

FIG. 3. Conductance with time

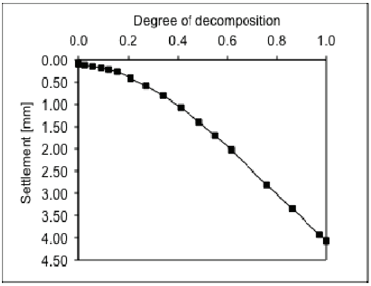

FIG. 4. Vertical displacement with degree of decomposition

Interpretation of dissolution using Λ

A quantitative interpretation of the relationship between void phase changes and dissolution can be gained from the DIV parameter Λ. Solid volume loss is determined using the degree of decomposition based on the initial salt mass (62 g) and salt specific density (2.16 Mg/m^3). Change in void volume is the difference between vertical displacement and solid volume loss.

Figure 5 shows the variation of Λ as a cumulative and an incremental parameter. The cumulative form of Λ is appropriate for predicting post-dissolution volumetric states, whereas the incremental form provides insights into the changing mechanics of dissolution. The data in Figure 5 show that cumulative Λ is at all times negative, which means that dissolution leads to much looser or open soil skeleton and the void ratio is at all times greater than its initial value.

More specifically, cumulative Λ is initially about -0.5 and decreases in the early part of the dissolution process – increases in void ratio are at their greatest. After about 10-15% dissolution, cumulative Λ steadily rises to reach a final value of -0.05. In other words, the long-term phase composition comprises a void volume that is 5% larger than the corresponding loss in solid phase volume.

The incremental Λ data shows initial values of approximately -0.8. Recall (Figure 1) that when $\Lambda = -1.0$, any loss in solid volume induces an equal increase in void volume and there is no change in overall volume. Dissolution at this stage leads to a much more skeletal structure. Incremental values of Λ then rise steadily and eventually become positive. Although not densifying the sample, the void volume during this stage is decreasing (but by less than the corresponding decrease in solid phase loss), which is consistent with the greater rate of vertical displacement observed in Figure 4.

Dissolution at other applied loads

Figure 6 shows cumulative Λ values for four tests (at vertical stresses of 12, 50, 112 & 237 kPa). There is a remarkable consistency in the four test data records and it is tempting to conclude that for this case, the mechanical consequences of dissolution are predictable. Furthermore, the rearrangement is a gradual, rather than episodic, process. The insensitivity to vertical load was not expected as data from landfills suggest a pronounced influence of waste depth (= applied load) on long term settlement (McDougall et al. 2004).

There are, however, other factors likely to control soil behaviour in these circumstances. They will not be discussed here but, to note, would include: (i) relative proportions and (ii) particle size distributions of the sand and salt fractions, (iii) rate of dissolution, (iv) shear strength and (v) stiffness of the particulate skeleton. This latter factor may explain the insensitivity to load observed here.

CLOSING REMARKS

There are many questions in landfill engineering that remain unanswered because waste is considered too unpredictable, too complicated or too heterogeneous to justify a more detailed analysis. It may be that the quantitative validation of an integrated landfill system model is still some way off – and the difficulties of translating the controlled laboratory-scale tests described herein to the landfill sale are one reason for that. The difficulties are not, however, insurmountable (see, for example, Ivanova et al. 2005) and the additional insights, based only on a qualitatively plausible interpretation, are sufficient to warrant further investigation.

Indeed, if a systematic mechanism of decomposition can be found in waste refuse then the ability to analyse and to predict long-term landfill settlement can be improved. This would be a key ingredient in a broader, more fundamental interpretation of landfill behaviour, which could revitalize landfill analysis and landfill modelling capabilities generally.

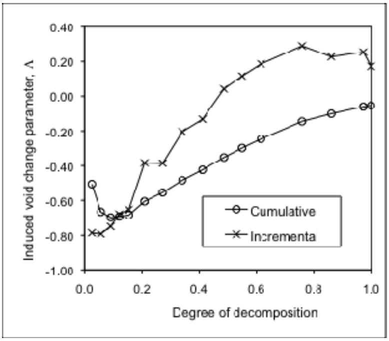

FIG. 5. Variation of void change parameter Λ during dissolution

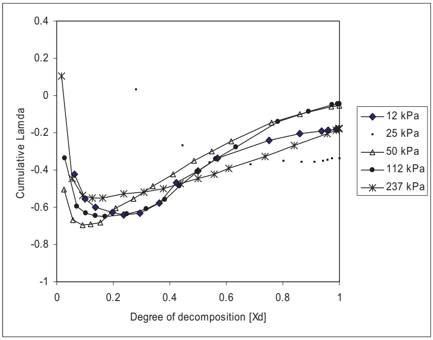

FIG. 6. Cumulative *Λ* for all tests, at loadings 12, 25, 50, 112, 237 kPa.

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Waste Mechanics Research Needs: A Perspective from Brazil

Claudio Fernando Mahler[1], Ph.D., Vinicius P. Guedes[2], M.Sc.
and Ronaldo L. dos S. Izzo[3], Ph.D.

[1]Prof. of the Civil Engineering Department on the Program of Pos-Graduation Courses of the Federal University of Rio de Janeiro - COPPE /UFRJ,
[2]Civil Engineer of LPS Consultant Engineering Company Ltd.
[3]Civil Engineer, Pos-Doc Researcher at the Civil Engineering Department of the Federal University of Rio de Janeiro - COPPE/UFRJ

Waste Mechanics is completely different from Soil Mechanics, but perhaps out of convenience it is increasingly addressed based on Soil Mechanics concepts. Ideally Continuum Mechanics should be used, but even in Soil Mechanics past empirical approaches are adopted as numerical tools are less available and knowledge of Continuum Mechanics more limited.

In Brazil, solid waste landfills were managed from a sanitary engineering viewpoint, and engineers operating the landfills were generally mechanical or electrical engineers, more concerned with waste collection and transport logistics than in fact with waste disposal and its possible impacts on the environment. It was only after the Bandeirantes landfill accident (see Figure 1) that geotechnical engineers were in fact called to play a more important role in landfill projects and management. It should also be mentioned that in most cases, landfill accidents do not involve people and when they do, they affect lives in areas that do not have the ability to engage the media so that the incident is not news or very quickly forgotten. Figure 2 shows the Bandeirantes landfill in operation years after the accident.

FIG. 1. Landfill accident (1991).
Photos: Kaimoto, L.S.A. (2006)

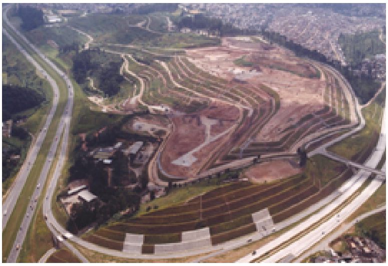

FIG. 2. New conformation (2006).

But what are the similarities and differences between Waste Mechanics and Soil Mechanics? Some ideas are provided below that may contribute to a better understanding of the two mechanisms.

Similarities

- Form of construction – landfill by layers;
- Mode of transportation – trucks;
- Projects require monitoring for a long period after closing down (for example, dams, tunnels and waste landfills);
- Both have distinct behavior when saturated and unsaturated.

Differences

- Grain size;
- Classification of materials:
    - Soils (clay, silt and sand);
    - Waste (glass, paper, cardboard, earth, leather, bones, metals, hard plastic, soft plastic, building materials, timber, rags, etc.);
- Compaction equipment;
- Base protection in waste landfills;
- Cover protection in waste landfills;
- Leachate drainage system in waste landfills;
- Gas drainage system in waste landfills;
- Fire and explosion hazards in waste landfills;
- Ongoing degradation process in waste landfills;
- Waste landfills may contaminate the environment (soil, water and air);
- Change in the physical and chemical characteristics in shorts periods of time (waste undergoes physical and chemical changes much faster than the soils).

What are the fundamental concepts to be considered in Waste Mechanics?

Which concepts must we need to examine in further depth to be able to improve waste treatment, irrespective of the socio-political factors, and which in fact are being increasingly discussed in all societies with a positive focus on the issue of waste or solid waste? In other words, with the concepts on waste management used knowadays in many countries, these wastes will continue being a waste problem 50 or 100 years from now. Our society will be obliged to treat this waste, although it is currently considered dispensable. Therefore, waste management in the future, as it is done in Germany, will provide disposal of only inertised waste.

In any case, many improvements will be necessary in the Third World current waste disposal procedures in order to improve disposal and lead to safer and more economical solutions, and permit, for example, more landfill expansions.

Another important aspect is that, unlike Soil Mechanics, Waste Mechanics addresses the study of a constantly changing material, not only as a function of the population's purchasing power that creates that waste (Table 1), but also from cultural habits, time of year (Figure 3) and so on, changes depending on numerous technological innovations. Plastic, for example, only began to be a more relevant waste component in Brazil in the mid-1960s.

Table 1: Average by weight composition of waste components.

Componentes	Average Weight Composicion			
	Alto Pinheiros	Butantã	Lapa	Marsilack
Glass	2,40	1,10	2,40	0,70
Metal	1,90	3,80	1,50	2,20
Plastic	22,10	21,30	16,80	20,70
Paper	27,20	21,20	12,20	10,30
Organic Mat.	43,20	49,00	61,80	63,90
Inert. Mat.	0,00	0,00	2,00	0,00
Others	3,20	3,60	3,30	2,20

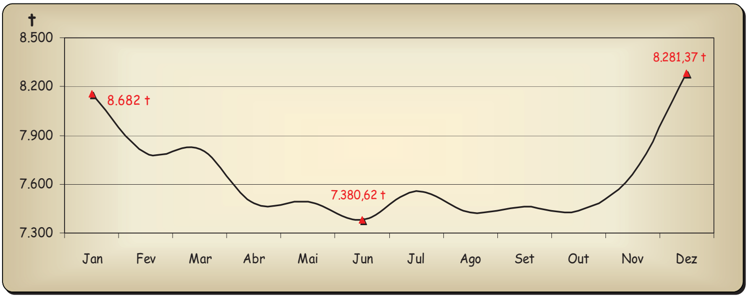

FIG. 3.Waste production variation versus month. Average value from 1993 to 2004 (Comlurb 2005).

In the 1980s the electrical/electronic industry began to be a more important waste component and the computer and telephone waste has also grown significantly since the 1990s. The study of waste, therefore, from its grading, gravimetric and morphological aspects is an ongoing necessity (Figure 4).

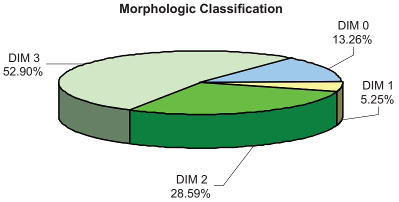

FIG. 4. Sum of the results obtained from the morphologic classification of the MSW substance groups under study. (see Borgatto 2006)

If we wish to improve waste disposal practices we will not only need to improve our knowledge of waste but also of its geomechanical characteristics.

In the short and intermediate term, obviously in developing countries the solution of waste landfills is still to be reached. We could consider a time span of 40 to 50 years. This is why consolidation studies, determining specific weight, permeability, porosity, strength, vertical and horizontal gas flows are extremely relevant for these countries with fresh waste and waste at different stages of aging.

In developed countries where a sanitary landfill is something of the past, inertised waste, whether by mechanical-biological treatment or heat processes must also be studied. These studies consist of consolidation, strength tests, characterisation of waste in terms of grading, determining specific weight, porosity and characteristic curve. Studies of consolidation and strength in an unsaturated condition with continuous measurements of suction are needed. Also studies to be performed to obtain an improved understanding of inertised waste and its possible applications in engineering.

Some examples of the equipment designed for this kind of testing and some results of consolidation tests with mechanical-biological unsaturated waste treatment are provided below (see Figure 5).

FIG. 5. Oedometric test wish suction measurement and triaxial test with direct suction measurements. (after Izzo 2008)

In short, there is still a long way to go to improve our understanding of waste mechanics. In its first stage, as in soil mechanics, as described above, we must learn about the material, its specific characteristics, behavior, and adopt testing procedures similar to those used in Soil Mechanics, but with much larger test samples. The use of the centrifuge is also always considered a possibility for testing fresh waste or mechanical-biological waste treatment. Experiments of this kind were performed during the 1990s by Jessberger and his team in Germany, and more recently by Calle (2006) in COPPE (Figure 6).

In numerical simulations of stability and waste behavior during the landfill's working life and after its closure, concepts of continuum mechanics, static and dynamic analyses, and geomatics shall be included to improve waste disposal procedures, whether inertised or not. Of course, in non-inertised waste, models of chemical and biological phenomena occurring in the waste during its degradation shall be adopted, including the transformation processes of organic matter and other components in gases and liquids.

Lastly, with regard to gases, many studies are currently in progress in Brazil, caused by the opportunity of CDM (Clean Development Mechanism) , sale of carbon credits, and the ability to use generated gas for energy. There is a growing need for onsite measurements of the quantities and quality of the gas. In general, the predicted quantities of gas have not corresponded to the measured results, so that gas studies are even more important. It is worth recalling that these studies are important not only from economic-environmental perspectives but also to relate landfill instability problems to gas generation(Figure 7).

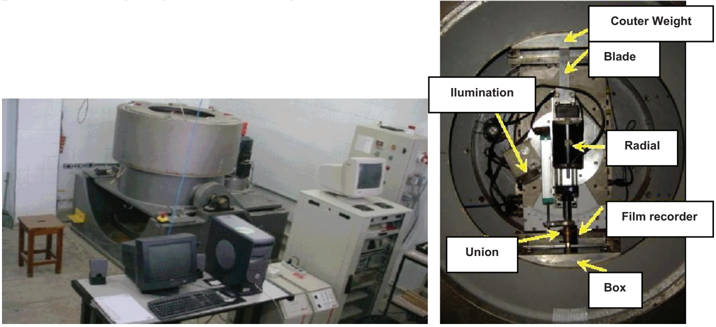

FIG. 6. Centrifuge device. (after Calle 2007)

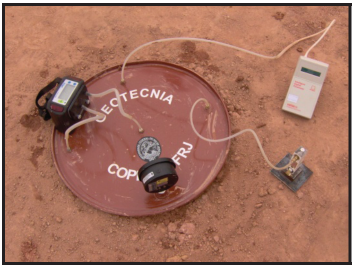

FIG. 7. Plate to measure gas flux through the soil cover of a MSW landfill. (after Guedes 2007)

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A Simple Index Value for Waste Mechanical Behaviour

I.R.Fleming, P.Eng.[1]

[1]Assoc. Professor, Dept Civil & Geol. Engineering, Univ. of Saskatchewan, Saskatoon, Canada S7N 5A9; Tel: (306)966-5341; FAX (306) 966-5427; ian.fleming@usask.ca

ABSTRACT

Significant advances have been made during the past two decades in the understanding of the mechanical behaviour of municipal solid waste, however challenges remain in improving the knowledge base and most importantly, in disseminating such knowledge to engineering practitioners. Large post-closure deformations have been observed in landfills, often interfering with buried infrastructure such as that used to collect landfill gas. Slope failures in landfills have been observed in all continents, in some cases with significant loss of life. Accumulating experience suggests that there are a limited number of key factors that govern the mechanical behaviour of landfilled waste masses. Since the effect of each individual factor is relatively predictable, it is proposed by the author that a quantitative index value be developed for comparison of the behaviour of different waste masses.

INTRODUCTION

Increasing urbanization has brought about increased size and height of landfill sites and several failures in high, steep landfill slopes have been documented in the literature (Hendron et al. 1999; Eid et al. 2000; Kolsch et al. 2005; Kavazanjian and Merry 2005). Concurrent with the trend toward higher, steeper landfills has been an increase in the provision of engineered systems for leachate collection and drainage and landfill gas capture and utilization. Short of catastrophic failure of waste slopes, there may be lateral deformations sufficient to impair function of gas collection and other engineered systems.

An increasing database has accumulated, comprising measurements of various mechanical properties from laboratory tests, field testing and back analysis of failed and stable slopes. Dixon and Jones (2005) presented an excellent review of the state-of the art with respect to the mechanical properties of municipal waste. There is undoubtedly room for debate as to which mechanical properties are the most important or the most in need of research (for example Dixon and Jones (2005) included lateral stiffness as well as compressibility. It is the opinion of this author that certain properties may be considered fundamental and it would be beneficial to reach a consensus regarding their expected range of values in municipal waste and the effect on these values of factors such as aging and degradation or increasing compaction. These *properties* include the following:

1. *Unit weight*
2. *Shear strength (i.e. Mohr-Coulomb shear strength parameters c and ϕ)*
3. *Compressibility (primary and secondary)*
4. *Horizontal in-situ stress (i.e. k_0 or Poisson's Ratio)*
5. *Hydraulic conductivity (horizontal and vertical, saturated and unsaturated)*

Similarly, there are a few key factors which may be known or measured or estimated without great difficulty and which are known or assumed to have an effect on the important mechanical properties of the waste. This list of *factors* might include the following:

a. *Compaction*
b. *Organic content (at placement)*
c. *Age*
d. *Daily/Interim cover soil (how much, what type)*
e. *Moisture regime in landfill (i.e. a wet bioreactor or a dry tomb)*
f. *Content of "reinforcing" fiber or sheet-like materials (timber, textiles, cardboard)*

It is the objective of this paper to consider waste properties in the context of these important factors in order to identify where the greatest degree of uncertainty exists for practitioners wishing to carry out analyses for any particular waste disposal site.

WASTE PROPERTIES

Unit Weight

The unit weight of waste has often been assumed from site records or estimated "from experience". There is certainly an ongoing need for consistent terminology and definitions (i.e. wet, dry and "apparent" unit weights are all used in practice). The importance of density is well established by various researchers, notably Zekkos et al. (2006) who propose an hyperbolic formulation in which the unit weight increases from a value at surface (as compacted) reaching a near-constant value at some depth. Compared with other properties, however, this author proposes that unit weight is relatively well understood and can be estimated by a knowledgeable practitioner with a reasonable range of uncertainty.

Shear Strength

The shearing resistance of waste has been characterized in terms of the Mohr-Coulomb failure criteria used in soils mechanics. Numerous laboratory and field tests have been carried out. There remain issues which merit discussion, for example:

- *the use of a strain cutoff to define "failure" (20%?);*
- *the required sample size;*

- *the effect of anisotropy;*
- *the potential for different results between intact and recompacted samples;*

As well, the relative merit of triaxial, direct shear and simple shear testing requires discussion, in the context of the availability, expense and ease of sample preparation and operation for the various laboratory apparati.

Compressibility and Horizontal In-situ Stress

In contrast with shear strength, stress-deformation characteristics have been less studied as summarized in Table 1. Recent work by the author suggests that an hyperbolic stress-strain formulation may be appropriate for triaxial tests on waste samples (Singh et al. 2007).

The horizontal stress, or value of K_0 has recently been evaluated by Singh and Fleming (2008) and it is suggested that K_0 (or ν, Poisson's Ratio) may be relatively constant for most municipal waste materials. Once researchers and practitioners agree on one or more consistent approaches for stress-deformation of municipal waste (i.e. linear elastic-perfectly plastic vs. non-linear hyperbolic), research should be directed toward the effect on the stress-deformation properties of degradation, aging, increased compaction etc.

Hydraulic Properties

The saturated hydraulic conductivity of waste has received significant attention, although the unsaturated water retention curve and unsaturated hydraulic conductivity of waste still require study. Fluid movement in landfills is important for bioreactor operation, leachate and gas management, however for the purpose of this paper, the significance of hydraulic properties is limited to the effect on pore pressure.

Most waste mechanics work has implicitly accepted Terzaghi's principle of effective stress for waste. Given that the skeleton of the porous material is not incompressible, it is this author's opinion that this fundamental assumption should be tested. Singh et al. (2007) showed data from testing of saturated intact waste samples supporting the use of effective stress analysis. It is acknowledged that there have, for several years, been numerous reasons to suppose that effective stress governs shear strength in waste (high pre-failure pore pressures due to leachate reinjection at Dona Juana and due to very high rainfall at Payatas), however this fundamental assumption has received relatively little scrutiny.

Table 1. Summary of Elastic and stress-deformation properties from literature

Reference	ν	K_o	G (MPa)	E_o' (MPa)	Method of estimation
Beaven and Powrie (1995)				0.14-2.4	"Pitsea compression cell" Constrained modulus increased from 0.14 to 2.4MPa for average vertical stress increase from 20 to 461 kPa
Carvalho & Vilar (1998)	0.25-0.35				From measurement of shear wav and compression wave velocity using crosshole method
Dixon et al. (1999)		0.1-0.9	2-14		Pressuremeter testing on 1-3 year old waste, G calculated at 1% strain
		1.0	25		Testing on 11 year old waste
Houston et al. (1995)	0.11-0.3				ν decreasing with depth
Landva et al. (2000)		0.26-0.40			Using 1-D large split ring consolidometer
Kavazanjian(2006)		0.3 0.2	(loose waste) (dense waste)		Using ultra thin tactile pressure sensors
Matasovic and Kavazanjian(1998)	0.25-0.40				ν obtained from measurement of shear and compression wave velocities
Sharma et al. (1990)	0.49		84.4		Compression and shear wave velocities measured using Downhole test method

ν - Poisson's ratio; K_o - At rest lateral earth pressure; G - Shear Modulus; E_o'= Constrained Modulu

FACTORS INFLUENCING MECHANICAL PROPERTIES OF WASTE

Compaction

The importance of compaction was highlighted by Gharabaghi et al. (2007) who considered stability of two landfills in Brazil at which the principal difference was compaction in lifts compared with end dumping. Other considerations equal, the effect of increasing the degree of compaction is to increase density, shear strength and decrease compressibility.

Aging and Degradation

All other things equal, a sample with greater organic content will undergo more significant changes as a result of aging and degradation. Samples with similar composition may exhibit different behaviour after being subjected to varying degrees of degradation. In this content, age itself may not be a useful metric, unless qualified for the expected rate of degradation processes in the waste mass. Figure 1 shows triaxial test results for two waste samples which had been similar prior to being statically consolidated and degraded in a laboratory compression cell (LCC) as described by Singh and Fleming (2008). The first sample had been only slightly degraded for a few weeks and compressed to 108 kPa. The second sample had been aggressively degraded for 6 months until the Volatile Solids reached 27% (from initial 57%) and had been compressed to 180 kPa. It is evident that the second sample is stronger and less compressible and it is reasonable to associate this with the higher stress to which the material had been consolidated. What is not clear is the role of the additional degradation and research is ongoing in this regard.

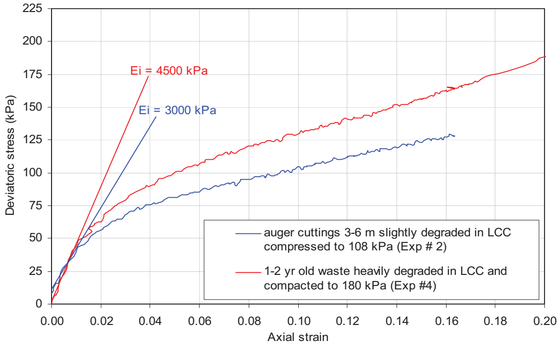

FIG. 1. Effect of degradation and consolidation on stress-strain behaviour of municipal waste (both samples tested in triaxial cell at cell pressure = 150 kPa)

CONCLUSION

A considerable database is developing regarding the mechanical properties of municipal solid waste. Table 2 presents the key mechanical properties and the likely effect on each as a result of some important key factors. It is suggested that the unknowns represented by blanks in Table 2 might represent "knowledge gaps" worthy of research. It is further proposed that an index value might be developed based on known attributes of a given waste mass and the likely effects of the various factors. Based on a preliminary consideration of the interaction of these factors, the author proposes that an index value might easily be determined for a waste mass. Given the anticipated effect of the various factors, such an index might be of the form:

$$I_W = \frac{C \cdot A \cdot S \cdot R}{O \cdot (A \cdot W)^k}$$

where I_W represents the index value ("Wasticity Index"?) and C,O,A,S,W,R are the various factors that are known or may be easily estimated. Obviously the form of such an index value merits considerable discussion and the author looks forward to the advice and input of many experienced and knowledgeable colleagues.

Table 2. Factors influencing mechanical properties of waste

Effect of increasing: →	Compaction	Organic Content	Age	Cover Soil	Amount of moisture	Fraction reinforcing material
	C	O	A	S	W	R
values for each factor	1 light 3 heavy	1 VS<30% 3 VS >60%	decades	vol fraction corr for type	1 dry 3 wet	?
Unit Weight	incr.	decr.	incr.	incr.	incr.	decr. ?
Shear Strength	incr.			soil type		incr.
Compressibility	incr.	incr. ?		decr. ?	incr. ?	
Horizontal stress						decr. ?
Hydraulic Cond.	decr. ?		decr.		decr. w time	

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Waste Mechanics Research Needs

Ikuo Towhata[1]

[1]Professor, Department of Civil Engineering, University of Tokyo, 7-3-1, Bunkyo, Tokyo 113-8656; towhata@geot.t.u-tokyo.ac.jp

INTRODUCTION

Municipal solid waste became a target of engineering studies merely a few decades ago when the size of cities became large and the amount of waste increased due to goods-consuming life styles. Most studies so far have addressed environmental issues so that ground water may be protected from pollution and odor as well as insects may be reduced. In this paper, the author would like to state that there are different problems concerning municipal solid waste that should be solved from a mechanical perspective.

The first problem is a collapse of waste landfill that is triggered by heavy rainfalls. The collapse may kill people who are living nearby and hence there is a need to mitigate this waste hazard. This problem is particularly important in mega cities of developing countries where the population is increasing rapidly and efforts for mitigation are not adequate. The second problem is the reuse of closed landfill areas. This idea comes from the situation in Tokyo, particularly, that lacks space resource for future development.

SAFETY PERSPECTIVE

One of the most famous collapses of landfill is the one in Payatas, the Philippines, that claimed more than one thousand lives of people living nearby. A similar collapse was triggered by heavy rainfall in the Leuwigajah landfill of Bandung, Indonesia, in 2005. This event killed 146 people who were living in the downstream area of the landfill. The City of Bandung has a population of more than one million generating large amounts of solid waste. The waste had been simply thrown from the top of a valley with minor compaction.

Figure 1 shows the head scarp after the collapse. The original waste was dumped without treatment. Figure 2 is a view downwards to illustrate that the failed waste mass traveled over a long distance. This significant run-out distance claimed lives of more than 100 residents. Figure 3 illustrates houses that were located beside the flow path of waste and hence survived the collapse.

Safety measures for waste landfill and dump sites are not sufficient in many nations from both environmental and mechanical perspective. This is because of the lack of recognition of the risk and the low priority in financial support. While a construction of a high dike or dam structure is desirable for protecting the downstream area from the collapse, this expensive measure is typically not possible. In this situation, the hazardous area should be publicized so that people may be aware of the risk (hazard mapping). To achieve this goal, the mechanical characteristics of municipal waste at large deformation and flow failure have to be understood. Moreover, information on travel distance of municipal waste (Figure 4) should be collected from past experiences.

FIG. 1. **Head scarp of failure of Leuwigajah landfill in Bandung of Indonesia.**

FIG. 2. View of Leuwigajah landfill failure in downstream direction.

FIG. 3. Houses that avoided burial under waste.

FIG. 4. Collapsed waste spreading toward rice field.

The author visited the failed landfill in Bandung in February 2006, one year after the collapse. The geometric information about the failed waste mass and flow is as follows:

- The landfill was developed by dumping waste into a valley. It started operation in 1992.
- The width of the landfill and the valley was about 150 m.

- The waste was underlain by natural clay deposit.
- Heavy rainfall occurred 3 days prior to the failure.
- The gradient of the line connecting the head scarp and the tip of the waste deposit was 6 degrees, which suggests that the shear resistance of the waste was very low.
- The maximum thickness of the waste was in the range of 33 to 43 m, which was obtained by measuring the head scarp height.
- The distance between the head scarp and the front of waste was about 900 m.
- The gradient of the bottom of the sliding was 5 %.

URBAN DEVELOPMENT

Municipal solid waste landfill is one of the essentially important components of a city. In spite of this importance, the construction of a landfill often encounters resistance from local people, who are concerned about possible environmental problems. Although current environmental technologies are able to prevent contamination issues, people still are concerned. It is therefore important for municipalities to ensure the prosperity and happiness of people who kindly accepted a landfill in their vicinity.

Development of a closed landfill for an industrial and commercial purposes may trigger local economical development creating more employment opportunities for local people. The author proposes a greater scope in this opinion paper.

FIG.5. Landfill island in operation.

FIG.6. Landfill island in operation.

Tokyo has historically developed since the end of 16th Century by reclaiming the sea by either soil or municipal waste. Even today, a huge landfill island is under operation and the final area of the latest island will be 480 ha (Figures 5 and 6). It is important that this island is located in front of the downtown and next to the Tokyo Harbor. Noteworthy is that there is an international airport next to this island. From this island, road transportation is already available to the airport area and downtown. It also deserves attention that the island is fully owned by the public.

Major cities in Japan have been developing and expanding without well-organized urban plan. Hence, the lack of large open space for future development is common. In Tokyo, however, the landfill island in the harbor offers an ideal space for future urban development, because the distance from the city center is not very long and the land is owned by the government. This idea is essentially the reuse or recycling of waste (landfill) not as a material resource but as space resource.

Only problem in the waste island is the instability from both mechanical and chemical perspective. While the chemical instability, i.e. generation of methane gas due to anaerobic environment, has been studied by many geoenvironmental researchers, very few studies has been done on the mechanical stabilization of MSW. Figs. 7 and 8 illustrate a typical mechanical problem, long-term subsidence.

FIG.7. Long-term subsidence of waste ground.

FIG.8. Distortion of road pavement on embedded pipe due to subsidence.

This paper proposes the use of preloading to mitigate the long-term subsidence of the waste ground and also the use of friction piles as a foundation of a low-rise building resting on landfill. Conventional end-bearing pile is not appropriate in a landfill island because the end-bearing pile has to penetrate through a clayey soil in order to reach a firm soil and the clayey layer is used to keep leachate within the island; penetration through clay will result in environmental pollution outside the island. Thus, a pile foundation has to develop significant skin friction and, for this purpose, a nodular pile with irregular shape is suitable (Figure 9). Studies on the subsidence and soil-pile interaction are, however, insufficient for a nodular pile.

FIG.9. Shape of nodular pile.

Research Needs in Solid Waste Mechanics

Jonathan D. Bray[1], F. ASCE and Dimitrios Zekkos[2], M. ASCE.

[1] Professor, Dept. of Civil and Environmental Engineering, University of California, Berkeley, USA
[2] Assistant Professor, Dept. of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA

INTRODUCTION

Our understanding of the response of municipal solid waste to monotonic and cyclic loadings has improved significantly over the last decade. However, several important issues remain unresolved. Standardized field characterization procedures, waste sampling protocols, specimen preparation methods, and laboratory testing techniques are required if significant advances are to be made over the next decade. The profession can only advance so far if confusion regarding what was tested, how was it tested, and what the results were continues as it has in many cases. Currently, many of the inconsistencies in our understanding of the static and dynamic properties of solid waste are caused by inconsistencies and uncertainty in waste properties characterization procedures and testing or reporting protocols.

The first “International Waste Mechanics Symposium” will hopefully address these issues as well as other important issues and provide a common framework for advancing the profession’s understanding of waste properties and mechanics through developing consensus on the performance and reporting of laboratory and field testing procedures. Based on limitations in our current state of knowledge of waste properties and mechanics, a number of critical needs in waste mechanics research are identified.

STANDARDIZED WASTE CHARACTERIZATION PRACTICES

There is a great need for the development of commonly accepted waste characterization practices, waste specimen preparation techniques, waste testing procedures, and a framework to report and to evaluate the results of field and laboratory testing programs. Common restrictions to utilizing the published results of waste testing studies include:

- Many studies do not report a sufficient amount of important information to enable one to use the presented data. Information on the field performance of solid waste landfills, or on the preparation and laboratory testing conditions of waste specimens, or on the waste characterization procedures utilized in the study is often incomplete.

- There are significant variations in the definition of some properties of MSW. As an example, there is no commonly accepted, universally applied definition of the moisture content of waste. This is a basic term that is required to help characterize the state of the waste. The waste's water content should be established at a standard heating temperature, and be clearly defined with respect to the amount and type of material to be tested. Depending on the heating temperature, but particularly, depending on the type of waste material that is tested (e.g., soil-like fraction, paper, plastic, or wood), significantly different values may be reported for the moisture content of waste. Similarly, the basic measure of the waste's organic content depends greatly on these types of factors, and it too is currently poorly defined. For example, the organic content of waste material that is smaller than 20 mm was found to be about 10-20%, but the "organic content" (loss of material at 440^{o}C) of wood was 84% and of paper was 60% for one case (Zekkos 2005). Such is also the case for other waste properties as well. For example, different definitions of the "peak" shear strength of waste have been proposed. Various definitions of waste strength include a limiting strain criterion, the mobilized stress at the maximum achieved strain or displacement, and the peak shear stress, regardless of the level of strain.
- There are deviations in the procedures used for the waste characterization and specimen preparation procedures. These deviations are so significant that it is often difficult to compare the results from different studies to develop meaningful findings.

The waste mechanics discipline is at the point where standardized waste characterization procedures are required if we are to advance the current state of understanding. Therefore, the development of a standardized, widely accepted and applied waste characterization framework is the top research need at this time.

FIELD INVESTIGATIONS

The research on municipal solid waste completed by Zekkos (2005) and Zekkos et al. (2005) has advanced an attractive methodology for performing and reporting field investigations of waste materials. After evaluating waste characterization procedures proposed by several engineers, and in particular the Standard Operation Procedures developed by Geosyntec Consultants to characterize waste at the OII Landfill in Los Angeles, California, and working through similar issues in their study of waste materials at the Tri-Cities landfill in Fremont, California, they provide methodologies that can be used as a starting point in the development of standardized methodologies for performing and reporting field investigations of waste materials.

The proposed waste characterization procedure includes three stages, which entail in situ waste characterization, primary geotechnical waste characterization, and secondary geotechnical waste characterization (Zekkos 2005; Zekkos et al. 2005). During drilling/trenching and waste sampling operations at a landfill, useful qualitative information is collected in the first stage. This includes descriptions of the composition, temperature, age, moisture, and degradation state of the waste. The second stage divides waste materials into those materials that are retained on the 20 mm (3/4 inch) sieve and those materials that pass through this sieve. The latter materials can be characterized and tested using conventional soil mechanics index property tests, such as sieve analysis, moisture content, and organic content. The relative by weight fraction of material greater and less than 20 mm is useful for describing the waste, as well as physical descriptions of the waste, such as color and amount of degradation. In the final stage of the proposed procedure, the material that is larger than 20 mm is categorized into its primary constituents, which include paper, soft plastics, wood, bricks, concrete, metal, glass, and tires.

One of the most important field measurements to perform at a solid waste landfill is to measure the unit weight of the waste. This is a basic property of utmost importance in many static and seismic stability assessments. Although there are significant variations in the unit weight of waste, the work by Zekkos et al. (2006) provided a useful framework for interpreting a landfill-specific characteristic unit weight profile. It is hoped that other engineers will employ this framework to characterize the unit weight of waste at other landfills in different areas of the world so that the recommendations resulting from their work can be generalized. In this paper, recommendations were provided regarding how best to measure the unit weight of waste, and it is also hoped that these procedures will be utilized (or modified if necessary with full documentation of the modifications) so that the profession has a common method for measuring the unit weight of waste.

Tremendous advancements have been made in measuring the stiffness of waste through shear wave velocity measurements. The Spectral Analysis of Surface Wave (SASW) technique and similar types of surface wave measurement methods are especially advantageous for measuring the shear wave velocity of waste (e.g., Kavazanjian et al. 1996), because these methods do not require boreholes, provide robust measurements, and are cost-effective. Additional shear wave velocity measurements are required at many landfills that are operated in different environments with differing waste streams to allow for generalization of the results from the relatively few studies that have been performed on waste landfills. Given the importance of the shear wave velocity property of waste in dynamic analyses, it is hoped that landfill operators and their consulting engineers will be motivated to perform these additional studies. Field estimates of the small-strain material damping of waste are less reliable and further work is warranted in developing cost-effective, reliable methods for estimating this important waste property.

Large strain stress-strain and strength properties of waste can be evaluated through carefully performed plate load-type field tests at waste landfills. Unfortunately, these types of tests are relatively expensive and time consuming and are generally limited to characterizing shallow waste at low confining stress. Improved field measurement procedures are required to provide stress-strain and strength property information for waste materials throughout the entire thickness of an existing landfill. There are several obstacles to applying technologies analogous to pressuremeter tests in the field, but additional work on such efforts is warranted. Testing size effects and sample disturbance will remain important issues that will need to be addressed satisfactorily in these studies.

LABORATORY INVESTIGATIONS

An extensive investigation of the monotonic and cyclic response of MSW through large-scale laboratory testing was performed as part of a NSF-funded collaborative research program. Systematic trends were identified for the waste samples collected from the Tri-Cities landfill that varied in age from less than 2 years old to 15 years old at the time of drilling (Zekkos 2005, Zekkos et al. 2008, Lee 2007). There is a need for additional comprehensive testing of waste at other landfills with significantly different operating practices or waste stream compositions.

The stress-strain response of the MSW was found to be significantly affected by waste composition, particularly the amount and type of fibrous waste material (Zekkos et al. 2007). The larger waste fraction typically consists of three broad categories of fibrous materials: paper, soft plastics and wood that are significant both in terms of their volume and weight. Research findings in reinforced soils, which have significant analogies to waste materials, indicate that these three types of reinforcement, which have significantly different physical and mechanical properties, should affect the waste response in different ways (e.g., Shewbridge and Sitar 1989; Gray and Ohashi 1983). The stiffness and strength of the fibrous waste will have an impact on the specimen's response. A systematic laboratory investigation could reveal how each of these three principal types of reinforcement affects the stress-strain response and shear strength of waste.

The stress-displacement response of MSW in direct shear was found to be significantly affected by the relative orientation of fibrous materials and the horizontal shearing surface. The fibrous materials were found to have a tendency to be horizontally oriented during specimen preparation, and when sheared in direct shear, the fibrous materials did not participate significantly in the stress-displacement response (Zekkos et al. 2007). As a result, typical direct shear tests on MSW are likely conservative and provide an estimate of the MSW shear strength along the weakest orientation. Direct shear tests performed with fibrous materials oriented parallel and perpendicular to the horizontal failure surface revealed significant differences in the response, with higher shear strengths for waste with fibrous materials oriented perpendicular to the failure surface. Hence, these test results confirmed the analogy to the response of reinforced soils. A careful examination of the response of reinforced soils, combined with tests on waste with different relative fiber orientations, such as the recent tests performed by Athanasopoulos et al. (2008) will provide useful information on the mechanics and the structural anisotropy of waste material. Tests with different types of fibrous waste materials oriented at different angles to the failure surface within different waste matrices at different water contents will yield additional important insights.

The effects of waste degradation need to be studied further. Some previous studies have indicated differences in older waste, and these differences were often attributed to waste degradation. However, older waste may also be different than younger waste due to changes in waste streams and operation procedures, and such differences should not necessarily be attributed to only waste degradation. Tests performed on waste from the Tri-Cities landfill, which varied in age from less than 2 yrs old to 15 years old, did not indicate significant differences either in the monotonic or the cyclic response of waste. In this case, however, although there were some visual differences between the younger and the older waste, the older Tri-Cities waste was not considered to be highly degraded. Monotonic and cyclic tests performed on old, degraded waste are required, and a comparison with the laboratory test results of waste at other landfills, where waste was not highly degraded, is warranted. The water content of waste will also likely be an important factor over time. This is particularly true for cases in which the moisture content is above field capacity (e.g., at bioreactor landfills or when the waste becomes submerged and fully saturated). Also of interest to engineering practice is the evolution of waste properties over time at an existing landfill due to the addition of liquids.

NUMERICAL ANALYSES

Comprehensive investigations of the static and seismic response of solid waste landfills using the advances in our understanding of waste properties from recent field and laboratory testing studies are warranted. Tremendous advancements in the profession's understanding of the static and seismic performance of solid waste landfills are possible as reliable, well calibrated, analytical procedures are employed to investigate critical landfill performance issues.

An unresolved issue at this time is the assignment of appropriate strain-compatible strength parameters for waste, for the individual components of the containment system and their interfaces, and for the shear strength of a weak foundation. Such strength estimates need to account for strain incompatibility and progressive failure in solid waste landfill system. Much has been learned on the stress-strain (or stress-displacement) response of the waste material and the containment system components in recent years, and advanced nonlinear numerical simulations that can reliably model response of each material and interface in the system, which is well calibrated against test results and case histories, could provide great insight regarding the development of sound criteria for the selection of stiffness and strength parameters of waste.

Similarly, re-evaluations of the seismic response of solid waste landfills using recently published information on the dynamic properties of MSW (e.g., Lin et al. 2004, and Zekkos et al. 2008) are warranted. Previous studies involving dynamic analyses of waste landfills have been made (e.g., Bray and Rathje 1998), but our understanding of waste mechanics has improved significantly in the last decade. Laboratory estimates of waste properties need to be evaluated by re-examining well documented case histories of field performance, due to possible particle size scale effects with laboratory testing. With reasonable waste properties and sound analytical procedures, the seismic performance of different landfill configurations should be studied to identify potential failure mechanisms and enhance our understanding. The potential for ground motion amplification (or de-amplification) needs to be evaluated using the revised dynamic properties, and the effects of waste material properties on the seismic slope stability of landfills should be re-evaluated.

CONCLUSIONS

The profession's understanding of the mechanical response of municipal solid waste (both monotonic and cyclic) has improved significantly over the last decade. Yet, several important questions remain unanswered as our treatment of waste properties becomes more sophisticated. Standardized field characterization procedures, waste sampling protocols, specimen preparation methods, and laboratory testing techniques are required if significant advances in waste mechanics research are to be made over the next decade. The waste mechanics discipline is at the point where standardized waste characterization procedures are required. Therefore, the development of a standardized, widely accepted and applied waste characterization framework is the top research need at this time. There are a myriad of other issues to investigate further, such as the use of advanced field and laboratory testing equipment and procedures, but the transfer of knowledge of waste property information is currently hindered by the lack of standardized, widely accepted methods for characterizing and testing waste.

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Author Index

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Subject Index