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Engineering properties of municipal solid waste

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Abstract

Mechanical behaviour of the waste body controls many aspects of landfill lining system design and performance, including stability issues and integrity of the geosynthetic and mineral lining components. Knowledge of the likely ranges of waste mechanical properties is required to assess potential modes of failure and hence to design the landfill engineering measures. This paper provides a summary of measurement and interpretation issues for the key engineering parameters used to define: unit weight, compressibility, shear strength, lateral stiffness, in situ horizontal stress and hydraulic conductivity. The topic of waste mechanics is developing rapidly and many papers have been published on waste mechanics, reporting results from both laboratory and in situ studies. Although waste is heterogeneous, many of the studies show that municipal solid waste has mechanical properties that vary in a consistent and predictable way (e.g. with respect to stress state and method of placement). An internationally agreed classification system and test standards are required to allow interpretation of published results. This will lead to development of appropriate constitutive models for waste and hence to optimization of landfill designs by considering waste/lining system interaction in full.

Keywords: Landfill engineering; Waste mechanics; Lining systems

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1. Introduction

1.1. Why is knowledge of waste mechanics important?

Geosynthetics form an integral part of modern landfill lining systems. Geomembranes and Geosynthetic Clay Liners (GCL) are used as barriers to leachate and gas, often in composite behaviour with compacted clay mineral layers. Geotextiles and geocomposite drainage materials are used as protection, separation and drainage layers. While the use of geosynthetics brings many benefits (e.g. ease of placement, uniform quality controlled predictable properties) they are also susceptible to damage leading to loss of function and their use introduces potential failure planes at interfaces between components (e.g. geosynthetic/geosynthetic and geosynthetic/soil). These can result in large-scale instability of the lining system and contained waste body. Behaviour of the waste body is a controlling factor in both the stability, ultimate limit state, of engineered landfill structures (e.g. large-scale movements leading to collapse) and integrity, serviceability limit state, of lining components (e.g. geomembrane and mineral barriers can be punctured/sheared and geotextile protection layers/geocomposite drains can be damaged and/or become discontinuous). Fig. 1 summarizes modes of landfill failure in which the waste body plays a role. Knowledge of engineering properties of waste is required to assess each mode and hence to design against their occurrence. Design of lining systems, including geosynthetic components, cannot be carried out without considering the lining system/waste body interaction.

Failures of landfills, although not common, occur on a regular basis in countries around the world. They include landfills incorporating geosynthetic materials and designed using common practices. Koerner and Soong (2000) and Jones and Dixon (2003) provide information on a range of landfill failures. High profile failures include: Kettleman Hills, USA (Seed et al., 1988; Byrne, 1994), Bulbul Drive, South Africa (Brink et al., 1999), Cincinnati, USA (Eid et al., 2000; Stark et al., 2000), Dona Juana, South American (Hendron et al., 1999) and Payatas, Philippines (reported in international media, 2000). There are many other failures that do not get reported. In addition to concerns about large-scale stability failures involving the waste body, designers must also consider interaction between the lining system and waste body. To do this, designers are increasingly using numerical modelling techniques. These require a constitutive model to represent the waste body behaviour (e.g. stiffness and shear strength). A common use of numerical modelling is to investigate the potential development of post-peak shear strengths on side slope lining component interfaces resulting from waste settlement (e.g. Long et al., 1995; Filz et al., 2001; Jones and Dixon, 2005). These types of analyses aid the selection of interface shear strength parameters for use in conventional stability assessments and allow investigation of potential integrity failure mechanisms (e.g. loss of geotextile protection to a geomembrane).

While it is not possible to fully characterize the engineering properties of waste due to its heterogeneous nature, it is important that its basic behaviour is understood and that likely ranges of the key engineering properties are known. Table 1 lists the

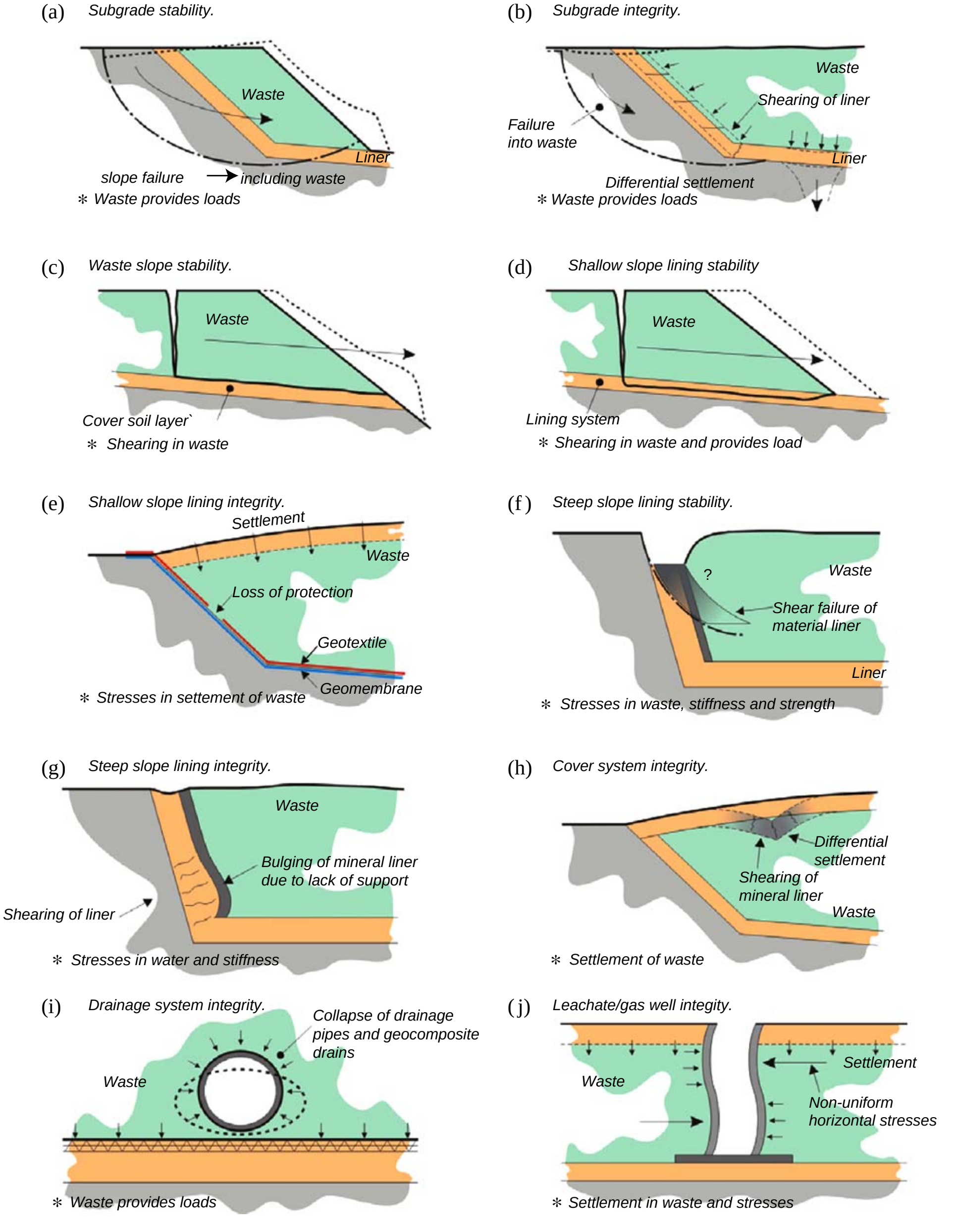

Fig. 1. Potential landfill infrastructure failure modes: stability and integrity.

properties required to perform an analysis of each of the failure modes summarized in Fig. 1. This paper reviews engineering behaviour of municipal solid waste (MSW) with respect to the information required for design. A brief summary is provided for

Table 1
Engineering properties of MSW required for design

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

each of the main engineering properties. References are made to key publications, methods of measurement and calculation are summarized, and where possible, typical ranges of values are given.

1.2. Material description

MSW is a mixture of wastes that are primarily of residential and commercial origin. Typically, MSW consists of food and garden wastes, paper products, plastics, rubber, textiles, wood, ashes, and soils (both waste products and material used as cover material). A wide range of particle sizes is encountered ranging from soil particles to large objects such as demolition waste (reinforced concrete and masonry). The proportion of these materials will vary from one site to another and also within a site. Life style changes, legislation, seasonal factors, pre-treatment and recycling activities result in a changing waste stream over time. Examples are increasing plastic and decreasing ash content over the past few decades in developed countries (e.g. Fig. 2). In addition, member states of the European Union will see a reduction in biodegradable waste in landfills through the introduction of Biodegradable Municipal Waste diversification targets in the Council of European Community (1999). It should be noted that the composition of MSW varies from region to region and country to country. For example, developing countries often have waste streams that contain more biodegradable material and less plastics, and countries such as Germany with well developed re-cycling and pre-treatment policies (e.g. the use of mechanical and biological pretreated waste), have wastes with less biodegradable content and a more uniform and consistent grading. These variations produce fundamental and significant differences in waste engineering behaviour and they must be taken into consideration when using results from the literature.

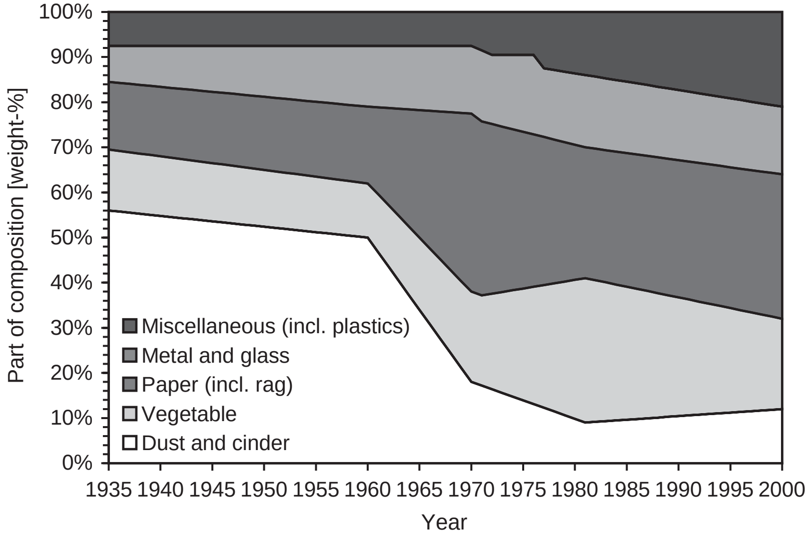

Fig. 2. Composition of UK MSW 1935–2000 (after Watts et al., 2002).

1.3. Waste mechanics

The current understanding of waste behaviour is far from being complete. For engineering the disposal of waste, researchers and practitioners have relied on their knowledge of the behaviour of soils. Although this has been helpful to some extent, there is an increasing realization that behaviour of waste should be considered in the context of a separate discipline of waste mechanics (also referred to as waste geotechnics). As a starting point, it is appropriate to compare some of the results from preliminary and novel studies on waste properties available in the literature with those of geological and engineered materials, e.g. granular soils, peat, reinforced soil. Similarities and differences in measured behaviour can then lead to the development of laboratory and field tests specifically for obtaining engineering properties of MSW. An increasing number of international researchers are investigating engineering behaviour of waste and its interaction with engineered containment systems.

Evaluating the engineering properties and hence behaviour of MSW bodies is challenging due to the variety of materials present. It is preferable to undertake testing on real materials in an undisturbed state. However, this is not always possible. Undisturbed samples cannot be taken and therefore laboratory tests have to be on disturbed material that is re-compacted into test apparatus. MSW can be highly structured material resulting from the method of placement and this structure will be destroyed. In addition, variation in composition between samples can be extreme, making it difficult to quantify the contribution to behaviour of the different components of waste or mechanisms of behaviour. It is also difficult to systematically change the proportion of waste constituents in order to investigate the role each plays. This is required in order to evaluate the impact of future changes in waste composition. Additional considerations are the very large size of test apparatus required to accommodate large particles, and health and safety requirements that dictate tests on real waste have to be carried out in a controlled laboratory environment. These are both expensive to construct and operate. An additional major factor is that engineering properties of waste vary with time due to the degradation process. At present there are no internationally accepted standard sampling and testing procedures for waste materials. In addition, there is presently no accepted guidance on selection of appropriate values of the engineering parameters for use in design, or agreed approaches for assessing waste behaviour as part of the design process.

1.4. Waste classification

There are a number of general waste classification systems in common use, and these have been developed to provide information for specific end uses, e.g. recycling/waste minimization, assessment of biodegradation potential and calorific value. However, for assessment of engineering behaviour a classification is required that groups waste constituents in terms of their mechanical properties. In a typical landfill there will be three distinct phases present—solid, liquid and gas. There may also be a need to distinguish between mobile liquid in large drainable pores and liquid in small pores (inter-particle), and liquid that is trapped, absorbed or otherwise bound to the solid fraction (intra-particle). The information required to classify waste components can be summarized as:

- Knowledge of component shape to distinguish between soil-like (three-dimensional, e.g. granular) and non-soil-like (two-dimensional, e.g. foils) components. This allows classification of components in relation to their potential for influencing mechanical behaviour of the waste mass (e.g. shear strength).
- Grading by size for each group of components.
- A distinction between the material groups (i.e. based on material properties—metal, paper, plastic), with dominant groupings established, in conjunction with information on the proportion (e.g. by weight) of the material groups in relation to the size and mechanical properties of components.
- An assessment of compressibility and potential for components to change shape.
- An assessment of degradation potential for both organic and inorganic components.

A number of the existing engineering classification systems are simply based on material groups (Siegel et al., 1990) or on the distinction between soil-like and non-soil-like, or fibrous, appearance (Manassero et al., 1996; Thomas et al., 1999). These existing classification systems do not fulfil the requirements of a rigorous classification framework. Table 2 provides a summary of classification systems including the parameters defined. A new classification framework for MSW that fulfils the requirements listed above has been proposed by Langer and Dixon (2004).

Table 2
Overview of existing classification systems

Author	Key classification criteria	Parameters
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 and inorganic materials	Degradability (easily, slowly, non) Shape (hollow, platy, elongated, bulky)
Grisolia et al. (1995a)	Degradable, inert and deformable material groups	Strength, deformability, degradability
Kölsch (1996)	Material groups	Size, dimension
Manassero et al. (1996)	Soil-like and other	Index properties
Thomas et al. (1999)	Soil-like and non-soil-like	Material groups

Further work is required to trial this classification on a range of waste types and to relate classifications to mechanical behaviour of the waste body.

1.5. Literature on MSW engineering properties

There is a growing body of literature on the measurement of engineering properties of MSW. Unfortunately, due to the lack of both agreed classification system and test standards it is difficult to interpret published results. Often the nature of the waste tested is not described in any detail and the test boundary conditions are rarely given. This makes it difficult to amalgamate the results into a common framework or to apply findings to other sites. This review concentrates on the key parameters of unit weight, compressibility, shear strength, lateral stiffness, in situ horizontal stress and hydraulic conductivity. Where possible, the variation of these parameters with time is also considered. This review has benefited from publications by Landva and Clark (1990), Fassett et al. (1994), Manassero et al. (1996), Eid et al. (2000), Chapter 6 of Qian et al. (2002) and Kavazanjian (2003), each of which was written to summarize the state-of-the-art.

2. Unit weight of MSW

As shown in Table 1, knowledge of unit weight is required for all aspects of landfill design, and therefore it is surprising that so few detailed studies have been conducted. Unit weight values vary significantly both between sites and within a single site. MSW has highly variable components, types and amounts of cover soil differ between sites, the percentage of inert and industrial wastes varies and placement procedures play an important role, as do environmental conditions (e.g. rainfall). Common difficulties in assessing MSW unit weight have been summarized by Fassett et al. (1994) as: separation of the contribution of daily soil cover; assessing the changes in unit weight with time and depth; the majority of reported values reflect waste near or at the surface; and obtaining data on the moisture content of the waste. Fassett et al. (1994) considered that the following factors should be recorded along with measured unit weights: MSW composition including daily cover and moisture content; method and degree of compaction; the depth at which the unit weight was measured; and the age of the waste. The form of the unit weight measurement should also be recorded and noted by those using the data. Values can be given as dry unit weight (sample could have been artificially dried), bulk unit weight (some moisture present but waste not saturated) and saturated unit weight. In most studies it is the bulk unit weight that is measured and reported.

2.1. Unit weight estimation methods

Unit weight can be estimated and measured using several techniques. These are summarized in Table 3. Methods based on direct field measurement are considered to be the most reliable as the influence of waste placement is considered as is the overburden stress in some methods. Most of the information in the literature relates to recently placed waste at low overburden stresses.

2.2. Factors affecting unit weight of waste

As with soils, the unit weight is affected by compaction effort and layer thickness, the depth of burial (i.e. overburden stress) and the amount of liquid present (moisture content). Unlike soils, the unit weight also varies significantly because of large variations in the waste constituents (e.g. size and density), state of decomposition and degree of control during placement (such as thickness of daily cover or its absence). It is generally believed that initially the unit weight of waste is very much dependent on waste composition, the daily cover and the degree of compaction during placement. But as the waste becomes older the unit weight becomes more dependent on the depth of burial, the degree of decomposition and climatic conditions. Although unit weight can vary significantly over short distances, this is not necessarily a major concern in design. Unit weight is used to calculate vertical and horizontal stresses. Average values of unit weight are acceptable in most design scenarios (e.g. average values of vertical stress acting on a basal geomembrane are used to design geotextile protection layers).

2.3. Waste components

Waste components have a controlling influence on the average unit weight of the waste mass. Individual waste components have a wide range of particle unit weights and these can change with time. Components may have voids within them in addition to those between components. This results in a significant percentage of waste particles behaving differently to soil particles due to their high compressibility. Degradation of components with organic content will result in a loss of mass,

Table 3
Methods for measuring unit weight

Location	Method of measurement	Comments	References
Field	• Large-scale replacement density measurements from waste surface	• Reliable but tests are all at low vertical stresses	Gotteland et al. (2002)
	• Replacement density measurement in boreholes	• Reliable and data obtained for a range of vertical stresses	Kavazanjian et al., (1995)
	• Gamma ray logging of boreholes	• Variable results due to range of particle types	—
	• Direct measurement of vertical stresses within waste body	• Reliable and shows changes related to vertical stress	Gourc et al. (2001)
	• Calculation from landfill volume and weight of waste materials	• Average values obtained are of little use	—
Laboratory	• Measurement of large-size samples	• Disturbed sample but large size and range of vertical stresses possible	Powrie and Beaven (1999)
	• Measurement of small-size samples	• Disturbed often pre-treated and sorted, unreliable	—
	• Measurement of individual component weights and percentages present in sample	• Time consuming and often inaccurate	—

changes in size and alteration of the mechanical properties (i.e. compressibility and shear strength). It will also change the density of the component. As a waste body degrades, void ratio reduces and hence a volume reduction occurs. Although there are few field measurements in degraded waste it is generally believed that degradation results in an increase in waste density, and hence unit weight.

2.4. Compaction

Since MSW is a particulate material and a large proportion of the components have a high void ratio and a high compressibility, compaction processes will reduce the voids within an individual component as well as voids between various components. The unit weight of compacted waste will depend upon the waste components, thickness of layer, weight and type of compaction plant and the number of times equipment passes over the waste. A layer thickness of 0.5–1.0 m will facilitate the achievement of good compaction and hence high unit weights, however it is not untypical for waste to be placed in layers of 2–3 m thick. This results in poor-to-moderate compaction. Fassett et al. (1994) conducted a detailed survey of bulk unit weight data from the international literature. A statistical analysis of the data is shown in Table 4. The degree of compaction was derived from an assessment of individual site practices. Poor relates to little or no compaction, moderate to 'old' practices and good to 'current' (1994) practices. The assessment was in most cases subjective but provides a useful guide. An important result is the large variation in unit weight when little or no compaction is used. Landva and Clark (1990) and Oweis and Khera (1986) report similar ranges of bulk unit weights. A summary of measured values from recent studies conducted in four countries is provided in Table 5. These are also consistent with the Fassett et al. (1994) reported values and indicate that current practice is still only achieving 'moderate' levels of compaction for placement of fresh MSW.

2.5. Depth

Unit weight of waste varies with effective stress, which is a function of depth. Fig. 3 produced by Powrie and Beaven (1999) shows the variation in dry density, saturated density and density at field capacity with vertical effective stress. The data was obtained by compressing samples of waste in a large diameter cylindrical tests

Table 4
Statistical summaries of bulk unit weight data for fresh waste (Fassett et al., 1994)

	Poor compaction	Moderate compaction	Good compaction
Range (kN/m^3)	3.0–9.0	5.0–7.8	8.8–10.5
Average (kN/m^3)	5.3	7.0	9.6
Standard deviation (kN/m^3)	2.5	0.5	0.8
Coefficient of variation (%)	48	8	8

Table 5
Bulk unit weights from international literature

Country	Measured bulk unit weights (kN/m^3)	Comments	References
United Kingdom	6	• Compacted in 2 m lifts using steel wheeled 21 tonne compactor	Watts and Charles (1990)
	8	• 0.6 m lifts using same compactor as above	
Belgium	5–10	• Common compaction practice	Manassero et al. (1996)
France	7	• Upper layers of fresh (non-degraded) MSW	Gourc et al. (2001)
USA	6–7	• Fresh MSW after initial placement	Kavazanjian (2001)
	14–20	• Degraded waste with high % of soil like material	

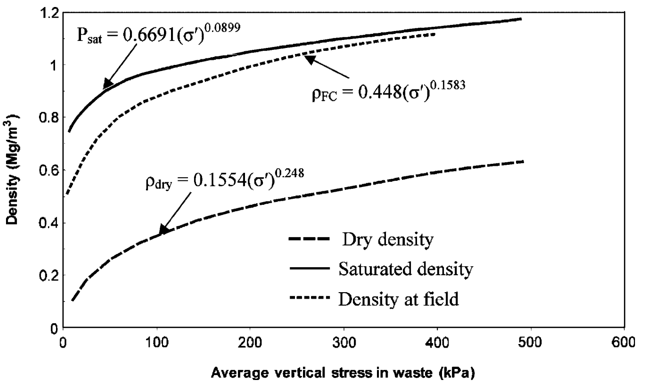

Fig. 3. Relationships between density and average vertical stress. Trend lines shown are based on average measured values (after Powrie and Beaven, 1999).

chamber. One of the implications of this work, in terms of the waste density achieved, is that compaction at the tipping face can have a similar effect to the burial of the waste by several meters of overburden (Powrie et al., 1998). Due to the difficulties and costs involved there are few field measurements of unit weight variation with depth. Gourc et al. (2001) present initial data obtained during filling of the Torcy landfill in France. The results shown in Fig. 4, as bulk unit weight against overburden stress, demonstrate a clear trend of increasing unit weight with stress level.

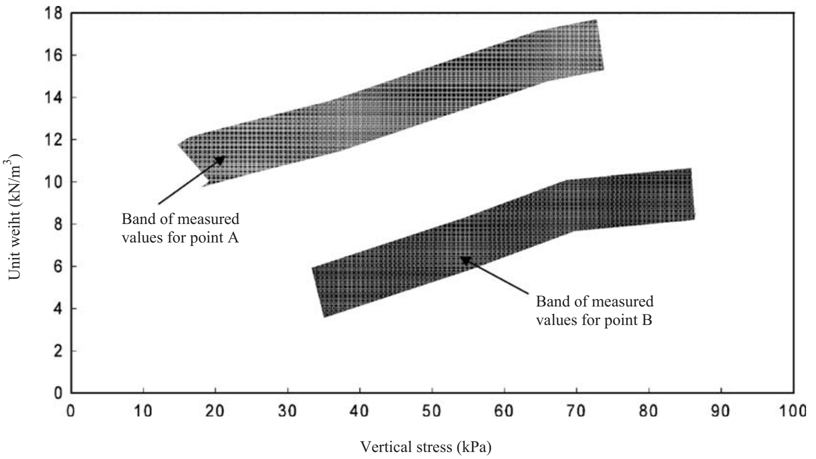

Fig. 4. Bands of measured bulk unit weights plotted against vertical stress (after Gourc et al., 2001).

2.6. Moisture content

Moisture content of waste depends on the initial waste composition, local climatic conditions, operating conditions, rate of decomposition and organic content. On exposure to water, the unit weight of any constituent absorbing water would increase (e.g. that of food waste, garden refuse, paper, textiles) due to increased moisture content of the intra-particle voids. These increases in individual particle unit weight are added to the increase in bulk unit weight resulting from increased leachate in the void spaces between particles of waste to produce increases in the bulk unit weight of the waste mass. Therefore, older waste would be expected to have a higher bulk unit weight than fresh waste. Although there is limited field evidence to support this proposed mechanism, the data from investigations such as those described by Kavazanjian (2001) provide some corroboration. Daily cover soils play an important role in controlling the amount and distribution of precipitation that enters waste. They result in highly structured waste bodies (i.e. horizontal layers of waste bounded by often low permeability layers of cover soils) and this can cause large spatial variations in the moisture content of waste. The phasing of final cap construction also influences the evolution of moisture content changes. Addition of liquid wastes and re-circulation of leachate will both have a fundamental influence on the magnitude and distribution of moisture contents, and hence on the magnitude and distribution of bulk unit weight.

3. Compressibility

The compressibility of MSW has been studied for many decades. Studies of settlement have been conducted to improve the efficiency of waste placement, predict final settlement profiles for the cap and to enable assessment of interaction between side slope barrier systems and the settling waste body (Section 1.1). This section provides a brief summary of methods used to calculate settlements and, where possible, ranges of typical values. Readers interested in more detailed information on settlements are recommended to review the key technical papers by Fassett et al. (1994), Manassero et al. (1996), Oweis and Khera (1998) and Gourc et al. (1998).

3.1. Calculation of vertical stress

It is usually assumed that traditional principles of soil mechanics theories of settlement can be applied to solid waste. The unit weight, γ, of a deposit increases with depth as discussed previously. The overburden pressure, σ, at a given depth, z, is

$$\sigma = \int_0^z \gamma \, \mathrm{d}z. \tag{1}$$

To take into account stress-dependent unit weight, the overburden pressure can be calculated using

$$\sigma = \sum_{i=1}^{n} \gamma_i z_i, \tag{2}$$

where unit weight, γ, is assumed to be constant within a given layer i and n is the number of layers.

3.2. Compression mechanisms

Mechanisms resulting in compression of waste have been summarized by Manassero et al. (1996) and are listed in Table 6, as are the interrelated factors affecting the magnitude of settlement. It can be assumed that the total settlement, δ_t,

Table 6
Waste compression mechanisms (Manassero et al., 1996) and factors controlling magnitude of settlement

Mechanisms resulting in settlement	Factors controlling magnitude of settlement
• Physical compression and creep (mechanical distortion, bending, crushing and re-orientation of particles) • Raveling settlement (migration of small particles into voids between large particles) • Collapse of containers and bridging components (physical/chemical changes such as corrosion oxidation) • Decomposition settlement (biodegradation of organic components) • Settlement of subgrade under applied waste loading	• Initial composition of waste (grading, particle shape, material properties of components, e.g. metal, paper) • Initial density and voids ratio • Layer thickness • Type, thickness and number of cover soil layers • Stress history (pre- and post-filling mechanical treatment) • Leachate levels and fluctuations • Environmental controlled factors (moisture content, temperature, gas generation) • Compressibility of subgrade

(excluding any contribution from the subgrade) is made up from two main components; primary compression (δ_p) and secondary compression (δ_s)

$$\delta_t = \delta_p + \delta_s. \tag{3}$$

Primary compression includes physical compression of particles (distortion, bending, crushing and particle orientation) and consolidation (significant for saturated waste bodies). In most wastes, physical compression will occur immediately on application of load (i.e. in response to placement of overlying layers of waste). Therefore, primary compression will occur in a period of a few days to a few weeks and hence can be considered to be short term. Incrementally linear compression models can be used to calculate primary settlements (Section 3.3).

Secondary compression includes all creep effects (i.e. mechanical compression under constant stress) and those relating to degradation (both chemical and biological). Creep effects include time-dependent particle distortion (i.e. bending, crushing), particle reorientation and raveling. Degradation includes collapse of containers due to a change in strength (e.g. corrosion) and degradation of organic compounds. Degradation potential of components is discussed by Landva and Clarke (1990) and is a key element of any classification system. Biodegradation is the main component of secondary compression in MSW landfills. Many methods have been proposed to characterize and predict secondary compression. The degradation process is influenced by a range of interrelated factors, all of which vary spatially within a landfill and with time (e.g. moisture content, temperature and stress level). Present methods of prediction are simplistic and many rely on curve fitting techniques. A brief introduction to calculation methods is provided in Section 3.4. Secondary compression occurs throughout the active life of the landfill and is usually the main component of total settlement.

3.3. *Primary compression*

The principal source of loading is self-weight, which results in waste settlement during construction. Waste placement can be considered to be a one-dimensional compression problem (e.g. waste is placed over a large area in relation to the thickness of the deposit). An increment of vertical effective stress $\Delta\sigma'_v$, produces an increase in vertical strain $\Delta\varepsilon_v$. Stresses are assumed to be effective for fresh waste due to its typical low-moisture content and hence strains are assumed to occur immediately on application of stress. A constrained modulus D, can be defined as

$$D = \frac{\Delta\sigma'_v}{\Delta\varepsilon_v} \text{ (units kN/m}^2 \text{ or MN/m}^2\text{)}. \tag{4}$$

The settlement during construction can be computed using

$$\delta_p = \sum_{i=1}^{n} \frac{H_i \Delta\sigma'_v}{D_i}, \tag{5}$$

where $\Delta\sigma'_v$ is the change in vertical effective stress, H_i is the thickness of the sublayer i of waste, D_i is the constrained modulus of layer i.

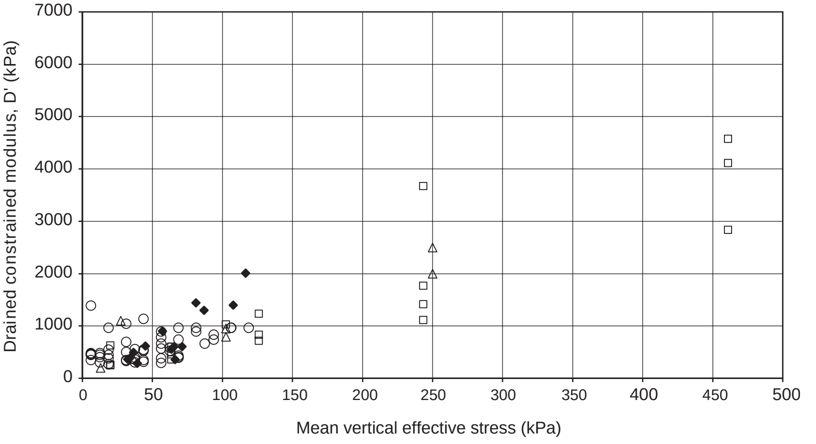

Fig. 5. Constrained modulus vs. stress level (after Dixon et al., 2004). ○ Gotteland et al. (2001); □ Powrie and Beaven (1999); Beaven and Powrie (1995); △ Landva et al. (2000) and ◆ Dixon et al. (2004).

The compression index (C_c) can also be used to relate increments of strain to increments of stress change (see Fassett et al., 1994). Primary compression will occur during waste placement. As the thickness of the waste increases the stiffness of the waste will also increase with depth. Constrained modulus is therefore not a constant but depends upon the level of mean stress in the layer under consideration. The compression of each layer is calculated separately using the relevant D value and the total primary compression is calculated as the sum of the individual layers (Eq. (5)). If the waste layer is saturated, the final primary compression will still be calculated using D but it will take place over an extended period, controlled by the permeability of the waste layer and length of the drainage path (i.e. standard consolidation theory). Note that $D = 1/m_v$ where m_v is the coefficient of compressibility in m^2/kN. Fig. 5 shows a summary of constrained moduli values for MSW related to stress level (Dixon et al., 2004). This data can be used to estimate primary compression.

3.4. Secondary compression

As discussed above, long-term settlement is mainly due to biodegradation and mechanical creep compression. It is common practice to model secondary compression using the following linear relationship on a settlement vs. log-time graph

$$\delta_s = C_\alpha H \log \frac{t}{t_p}, \tag{6}$$

where t is the time at which settlement due to secondary compression is required ($t > t_p$); t_p is the time for completion of primary compression and C_α is the secondary compression ratio given by

$$C_\alpha = \frac{\Delta\varepsilon}{\log t_2 - \log t_1}. \tag{7}$$

Table 7
Secondary compression parameters for MSW material (after Oweis and Khera, 1998)

Material	C_α
Ten year old landfill	0.02
Fifteen year old landfill	0.24
Fifteen to twenty year old landfill	0.02
Old landfill	0.04
Old landfill with high soil content	0.001–0.005

There is some field data obtained from long-term settlement monitoring studies to support this approximation. Oweis and Khera (1998) published values of C_α for a range of waste materials obtained from the literature. Table 7 shows selected values from their summary and demonstrates the problems of trying to use one C_α value for the entire period of secondary compression. As the rate of degradation is unlikely to be constant with time, it is not surprising that C_α is not a constant. Gourc et al. (1998) provide a comprehensive review of available calculation methods. Fassett et al. (1994) and Manassero et al. (1996) both give useful summaries of secondary compression data. Settlement prediction techniques based on modelling the biodegradation process are under development and appear promising (e.g. McDougall and Pyrah, 2001).

3.5. Total compression

Actual computations of total compression (i.e. settlement) can be complex. For example, to estimate the total settlement of a waste deposit, the following considerations will be necessary for each of the layers in the landfill:

- settlement of waste from self-weight (primary compression);
- settlement from the weight of each subsequent layer (including final cover) that overlies the given layer (primary compression);
- settlement due to secondary compression, taking into account that C_α is likely to decrease with age;
- settlement of the mineral basal liner (if present) due to primary and secondary compression; and
- settlement of any compressible subgrade.

Due to the heterogeneous nature of landfill constituents and their varied rates of decomposition, differential settlements occur. The problem is further complicated by the fact that adjacent cells are completed at different times and filling often takes place on top of older waste deposits. Differential settlements are important as they can jeopardize the stability of the final cap and integrity of geosynthetic elements (e.g. geomembranes) and mineral layers (e.g. compacted clay barriers).

4. Shear strength

At present there is limited information on in situ MSW shear behaviour. Shear strength of MSW is usually defined using the Coulomb failure criterion. This is commonly used in soil mechanics and in studies of other particulate materials. The shear strength parameters that define the failure envelope are the slope of the failure envelop (ϕ) and intercept on the y-axis (c). The intercept, c, can denote real cohesion between particles, but is often a function of one or more of the following: curvature of the failure envelope, variation between samples, measurement errors, or an indication of tensile strength. Therefore, it is common to define it as the 'apparent cohesion' or 'cohesion intercept'. Care should be exercised when applying experience of shearing in soils to the study of MSW. Waste contains particles that are compressible, can sustain large tensile strains (e.g. plastic) and can change with time (e.g. through degradation). An outcome of using the Coulomb criterion is that it gives an increase in shear strength with increasing stress level, based on the slope of the failure envelop, and hence with depth of burial. This is consistent with waste being considered as a frictional material.

4.1. Measurement of MSW shear strength

Table 8 provides a summary of the advantages and disadvantages associated with currently available approaches for obtaining information on shear behaviour of MSW. For the reasons outlined in Section 1.3 it is both difficult and costly to obtain representative and hence reliable strength parameters for MSW (i.e. large particle size, heterogeneity, control of structure, etc.). Therefore, it is preferable to obtain values from field studies (Kavazanjian, 2003). Back analysis of landfill slope failures, cut slope trials and existing stable slopes can provide information on the shear strength of a large mass of waste, but poor quality input data makes such analyses problematic and often unreliable. In situ techniques for measuring shear strength are presently inadequate and unreliable. An in situ technique for measuring the shear strength of MSW at a range of depths and for material with varying degrees of degradation is urgently required. Results from laboratory tests should be viewed with skepticism. The waste will have been disturbed, and hence the structure will have been lost, large particles may have been removed or processed and the in situ density and stress conditions may not have been reproduced. Many of the studies in the literature have used triaxial compression tests. Kavazanjian (2001) provides a detailed assessment and concludes that triaxial compression testing is not an appropriate technique for measuring the shear strength of MSW. Inability to cause shear failure in laboratory tests has led to shear strength being related to levels of strain (i.e. different shear strength parameters are given for each strain level). While this approach has some merit if used in design to try and control strains in the waste body, it can lead to confusion and hence great care should be taken in applying such values. The most appropriate laboratory technique is the direct shear test, although the general concerns regarding the applicability of laboratory tests discussed above still apply.

Table 8
Review of methods for measuring shear behaviour of MSW

Location	Method of measurement	Comments	References
Field	• Back analysis of slope failures	• Adequate information seldom available (e.g. pore pressures, shape and position of shear surface)	Koerner and Soong (2000)
	• Back analysis of cutting slope experiments	• Large deformations observed but not shear failure	Singh and Murphy (1990), Cowland et al. (1993)
	• Back analysis of existing stable slopes	• Changing waste composition means past experience is not a guide to future performance	Gotteland et al. (2002)
	• In situ direct shear tests	• Difficult to perform and results relate to low levels of stress	e.g. Jessberger and Kockel (1993)
	• SPT, CPT and vane tests	• No clear relationship between penetration resistance and MSW shear strength, could provide useful information in degraded more soil like materials	
Laboratory	• Triaxial compression	• Disturbed samples, peak shear strength not obtained due to compression and densification of sample	Jessberger (1994), Grisolia et al. (1995b)
	• Direct shear	• Large device required (e.g. $1 \times 1 \times 1$ m), disturbed samples, large displacements required to mobiles peak shear strength	Kolsch (1995), Gotteland et al. (2001)
	• Simple shear	• Large device required, disturbed samples, useful information on shear stiffness (used in seismic analyses)	Kavazanjian et al. (1999)

4.2. Measured shear strength values

The majority of the studies included in this review obtained strengths from direct shear box tests and back-analyses of failures. Those requiring more detailed information should read Manassero et al. (1996), Jones et al. (1997) and Kavazanjian (2001) all of which provide summaries of shear strength parameters from the literature. Table 9 gives waste shear strength parameters summarized by Jones et al. (1997) although it is by no means a comprehensive summary. It is included to demonstrate the wide variation in values that can be obtained. Given the large range of possible wastes and the difficulties involved in measuring shear strength, the large scatter is not surprising.

Manassero et al. (1996) suggested that the failure envelope shown in Fig. 6 could be used as a starting point in design if no site-specific data is available. Design values of c and ϕ are defined according to three distinct zones:

- *Zone A*: corresponding to very low stress ($0\,\text{kPa} \leqslant \sigma_v < 20\,\text{kPa}$) where the MSW behaviour can be described as being only cohesive. In this case, $c = 20\,\text{kPa}$.

Table 9
Examples of measured shear strength parameters from the literature (Jones et al., 1997)

Reference	Shear strength parameters		Method	Comments
	c' (kPa)	ϕ' (°)		
Jessberger (1994)	7	38	Not stated	Reporting Gay and Kaiser (1981)
Jessberger (1994)	10	15	Back analysis	Reporting Spillman (1980)
Jessberger (1994)	10	17	Back analysis	Reporting Spillman (1980)
Jessberger (1994)	0	30	Estimate	From field observations
Jessberger (1994)	0	40	Estimate	From field observations
Jessberger (1994)	7	42	Simple shear	Reporting Gay and Kaiser (1981). Nine month old MSW
Jessberger (1994)	28	26.5	Simple shear	Fresh MSW. Reporting Gay and Kaiser (1981)
Fassett et al. (1994)	10	23	Suggested values	Suggested by authors
Kolsch (1995)	15	15	Suggested values	Suggested by author
Kolsch (1995)	18	22	Suggested values	Suggested by author
Cowland et al. (1993)	10	25	Back analysis	Deep trench cut in waste. Suggested values by authors
Del Greco and Oggeri (1993)	15.7	21	Direct shear	Tests on baled waste Lower density bales
Del Greco and Oggeri (1993)	23.5	22	Direct shear	Tests on baled waste Higher density bales
Landva and Clark (1986)	19	42	Direct shear	Old refuse
Landva and Clark (1986)	16	38	Direct shear	Old refuse
Landva and Clark (1986)	16	33	Direct shear	Old refuse + 1 year
Landva and Clark (1986)	23	24	Direct shear	Fresh, shredded refuse
Landva and Clark (1986)	10	33.6	Direct shear	Wood waste/refuse mixture
Golder Associates (1993)	0	41	Direct shear	Project specific testing

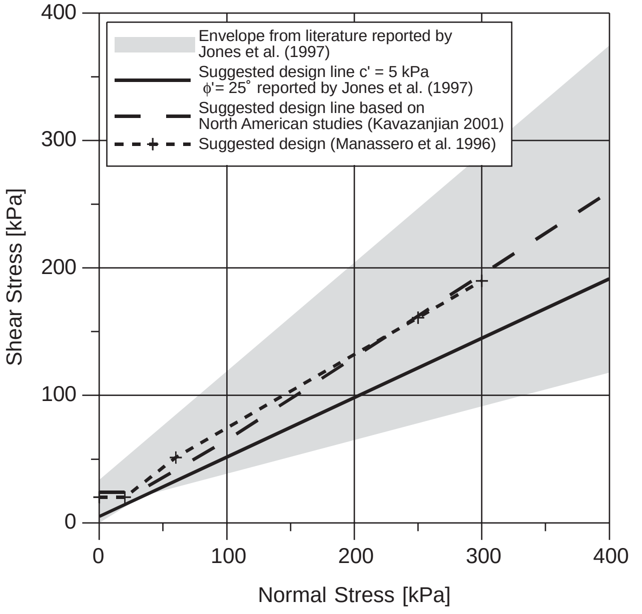

Fig. 6. Suggested MSW shear strength envelopes for design (after Jones et al., 1997).

- *Zone B*: corresponding to low to moderate stresses ($20\,\mathrm{kPa} \leqslant \sigma_v < 60\,\mathrm{kPa}$). In this case, $c = 0\,\mathrm{kPa}$ and $\phi \approx 38^\circ$.
- *Zone C*: corresponding to higher stresses ($\sigma_v \geqslant 69\,\mathrm{kPa}$). In this case, $c \geqslant 20\,\mathrm{kPa}$ and $\phi \approx 30^\circ$.

In a similar approach, and based on data from North American studies, Kavazanjian (2001) suggested $c = 24\,\mathrm{kPa}$ and $\phi = 0$ for normal stress below 30 kPa and $c = 0$ and $\phi = 33^\circ$ for higher normal stresses. This envelope is also shown in Fig. 6. It is believed that some of the Kavazanjian (2001) data was considered by Manassero et al. (1996) and therefore contributed to development of their envelop. Based on the data in Table 9, Jones et al. (1997) suggested a design line defined by $c = 5\,\mathrm{kPa}$ and $\phi = 25^\circ$ (Fig. 5). The three 'suggested' design conditions differ and therefore caution should be exercised when using the literature to obtain values for use in assessment of specific site and waste conditions. It would be considered non-sensical to suggest that a single failure envelope could be used for all soil types and suggesting the same for waste is equally ridiculous.

Kolsch (1995) has investigated the tensile strength of MSW using a modified version of the large shear box. This research was aimed at assessing the contribution to shear strength from the reinforcement provided by waste fibres (e.g. plastic sheets). The results obtained help explain the stability of steep cut faces in waste and of deep tension cracks that have been observed to form in waste masses under certain circumstances. However, further investigations to quantify the contribution of tensile strength are required before it should be used routinely in design.

4.3. Use of waste shear strength in landfill design

Knowledge of shear strength is required in order to assess waste and lining system slope stability. Landfill failures tend to be controlled by shear surfaces forming along interfaces within the liner system or within weak underlying soils. However, failures do occur entirely within the waste mass, and those that are controlled by weak zones and interfaces still often have a section of the shear surface forming in the waste. Therefore, while it is important to evaluate weak interfaces and/or poor foundation materials it is also necessary to estimate the strength properties of waste when conducting stability analyses. Waste slope design and assessment is presently based substantially on experience (i.e. "x" degree angle slopes have been stable for "y" years therefore this angle can be used for new slopes). Summaries of results from international research are also presently used in design as discussed above. An approach based on past experience is flawed for two reasons: (i) MSW slope failures do occur; and (ii) The constituents, and hence mechanical properties, of new MSW are constantly changing. In addition, mechanical properties of MSW change with time due to the degradation process and a slope could become unstable tens of years after its formation. The design of safe waste slopes in both the short- and long term is critical to the management of sites and hence optimization of the landfill construction process, and ensuring the required performance of the lining components. Many of the failures recorded in the literature are of temporary waste slopes.

5. Lateral stiffness

Information on the lateral stiffness of MSW is required to assess the performance of steep side slope lining systems that rely in part on the waste for their stability and integrity. To date, Dixon and his co-workers have published the only information on lateral (i.e. horizontal) waste stiffness (Dixon and Jones, 1998; Dixon et al., 2000). This section provides a brief summary of the results obtained by carrying out pressuremeter tests at different depths in MSW of varying age. This research was conducted as part of a project to investigate the interaction between steep slope lining systems and adjacent waste.

5.1. Stiffness parameters of MSW

Elastic parameters such as shear modulus (G), Young's modulus (E) and Poisson's ratio (v) can be used to quantify the response of a material to a change in stress (i.e. calculate strains). The parameters are related, as is the constrained modulus (D) introduced previously, and an example of their interdependence is given by

$$G = \frac{E}{2(1+v)}. \tag{8}$$

In situ measurement of such parameters is required. Waste placement methods, waste type and depth of burial will have a fundamental influence on the measured values. Tests on disturbed samples will not provide representative results. The measured values are dependent on, and therefore can be related to, other physical properties such as density and stress level.

5.2. Lateral shear stiffness parameters obtained from pressuremeter tests

Pressuremeter testing is a standard technique used in soil and rock mechanics to measure stiffness parameters (e.g. in situ lateral shear stiffness) and other ground properties such as in situ horizontal stress and, in certain materials, shear strength parameters. Dixon and Jones (1998) and Dixon et al. (2000) described a novel method of obtaining in situ stresses and shear stiffness values using the pressuremeter test in MSW. The test takes the form of inflating a membrane to expand a preformed cylindrical test pocket. The pressure required to expand the pocket (and hence deform the surrounding material) is related to the magnitude of radial expansion. Tests have been carried out in both fresh and partly degraded MSW at depths to 17.0 m below ground level. In excess of 30 individual tests have been conducted.

Stiffness values are obtained by calculating the slope bisecting small cycles of unloading and reloading. Fig. 7 shows a typical pressuremeter test result for MSW. Unload/reload loops can be used to obtain values for elastic shear modulus. Fig. 8 shows the measured relationship between shear modulus and maximum cavity pressure (i.e. horizontal stress in the waste adjacent to pressuremeter) at the start of the unload/reload loop, for wastes of different ages. General trends of increasing stiffness with stress level are observed, and the older waste (12–15 year old partly degraded) appears to be less stiff than fresh waste (1–5 year old) for comparable stress levels. The observed scatter of data is unsurprising and results from using different strain amplitudes for the unload/reload loops and by variability of the waste composition (i.e. some tests are in pockets of stiff construction rubble rich waste and some in weak wet waste). It should be noted that the degraded waste may have a different initial composition than current fresh waste, and hence this observed lower stiffness could be a result of waste composition rather than degree of degradation. The trend of increasing stiffness with mean stress, and hence depth, is

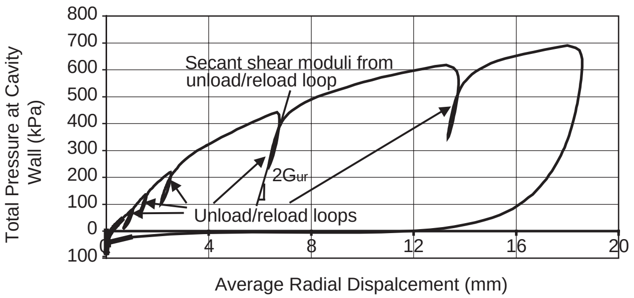

Fig. 7. Example result of a pressuremeter test in MSW.

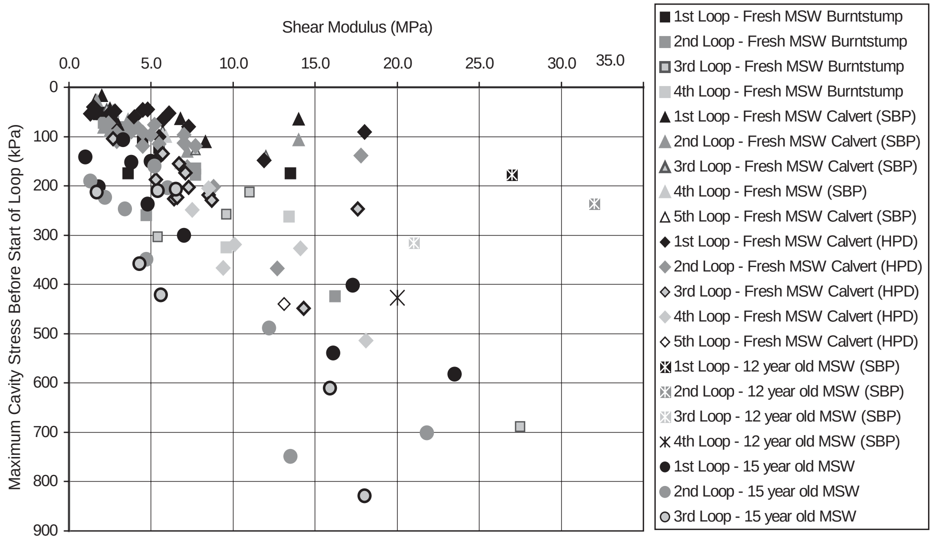

Fig. 8. Shear modulus vs. maximum stress at start of unload/reload loops for fresh and partially degraded MSW-SBP are self-boring pressuremeter test and HPD are high-pressure dilatometre tests.

as expected for a drained particulate material. Although there are no other studies in the literature to corroborate these results, the systematic and consistent behaviour observed provides confidence in the validity of the measured trends.

6. Horizontal in situ stress

Knowledge of horizontal in situ stress is required in order to aid assessment of stability and integrity of both shallow and steep slope lining system components and the performance of structures buried in the waste body such as leachate and gas wells. Measurement of horizontal stress in a particulate material such as waste is difficult because the act of introducing a measuring instrument will alter the stress being measured. For a body at rest, horizontal stresses (σ_h) can be related to vertical stresses (σ_v) by the coefficient of each pressure at rest (K_0) where

$$K_0 = \frac{\sigma_h}{\sigma_v}. \tag{9}$$

6.1. Laboratory study

Laboratory measurement of horizontal stress in a waste body can only provide an indication of possible field behaviour. Laboratory samples cannot easily replicate the field conditions, especially particle size and method of placement, and hence the structure of the sample cannot be reproduced. These factors play important roles in the generation of horizontal stresses. Landva et al. (2000) have produced the only results from a laboratory study of MSW. They conclude that K_0 values in the order of 0.35–0.4 would be typical for fresh MSW and that K_0 would be expected to increase towards a value of 0.5 if less reinforcing material was present. If the degradation process destroys reinforcing material, these results indicate that K_0 values, and hence horizontal stresses, will increase with time. To date, this has not been substantiated by field measurements.

6.2. Field measurements

An estimation of K_0 values have been made using results from pressuremeter tests. The preliminary results from the study are shown in Fig. 9 (Dixon and Jones, 1998). It can be seen that there is no clear relationship between K_0 and depth. This is due to disturbance caused by insertion of the pressuremeter (i.e. changing the values of

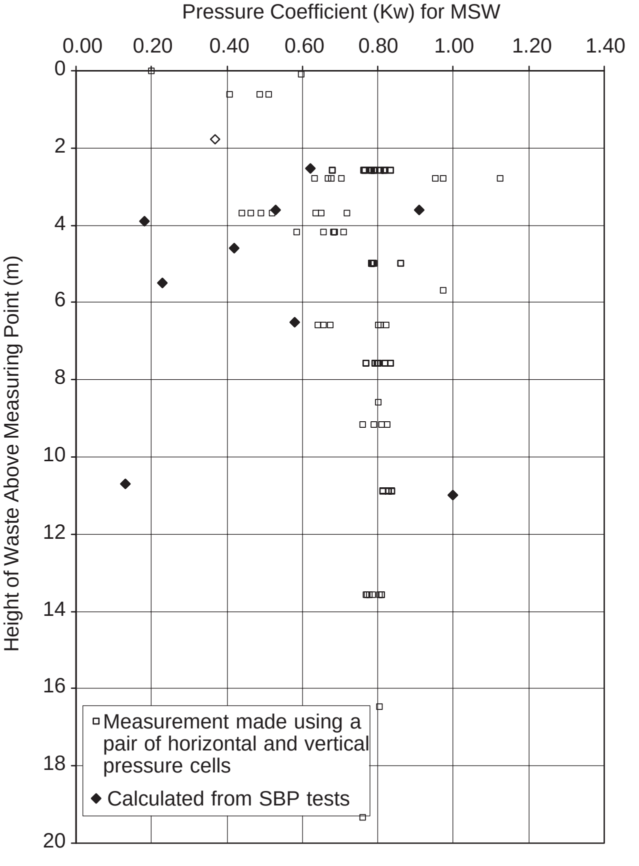

Fig. 9. Coefficient of earth (waste) pressure at rest measured using pairs of pressure cells (Dixon et al., 2004) and calculated from self-boring pressuremeter tests (Dixon and Jones, 1998) vs. depth of burial.

horizontal stress being measured) and the heterogeneous nature of the waste tested. However, the results do appear to be suggesting that higher values than those obtained by Landva et al. (2000) might be applicable for in situ material. Dixon et al. (2004) report direct measurements of horizontal stresses in MSW. Pairs of pressure cells were buried in waste at a range of depths to measure vertical and horizontal stresses as part of a study of steep slope lining system performance. The preliminary measurements have been used to calculate waste pressure coefficient values (K_w), which can be interpreted as K_0 values (Dixon et al., 2004), and these are also shown in Fig. 9. As with the pressuremeter test results, values consistently higher than those proposed by Landva et al. (2000) are indicated.

7. Hydraulic properties

Waste hydraulic conductivity is important to landfill designers because of the influence it has on leachate pressure distributions in the waste body and hence on the magnitude and distribution of effective stresses and therefore on shear strength. The heterogeneous nature and placement controlled structure of MSW result in widely varying permeability values in a given deposit. There is limited information in the literature on MSW hydraulic conductivity measured in situ and therefore the current understanding is incomplete. However, field observations of fluid flow in waste bodies and extensive large-scale laboratory experiments provide some information for use in design.

Placement of waste in layers and the use of daily cover soil (often of relatively low permeability) result in waste bodies having a structure of sub-horizontal layers and with foil like particles (e.g. paper and plastic) orientated horizontally. This produces anisotropic hydraulic properties with higher permeability in a horizontal direction. Perched leachate is often found above cover soil or low-permeability layers, and horizontal seepage of perched leachate day-lighting onto temporary waste slopes has been observed in many landfills. In addition to waste structure, a second major control on permeability is stress level. A comprehensive study of waste hydraulic conductivity was reported by Powrie and Beaven (1999) using a large size compression chamber. They found that the hydraulic conductivity of non-degraded MSW could reduce by over three orders of magnitude to approximately 10^{-8} m/s between placement and burial to a depth of 60 m due to compression. Absorption of fluid by waste particles, flow through partially saturated material and the influence of gas generation on hydraulic conductivity all require further investigation. The stress dependency of waste hydraulic conductivity has major implications for the operation of leachate extraction and recirculation systems, and basal and side slope drainage design. These all influence the pore water pressure distributions within the waste body, and hence the effective stresses and shear strength. Generation of high leachate pressures has been a significant factor in a number of large landfill failures (e.g. Brink et al., 1999; Hendron et al., 1999).

8. Summary of key issues

The current understanding of waste behaviour is far from complete. Evaluating the engineering properties and hence behaviour of MSW is very difficult due to the variety of materials present and the influence of waste structure. Knowledge of unit weight of MSW is required for all aspects of design. Initially the unit weight of waste is dependent on waste composition, the daily cover and the degree of compaction during placement. As the waste becomes older, the unit weight becomes more dependent on the depth of burial, the degree of decomposition and climatic conditions. Mechanisms resulting in settlement of waste include physical compression and creep, raveling, collapse of containers and bridging components and decomposition due to biodegradation of organic components. For simplicity, the total settlement of a MSW landfill can be taken as the combination of primary and secondary compression. Primary compression includes the physical compression of components and consolidation. Secondary compression includes all creep effects and those relating to degradation.

Knowledge of shear strength is required in order to assess waste slope stability. In situ measurement of waste shear strength is at present not possible. Back-analysis of failures provides the most reliable way of obtaining data, although this method is not without difficulties due to problems obtaining adequate detailed field information. Laboratory methods have been used widely but results from such studies should be interpreted carefully due to their association with disturbed samples. Of the methods available, the direct shear box produces the more reliable information. Although various strength envelopes have been suggested for design, a conservative approach should be taken due to the heterogeneity of the waste.

Information on the lateral stiffness of MSW is required to assess the performance of steep side slope lining systems that rely in part on the waste for their stability and integrity. The most comprehensive study to date has involved conducting pressuremeter tests in both fresh and partly degraded MSW at a range of depths. General trends of increasing stiffness with stress level are observed, and the older waste (partly degraded) is shown to be less stiff than fresh waste (little degradation) for the same stress level. Knowledge of in situ horizontal stresses is required to assess lining component performance post waste placement. Obtaining representative values is very difficult and this accounts for the small amount of information in the literature. Knowledge of waste hydraulic conductivity is required in order to understand leachate pressure distributions, and hence effective stresses, within the waste body. Structure and stress dependency are the controlling factors.

Measuring and interpreting MSW engineering properties are extremely difficult tasks. However, knowledge of unit weight, vertical compressibility, shear strength, lateral stiffness, in situ stresses and hydraulic conductivity is fundamental to the assessment of landfill stability and integrity of both geosynthetic and mineral lining components. An internationally agreed classification system and test standards are required to allow interpretation of published results. This will lead to development of appropriate constitutive models for waste and hence to optimization of landfill designs by considering waste/lining system interaction in full.

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