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Classification and Mechanical Behaviour Relationships for MSW: A Study Using Synthetic Wastes

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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. The constituents of MSW deposits vary between countries and regions and are constantly altering as a result of changes in life style and legislation. This paper describes an investigation using a family of synthetic wastes to assess the relationship between classification and mechanical behaviour of the waste body via a programme of one dimensional compression and direct shear tests. Measured mechanical behaviour is compared with results for real wastes to assess the validity of using synthetic samples. Compression and shear behaviour of the synthetic wastes was found to be within the range of published values for real waste. Both stiffness and shear strength values for a synthetic 'real' waste were found to be at the lower bound of published values. Lower unit weights and dry conditions for the synthetic wastes are considered to be responsible for the observed differences with real waste behaviour. It is concluded that synthetic wastes can be used to assess the relationship between classification and mechanical behaviour and that compression and shear behaviour can be related to waste classification.

Subject headings: Municipal wastes; synthetic materials; classification; compressibility; shear strength

INTRODUCTION

Landfilling of waste material is the primary method of disposal worldwide. Although there are concerted efforts being made in many countries to minimize, reuse and recycle waste materials, the landfilling of waste is set to continue for the foreseeable future. In the UK alone there are currently in the order of 1500 operational landfill sites, which accept a range of municipal solid wastes (MSW) and industrial wastes. This compares with about 2300 active landfills in the USA. Waste represents the largest structural element in a landfill. Design of landfills must consider stability both within and between elements of the lining system and the waste body to ensure that uncontrolled slippage does not occur. However, the design must also consider long-term integrity of the lining system, for example assessment of strains generated by settlement of the waste body (Jones and Dixon 2005). Despite the critical role of waste, knowledge about its mechanical behaviour is still limited. The continuing occurrence of landfill failures (e.g. Koerner and Soong, 2000; Jones and Dixon, 2003), introduction of new landfill construction practices, development of new design methods and ongoing changes in waste materials disposed of in landfills, together with the legislative need to minimize the risk to human health and the environment, have all contributed to the need for improved knowledge on waste mechanical behaviour. Evolving waste streams mean that past experience could be a poor guide to future behaviour.

The constituents of MSW deposits vary between countries and regions and are constantly altering as a result of changes in life style and legislation. The rate of change may increase over the next decade due to increasing efforts to recycle and pre-treat MSW by mechanical and biological processes. In addition, it is expected, although not proven, that degradation results in time dependant changes in mechanical properties of a deposit. It is not possible to fully characterize the engineering properties of waste due to its heterogeneous

nature, however it is important that basic behaviour is understood and that likely ranges of the key engineering properties are known. 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.

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 rarely possible. Undisturbed samples are extremely difficult to obtain and therefore laboratory tests are conducted on disturbed material that is re-compacted into test apparatus. 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. This is required in order to evaluate the influence of waste composition on mechanical behaviour.

Limited, and often site specific, information is currently available on the mechanical properties of municipal solid waste. Published results of studies are often difficult to interpret and compare due to limited information on the composition of tested materials. This is compounded by the lack of a universally accepted classification that is related to mechanical behaviour (i.e. analogous to soil classification). Dixon and Langer (2006) have proposed a waste classification related to waste mechanical behaviour. This paper describes an investigation using a family of synthetic wastes to assess the relationship between the Dixon and Langer (2006) classification framework and mechanical behaviour of the waste body via a programme of compression and shear tests. The aim is to assess whether systematic changes in waste classification can be related to changes in mechanical properties. One-

dimensional compression tests and large scale direct shear tests have been conducted on synthetic wastes with a range of classifications. Measured mechanical behaviour is compared with results for real wastes to assess the validity of using synthetic samples. It is not intended that measured behaviour of synthetic wastes should be used by designers. It is the validity and usefulness of the classification system that is the focus of this paper.

SYNTHETIC WASTE

A classification system is required to describe component characteristics both in their initial state (i.e. as delivered to a landfill) and also in any altered states. Placing waste in a landfill changes component properties such as size and shape due to physical forces (e.g. compaction and overburden) and degradation occurs over time. The classification proposed by Dixon and Langer (2006) has been used to describe materials used in this study. Only a brief summary of the classification framework is provided below, with full details given in Dixon and Langer (2006).

- Components are sorted into material groups (paper/cardboard, flexible plastics, rigid plastics, metals, minerals, wood/leather/textiles, organics and miscellaneous materials);
- Components in each material group are divided into the following shape-related subdivisions:
 - Reinforcing components (one-, two-dimensional; e.g. plastic bags, sheets of paper)
 - Compressible components (three-dimensional components)
 - High compressibility (e.g. putrescible materials, plastic packaging, balls of paper)
 - Low compressibility (e.g. metallic cans)
 - Incompressible components (three-dimensional; e.g. bricks, pieces of metal);

- Size of waste components are graded within each shape-related subdivision; and
- Degradation potential of material groups within each size range is assessed.

Sorting and sizing of components has to be done by hand to identify material types, allocate components to a shape-related subdivision and to size irregular and often deformable components (i.e. sieving is not appropriate). Components that can be easily compressed by hand are defined as high compressibility and those that can not, but have compression potential, as low compressibility. The framework can be applied to different stages of the deposition process and hence component stress history. For example, the initial stage for components delivered to site, after placement, and in the long term following degradation. Components can change shape-related subdivision as a result of compression and degradation (i.e. compressible to incompressible). Figure 1 shows an indicative classification of a waste using information reported by Kölsch (1996) for the three stages of component history based on mass relationships between reinforcing, compressible and incompressible components. Also shown in Figure 1 are the synthetic waste compositions used in this study and the result of a waste sorting analysis at a UK landfill.

It is proposed that synthetic waste samples can be used to study mechanical behaviour of MSW. Potentially, synthetic wastes have a number of advantages: Components can be used that are clean thus overcoming health and safety concerns and the need to use a laboratory with environmental controls; using a composition of selected components can minimize uncertainty regarding component size, shape and material properties; and variability between sample properties can be measured and controlled. Using synthetic wastes provides the opportunity to examine the influence on mechanical behaviour from systematic changes in material composition (i.e. classification). Key requisites for a synthetic waste are that the components used are representative of the range found in a given MSW deposit (e.g. material type, size and structure) and that these can be mixed in proportions to reproduce a

particular waste classification. A reference classification for ‘typical’ MSW has been obtained by conducting a waste sorting analysis on a sample from the Narborough landfill in the UK. This reference MSW has been used to select synthetic waste components that can replicate those found in MSW. These synthetic components have then been used to construct a number of synthetic wastes with a range of classifications (Figure 1) and these have been used in an assessment of the relationship between classification and mechanical behaviour. All components and synthetic wastes were in a dry state except for components representing organic material (see below). This is an important factor for consideration during interpretation of results from the mechanical tests and when carrying out comparisons with behaviour of real waste .

Derivation of synthetic wastes

A MSW volume of approximately 1m^3 was sorted in accordance with the Dixon and Langer (2006) classification system. Figure 2 shows the results of the survey. To assess whether synthetic waste could represent this ‘real’ waste, the first step was to derive an equivalent synthetic waste. However, there are too many combinations of material and component sizes to realistically represent each with a synthetic alternative. Therefore, the component fractions had to be minimized in order to get a simpler but still representative synthetic waste. The procedure for selecting which fractions of a specific material group could be omitted is described by Langer *et al.* (2005). The fractions labeled ‘negligible’ in Figure 2 were omitted and the percentages of remaining fractions were corrected (i.e. so as to add up to 100%). This modified mass distribution was used to produce an equivalent synthetic ‘real’ waste sample SW_09.

Most component types present in real waste can be used directly in the synthetic samples. Components such as beverage cans, rigid and flexible plastic packaging, paper/cardboard and textiles can be employed provided that they are in an unsoiled state.

Organic material was replaced by lumps of clay with ranges of moisture content to produce soft to firm shear strengths (e.g. the organic material such as food waste in the Narborough sample had soft to firm easily deformable behaviour). To prevent the clay from contaminating surrounding materials (i.e. introducing water into the waste) each piece was wrapped in flexible plastic. Miscellaneous components (typically with sizes $\leq 120\text{mm}$) were represented by clay (i.e. organic material), plastic and paper, as the waste sorting analysis showed that this material is a mixture of components from different material groups. Mineral material was represented by sand, gravel and brick fractions. Synthetic waste components were selected based on consideration of both shape and size (Table 1). Figure 3 shows components used in this study.

Synthetic waste compositions used in the testing program

Nine synthetic wastes (SW) were used in this study. Table 2 shows the percentages of materials forming each synthetic waste and the classification of each is given in Figure 1. Only synthetic waste SW_09 was designed to represent 'real' waste. The remaining eight synthetic samples were selected to be represent a range of classifications (see Figure 1) and hence potentially have a range of mechanical behaviour. These samples are not intended to represent real waste compositions. Synthetic waste SW_01 was designed to be a low compressible waste, comprising mainly sand with a small percentage of sheets of paper (i.e. reinforcing components). SW_02 is a mixed waste with a high percentage of compressible and reinforcing components (e.g. aluminum cans and sheets of paper respectively). It was anticipated that this composition would produce highly compressible behaviour. Incompressible material (e.g. tire shreds and brick fractions) account for the highest percentage mass in composition SW_03, although there is also a high percentage of compressible (low) components (e.g. aluminum cans - unflattened) resulting in SW_03 being regarded as likely having a very compressible character. Synthetic wastes SW_04 and

SW_05 contain a large amount of flattened aluminum cans, and represent compositions that have one component type dominating the composition. In a flattened state the cans are incompressible and elongated such that they act as reinforcing elements. SW_05 was used to investigate the impact of changing the ratio between dominating components (i.e. cans). In wastes SW_06, SW_07 and SW_08, the percentages of plastic packaging and flattened cans were tested in a sand matrix to assess the impact on behaviour of relatively small changes in percentages by mass of components. The sand matrix results in a significantly increased waste unit weight. Synthetic waste SW_09 represents the real waste assessed in the sorting analysis and for which data is presented in Figure 2.

All nine synthetic wastes were tested in the direct shear apparatus, however as there were only small differences expected in the compression behaviour between SW_04 and SW_05, and between SW_06 to SW_08, for these waste types only SW_04 and SW_07 were tested in the compression cell. Repeatability tests were conducted on series SW_02 in the compression cell with two additional tests conducted using identical compositions (SW_02_1 and SW_02_2) and a third test (SW_02_3) with double the unit weight. The influence of sample unit weight on behaviour is discussed following presentation of the test results.

COMPRESSION BEHAVIOR

Test method

One-dimensional compression behaviour was investigated using a rigid container with plan dimensions 0.5 x 0.5 metres and allowing a maximum sample height of 0.75 metres. The front of the box was formed of a 35mm thick glass plate that allowed visual monitoring of the compression process. A motorized jack was mounted to the top of the box and applied the vertical stress through a stiff loading plate at a constant rate of strain. Applied load and vertical displacements of the load plate were recorded. Samples of synthetic waste had a

defined mass calculated to achieve a target ratio between the shape-related subdivisions. For each test, all components were in a virgin condition prior to placement (e.g. compressible components such as plastic packaging had not previously been loaded) unless specifically identified, such as the use of flattened aluminum cans in some tests. Components were mixed and then placed into the compression cell in one to five layers with each layer compressed under a nominal dead load of 3kPa prior to placement of the next layer. The number of layers used in each test depended on the compressibility of the sample, with five layers used for the most compressible wastes in order to place the required mass of material into the chamber. Samples were compressed to a limiting state, being either a maximum normal load for wastes with low compressibility, or a maximum vertical compression for highly compressible synthetic wastes. Changes in waste structure during compression was recorded using photographs. A digital cameral was placed in front of the compression cell and pictures taken at time intervals. Fiducial markers placed on the glass allow assessment of component compression and development of structure. At completion of each test the waste sample was carefully extruded from the cell, deconstructed to examine the structure and components were assessed to record physical changes.

Compression results

The six synthetic wastes tested can be grouped into incompressible compositions (SW_01, SW_07), compressible compositions (SW_02_1, SW_02_2, SW_02_3, and SW_03), a mono-component dominated composition (SW_04), and a simulation of real waste (SW_09). Figure 4 provides a visual record of compression history for SW_01, SW_02_01 and SW_09 for five load increments with associated applied stress and compression values given. Table 3 contains measured changes in sample height and associated stress level for the three wastes. These measurements have been used to calculate incremental values of constrained modulus and these are plotted in Figure 5 (note that alternatively this information could be used to

calculate values of modified compression index). Constrained modulus is a secant modulus relating increments of applied vertical stress ($\Delta\sigma_v$) to resulting increments of vertical strain ($\Delta\varepsilon_v$) and is plotted against the mean vertical stress applied during the increment:

$$D = \Delta\sigma_v / \Delta\varepsilon_v \quad (1)$$

Results for waste SW_01 are dominated by the large percentage of sand and this produces a relatively high initial unit weight of 11.4kN/m^3 . Visual assessment (Figure 4a) shows that limited component compression occurred, although the paper deforms even at low applied stresses. Compression is dominated by particle (i.e. sand) re-organization progressively reducing voids formed during initial sample placement. The high sand content also results in a relatively small vertical compression of 136mm (23% strain) generated by an applied vertical stress of 253kPa.

A very low initial unit weight of 0.3kN/m^3 was achieved for sample SW_02_1 due to the light dead load compaction of 3kPa used to place the sample in the cell and the large percentage of light and highly compressible components. This synthetic waste exhibited very high compressibility as shown in Figure 4b, and demonstrated by the calculated very low values of constrained modulus. A large displacement of 430.2mm (71% strain), was achieved by a vertical stress of just 36kPa. Components deformed at very low vertical stresses (e.g. balls of paper and plastic bags) with component rearrangement dominating behaviour for vertical stress $<10\text{kPa}$. From frame 3 in Figure 4b onwards (vertical stress $\geq 14\text{kPa}$) compressible component deformation is clear (e.g. rigid plastic packaging). Constrained modulus values for SW_02_1 increase with stress level, with a low maximum value of 160kPa at a vertical stress of 32.5kPa.

Real waste simulation sample SW_09 had a low initial unit weight of 1.0kN/m^3 , again caused by the inclusion of a large percentage of light and highly compressible components and the use of the nominal dead load (3kPa) during placement of the sample. A final vertical

strain of 73% was associated with an applied vertical stress of 102kPa (Figure 4c). The waste sample showed similar characteristics to the other compressible compositions (e.g. SW_02_1, SW_02_2 and SW_03) and the final unit weight achieved is comparable to SW_03. From the time series pictures in Figure 4c, a threshold value for crushing of compressibility components is not visible. However, as observed for sample SW_02_1, components deformed from the start of stress application. Discussion of the measured behaviour, including the significance of the low unit weights achieved, and comparison with compression characteristics of real MSW is presented below.

SHEAR BEHAVIOR

Test method

The direct shear device used in this study has sample dimensions length 1.0m, width 1.0m and height 0.8m. The size of the apparatus allows the use of large size waste components (i.e. in the order of 0.5metres) and the generation of significant shear displacements (i.e. up to 260mm). The device was designed and constructed by LIRIGM, Joseph-Fourier-University, Grenoble, France, and has been used previously for research on real waste (Gotteland *et al.* 1995, 2000, 2001 and Thomas *et al.* 1999). Details of the design and operation of the device are provided by Gotteland *et al.* (2000). In summary, shear force is applied in strain controlled tests using an electric screw jack and recorded using a load cell. Normal stress is applied using four matched and connected hydraulic jacks and vertical and horizontal deformations are measured using linear strain transducers.

Each shear test comprised the following stages: Filling; compaction; application of test normal stress; shearing at a defined rate to a displacement of approximately 110mm; carry out an unload/reload cycle to measure elastic shear stiffness; and continued shearing at original rate to a maximum displacement in the order of 260mm. All real waste components have a stress history resulting from the initial storage conditions (i.e. manual compression in

household storage), collection operations (i.e. filling and emptying of collection vehicle) and finally due to site deposition and compaction methods employed. The large forces used to compact waste in modern landfills have an influence on subsequent component behaviour. In an attempt to provide the synthetic components with an appropriate stress history, each sample was compacted using a static applied normal stress of 75kPa. This value is equivalent to a waste overburden in the order of 10 metres, and it has been reported that 10 metres of overburden can produce unit weights equivalent to modern compaction equipment (Powrie *et al.* 1998). Waste was placed in layers the same as in the compression tests, with each layer compacted using a normal stress of 75kPa in order to introduce the required mass of waste into the shear box. The compaction stress was applied using the hydraulic jacks, which were monitored and adjusted until a constant normal stress was established following placement of the final layer. This took up to 15 minutes for creep compression of the waste to be completed and the stress to become constant. Thereafter, the sample was unloaded or loaded to the test normal stress (i.e. 25, 50, 75 or 100kPa) and time allowed for the normal stress to become constant before the start of the shearing phase (i.e. in the order of 15 minutes). A normal stress of 100kPa was only used for the low compressible wastes (e.g. SW_01). When testing the high compressible wastes a maximum normal stress of 75kPa was used due to constraints in producing a sufficient volume of waste for shearing (i.e. higher normal stresses compressed the waste to a degree such that there was an inadequate height of waste above the shear plane). A shearing rate of 6mm/min was selected following a study using both faster and slower rates, which demonstrated that 6mm/min produced comparable shear behaviour to slower rates. Following completion of each test, the sample was deconstructed and components examined for physical change.

Direct shear results

Results for example tests in low compressibility (SW_01), high compressibility (SW_02) and synthetic real waste composition (SW_09) are given in Figure 6 in the form of shear stress vs. displacement graphs. Also given are the initial and final unit weights for the shearing phase. Shear strengths mobilized at displacements of 240 to 260mm have been used to define Coulomb failure envelopes and obtain shear strength parameters apparent cohesion c' and mobilized friction angle ϕ' for best fit straight lines (Figure 7). In some tests a peak or ultimate shear strength was recorded but in several, tests displacements were insufficient to mobilize ultimate strengths, although the shear strengths vs. displacement relationships were approaching the horizontal.

The test at 100kPa on waste SW_01 was disrupted at 25mm displacement due to a rapid normal stress decrease (Figure 6). The normal stress was re-applied and the test continued. Peak shear stresses were not observed in the SW_01 tests although all curves are flattening towards a limit value as displacements approach 250mm. Vertical strains during shearing demonstrated contractant behaviour with the exception of the lowest normal stress of 25kPa. The sample in the 25kPa test had an over-consolidation ratio of 3 (i.e. based on the compaction load of 75kPa) and this may have resulted in the observed dilatant behaviour. The Coulomb failure envelope for composition SW_01 (Figure 7) gives a mobilized friction angle of 38.8° and an apparent cohesion of 28.5kPa for a best fit straight line through the measured maximum shear stress values.

The 75kPa test of compressible synthetic waste sample SW_02 exhibited a peak followed by a reduction in shear stress. It is believed that this peak was a result of a component becoming jammed between a rib of the load transmission plate and the leading edge of the bottom box. The ribs were welded to the load transmission plate at 200mm spacings and ran perpendicular to the direction of shearing. The peak stress corresponded to a displacement of 200mm and the sample height was low. A brick fragment was observed in

this location during dismantling of the sample and this confirmed the assumed behaviour. The Coulomb envelope (Figure 7) was defined using the shear stress recorded at the maximum displacement for the 75kPa test rather than the peak value. All three samples demonstrated contractant behaviour with vertical strains up to 13%. The Coulomb failure envelope is defined by an apparent cohesion of 11.5kPa and mobilized friction angle of 28.7°.

Shear behaviour for the real waste simulation SW_09 is shown in Figure 6. The 75kPa test again produced a peak shear stress but the interpretation of this is the same as for test SW_02 (i.e. a jammed waste component) and the shear stress mobilized at the maximum displacement has been used to define the Coulomb failure envelope (Figure 7). The curves for the 25 and 50kPa tests reach ultimate values. All samples demonstrated contractant behaviour with vertical strains up to 10%. The Coulomb failure envelope is defined by an apparent cohesion of zero and mobilized friction angle of 33.9°. A summary of shear strength parameters defining best fit straight lines through each set of peak shear strengths is given in Table 4 for all nine synthetic wastes.

DISCUSSION

Assessment of results obtained from the mechanical tests is required to investigate whether the synthetic wastes have comparable mechanical behaviour (compression and shear) to real MSW (i.e. reported in the literature) and hence to assess the validity of using synthetic wastes in such studies. In addition, the results are used to investigate whether differences in measured mechanical behaviour of the synthetic wastes can be related to sample classification using the Dixon and Langer (2006) system.

Measured mechanical behaviour

Compression behaviour of all the synthetic wastes can be compared in Figure 5. Considering waste classification, the samples containing small percentages of high compressible components (e.g. SW_01) exhibit the highest constrained modulus values. The modulus values of wastes containing a high percentage of compressible components (e.g. SW_02_3 and SW_09) are similar, located in a clearly defined range and are significantly lower than the samples containing a low percentage of compressible components. Figure 5 also compares the constrained modulus data from the synthetic wastes with real waste values from the literature. There is insufficient information to classify these real wastes. The values labeled Dixon *et al.* (2004) are derived from field measurements of waste compression made during placement of fresh MSW in an active landfill with bulk unit weights in the range 8 to 10kN/m³, as are the values reported by Watts and Charles (1999) with bulk unit weights 5.4 to 8kN/m³. The remainder of the data is from large scale compression tests: Jessberger and Kockel (1993) bulk unit weights 7 to 10kN/m³; Beaven and Powrie (1995) and Powrie and Beaven (1999) dry unit weights 2 to 7kN/m³; and Landva *et al.* (2000) bulk unit weights 7.7 to 10.4kN/m³. The bold straight line is a recommendation value for fresh waste from the German Geotechnical Society (DGGT, 1997) for use in preliminary design.

An important consideration when comparing mechanical behaviour of synthetic and real waste is the unit weights of the materials. The unit weights of the synthetic samples are a function of the light components employed and low placement compaction forces used. In addition, some of the synthetic samples are formed using percentages of components that are not representative of common real wastes. It is expected that synthetic waste unit weights will vary within a wide range. The key material is SW_09 as the aim is for this to be a synthetic replica of the ‘typical’ UK MSW sample classified in the sorting analysis. This had a unit weight of 1.0 and 3.9kN/m³ at the start and end of the compression test respectively and 2.2

to 3.6kN/m^3 , depending on the normal stress at the start of shearing, in the direct shear tests. These values appear to be low when compared with the range of 5 to 8kN/m^3 reported in the literature for moderate compaction of fresh MSW (Dixon and Jones 2005) and with the results from an extensive programme of field measurements of unit weight conducted by Zekkos *et al.* (2006). However, it must be considered that the values for synthetic wastes are dry unit weights (i.e. ignoring the small amount of moisture in the clay lumps used to represent organic material). Powrie and Beaven (1999) have shown that dry unit weights in the order of 2 to 4kN/m^3 equate to bulk unit weights in the range 6 to 8kN/m^3 for the same waste at field capacity. Kavazanjian (2006) has noted that most MSW are at or below field capacity where the addition of liquids are prohibited. It can be concluded that although sample SW_09 has low unit weights these are not unrealistic considering that the material is dry, although they are at the lower bound. This could be due to the use of dead load to compact the samples (i.e. 3kPa in the compression tests and 75kPa in the direct shear tests). It has been reported that a level of vertical stress in the order of 75kPa should be equivalent to compaction using modern plant (Powrie *et al.* 1998). However, the shearing mechanism generated by a sheep's foot roller is not replicated using dead load and this might have contributed to the lower bound unit weights achieved in this study.

Although there is little conclusive evidence in the literature, the presence of water in a waste is expected to have an influence on the mechanical behaviour of some components (i.e. softening of paper and cardboard) and hence is likely to modify compression and shear behaviour of the waste body. As the synthetic wastes were tested dry, there is a possibility that differences in behaviour in comparison to real waste might be due to differences in water content. Further research is required to investigate the role of water content on MSW mechanical behaviour.

The constrained modulus values for the synthetic wastes are in the same range as the literature values for real MSW for the vertical stresses achieved (i.e. <200kPa). The low compressibility synthetic waste (SW_01) is located towards the upper bound of all the stiffness data, while the compressible composition (SW_02_3) describes the lower bound of the complete data set. The replica MSW synthetic sample SW_09 is also at the lower bound of the literature data for real waste. The GDA recommendation line is in the middle of the combined data set. The majority of the data reported by Watts and Charles (1999), Dixon *et al.* (2004) and Jessberger and Kockel (1993) is located between the GDA recommendation line and the upper bound (i.e. the field measurements give relatively high stiffnesses), while most of the data from Landva *et al.* (2000) and Beaven and Powrie (1995) and Powrie and Beaven (1999) is located close to the GDA recommendation and between it and the lower bound (i.e. the laboratory samples have a lower stiffness). This indicates that laboratory derived stiffness values may be lower than field values and this could be a function of difficulty achieving field representative unit weights for laboratory samples using dead load compaction techniques that do not reproduce modern site practices, as discussed above. Despite the differences in moisture content between synthetic and real wastes, and hence in unit weights, it has been shown that the synthetic wastes investigated in this study have magnitude and trends of constrained stiffness that are comparable to real waste. It can be concluded that the use of synthetic wastes to assess the relationship between classification and compression behaviour is valid.

The different families of wastes tested in the direct shear apparatus can be summarized as: low compressibility (SW_01 series, SW_06, SW_07 and SW_08) with high unit weights; and high compressibility (SW_02, SW_03 and SW_09) and mono-component compositions (SW_04 and SW_05) with comparably low unit weights. The low compressibility compositions produced the highest shear strengths for the synthetic waste

compositions and this is a function of the inclusion of reinforcing components and the high unit weights (Figure 7). For example, the reinforced sand compositions (e.g. SW_01) produced the highest shear strengths and the high compressibility and mono-component compositions produced the lowest shear strength, with the real waste simulation (SW_09) producing the lowest mobilized shear strength of all samples. Figure 7 includes shear strength data for real waste obtained using the same direct shear apparatus employed in this study (Gotteland *et al.*, 2000). Tests were conducted on non-hazardous industrial waste (NHIW) and domestic waste (DW). NHIW contained high percentages of paper, textiles and inert materials, while DW contained slightly more wood, plastic and cardboard. Both compositions contained a high percentage of fine soil like particles. Bulk unit weights for the waste materials were in the range 9.6 to 10.7kN/m³ for NHIW and 7.9 to 10.8kN/m³ for DW. There is insufficient information available to classify the samples using the Dixon and Langer (2006) system. The Gotteland *et al.* (2000) shear strength parameters are obtained from best fit straight lines through mobilized shear strengths measured at approximately 20% shear strain and are presented in Table 5.

Shear strengths for the synthetic wastes are, apart from SW_01 and SW_07, lower than for the real waste samples. The differences in shear strength could be a function of the higher unit weights of the real waste samples leading to greater interlocking of particles and mobilization of tensile forces in reinforcing elements. The synthetic and real wastes have comparable mobilized friction values but widely differing apparent cohesions. A key factor could be that the real wastes are reported to contained a large amount of fine soil like components (e.g. up to 66% by mass of the sample) and to have a significant moisture content, although the value is not given.

Figure 8 is a summary of suggested design lines and a design envelope for shear parameters from the literature (Van Impe and Bouazza, 1996; Jones *et al.*, 1997; Eid *et al.*,

2000 and Kavazanjian, 2001). It is an extended summary of design values proposed by Manassero *et al.* (1997). The shear test results for the synthetic wastes are shown for comparison. The synthetic waste strengths are located within the upper and lower bounds of the envelopes proposed by Jones *et al.* (1997) and Eid *et al.* (2000). The two distinctive groups within the synthetic waste compositions (e.g. sand dominated and compressible component dominated samples, the latter group including synthetic ‘real’ waste SW_09) are found near the upper and lower bounds of the envelopes respectively. Comparison with values from the literature must be handled with caution. Often, mobilized shear strengths and derived parameters are published but boundary conditions such as maximum displacements and component sizes are seldom reported thus leading to the potential for incomplete and/or misleading interpretations. The synthetic wastes demonstrate magnitudes of shear strength that are comparable to real wastes, although the synthetic ‘real’ waste SW_09 is at the lower bound. It can be concluded that the use of synthetic wastes to assess the general relationship between classification and shear strength is valid. However, a more detailed consideration of the relationship between classification and shear strength is not currently possible due to a lack of information on the role of waste structure, unit weight, water content and displacements required to mobilize ultimate strengths. The use of shear strength data from the literature in design is a high risk practice unless there is detailed information available to allow comparison of classifications for the waste used to obtain the literature values and the expected waste at a specific site.

Relationship between waste classification and mechanical behaviour

A key aim of the study is to investigate the relevance of the Dixon and Langer (2006) classification system to mechanical behaviour. If validated, the classification framework could be used by researchers and practitioners to present and compare waste mechanical

behaviour. Constrained modulus (D) values from the compression tests calculated for a mean vertical stress of 50kPa for each synthetic waste are presented in Figure 9 where they are related to the classification framework based on percentages by mass of shape-related subdivisions: incompressible, compressible and reinforcing components. From this, a trend of decreasing shear modulus is obtained as mass dominance of incompressible components changes to a dominance of compressible components. It also indicates that reinforcing components can result in increased stiffness (i.e. comparing SW_05 to SW_02 and SW_09). The maximum shear strengths measured in each of the 50kPa normal stress direct shear tests are presented in Figure 10. The figure shows high shear strengths for incompressible compositions and low strengths for compressible and mono-component compositions. It also appears that an increase in percentage of reinforcing components results in higher shear strength in the compressible wastes (i.e. comparing SW_05 to SW_02 and SW_09) but further testing is required to investigate this in more detail. Figures 9 and 10 demonstrate that the waste classification proposed by Dixon and Langer (2006) can be linked to mechanical behaviour by using mass relationships of shape related components. It could be argued that a clearer relationship would be provided by considering waste composition in terms of volume rather than mass. This is because components with a small mass but large volume such as plastic packaging can have a significant influence on behaviour. Figure 11 shows the same data as in Figure 9 but plotted using percentages of components by volume. While this appears to provide a clearer pattern of behaviour, a number of assumptions are required to obtain the volume relationships and therefore the volume values have a wide range of potential error. It should be noted that in order to relate mechanical behaviour to waste classification, a reference stress or strain state must be used. Figures 9, 10 and 11 only provide snapshots of general trends in mechanical behaviour because initial conditions (e.g.

unit weight and water content) of the samples are not differentiated. The measurements for synthetic wastes presented in this paper should not be used in design.

SUMMARY

A family of synthetic wastes was designed based on the results of a waste sorting analysis conducted on an example sample of UK MSW. A reduced number of material types, sizes and shapes was selected by considering the dominant components in the real waste composition. Nine waste components were used to produce nine synthetic waste compositions that fit into the four general groups of incompressible, compressible, mono-component compositions and a 'real' waste synthetic sample (SW_09).

Shear behaviour of the synthetic waste compositions was investigated using a large direct shear device. In the majority of tests a peak failure state was not obtained, even with shear displacements up to 260mm. As tested samples contained components with a size larger than the maximum achievable shear displacement, and also given that some of these components can undergo large extension (e.g. plastic sheets), it is to be expected that peak strengths may not be mobilized in such tests. However, in all tests the slope of the shear stress vs. displacement curve was decreasing to the horizontal indicating that maximum measured shear stresses were close to the peak/ultimate shear strength. Synthetic waste mobilized shear strengths were in the same range as values from tests on samples of real MSW obtained both using the same shear device and using different experimental procedures. Incompressible compositions (high unit weight with a large portion of soil particles) produced high shear strengths close to values for real MSW, while compressible compositions including SW_09, resulted in shear strengths at the lower limit of design ranges found in the literature. The reported results demonstrate that the synthetic wastes can have comparable shear behaviour and strength properties to real MSW.

Constrained moduli for the synthetic wastes were comparable to values from the literature. Results for the compressible, mono-component and 'real waste' compositions gave moduli at the lower bound of MSW values reported in the literature. The incompressible compositions exhibited stiff compression behaviour and were located towards the upper bound of literature values. These relationships are valid for vertical stresses up to 200kPa.

Waste streams are constantly evolving in response to legislation and changes in consumer behaviour. Therefore, designers of landfill facilities must be aware of potential changes in waste mechanical properties and the possibility that past experience may be a poor guide to future waste behaviour. It is necessary to assess mechanical properties of a waste based on its component properties, moisture content, unit weight and stress state. Although further work is required to extend the range of synthetic wastes investigated and to assess the influence of unit weight and water content, the procedure and results presented in this paper provide evidence that mechanical behaviour can be related to the proposed classification framework. Use of the classification by researchers and practitioners when reporting results from mechanical tests on MSW would enable effective sharing of information, facilitate interpretation of measurements and aid development of constitutive models for waste materials that incorporate factors related to composition. Following further development, the classification could also become the basis of a procedure for assessing the likely impact on landfill engineering of evolving waste types. It is advised that results for synthetic wastes should not be used in design. Unlike real MSW, the synthetic wastes were dry and had unit weights at the lower bound of typical values for MSW reported in the literature.

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NOTATION

The following symbols are used in this paper:

$\Delta\varepsilon_v$	Vertical strain increment [%]
γ_0	Initial unit weight [kN/m ³]
γ_e	Unit weight at maximum applied stress [kN/m ³]
ϕ'	Mobilized friction angle [°]
σ	Stress [kPa]
$\Delta\sigma_v$	Vertical stress increment [kPa]
τ	Shear stress [kPa]
c'	Apparent cohesion [kPa]
s	Settlement (compression test), horizontal displacement (shear test) [mm]
D	Constrained modulus [kPa]

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Table 1. Replacement components used to construct synthetic waste samples

Material group	Replacement	Shape-related Subdivision	Size [mm]
Paper/Cardboard	A4 paper	Reinforcing	120-500
Flexible plastics	Waste bags	High compressible	120-500
Rigid plastics, rubber	Tire shreds	Incompressible	120-500
	Packaging	Low compressible	120-500
	Beverage bottles		
Metals	Aluminum beverage cans	Low compressible	120-500
Minerals, glass	Leighton Buzzard Sand	Low Compressible	<10
	Brick Fractions	Incompressible	40-120 120-500
Wood, leather, textiles	Textiles	Reinforcing	500-1000 >1000
Organics	Lumps of clay	High compressible	40-120 120-500
	Soil, clay	Low compressible	<10
Miscellaneous	Plastic, paper, clay	High compressible	10-40
	Plastic, paper	Reinforcing	40-120

Table 2. Synthetic waste compositions

Components	Unit	SW_01	SW_02	SW_03	SW_04	SW_05	SW_06	SW_07	SW_08	SW_09
Aluminum cans	[mass-%]	0%	20,0%	15,0%	49,9%	70,0%	0,3%	2,6%	4,2%	5,1%
Paper	[mass-%]	1,1%	40,2%	18,1%	0%	0%	0%	0%	0%	21,2%
Textiles	[mass-%]	0%	14,1%	7,2%	0%	0%	0%	0%	0%	2,4%
Flexible plastic bags	[mass-%]	0,1%	7,7%	0%	0%	0%	0%	0%	0%	16,8%
Rigid plastic packaging	[mass-%]	0%	10,2%	0%	5,0%	15,0%	0,3%	2,6%	4,2%	4,0%
Rigid plastic bottles	[mass-%]	0%	7,7%	0%	0%	0%	0%	0%	0%	3,1%
Tire shreds	[mass-%]	0%	0%	29,9%	24,9%	15,0%	0%	0%	0%	1,2%
Brick fractions	[mass-%]	0%	0%	29,9%	20,2%	0%	0%	0%	0%	2,0%
Leighton-Buzzard Sand	[mass-%]	98,8%	0%	0%	0%	0%	99,4%	94,9%	91,5%	7,5%
Clay	[mass-%]	0%	0%	0%	0%	0%	0%	0%	0%	36,7%

Table 3. Sample compression and stress state for selected synthetic waste compression tests

Synthetic Waste	Change in Height, Δh [mm]	Applied Vertical Stress at start of increment, σ_v [kPa]	Stress Increment, $\Delta\sigma_v$ [kPa]
SW_01	1.9	0.6	4.1
$h_0 = 560\text{mm}$	3.8	4.7	5.1
$\gamma_0 = 11.4\text{kN/m}^3$	14.2	9.8	15.2
$\gamma_e = 14.9\text{kN/m}^3$	19.2	25.0	24.7
	13.9	49.7	25.5
	11.2	75.2	25.3
	24.3	100.5	50.1
	33.4	150.7	98.3
	-	249.0	-
SW_02_1	142.4	0.0	5.0
$h_0 = 620\text{mm}$	80.7	5.0	5.0
$\gamma_0 = 0.3\text{kN/m}^3$	156.5	10.0	14.9
$\gamma_e = 0.9\text{kN/m}^3$	59.2	24.9	15.1
	-	40.0	-
SW_09	35.5	0.0	4.9
$h_0 = 625\text{mm}$	76.6	4.9	5.1
$\gamma_0 = 1.0\text{kN/m}^3$	184.2	10.0	15.0
$\gamma_e = 3.9\text{kN/m}^3$	97.9	25.0	25.2
	44.3	50.2	25.1
	19.8	75.3	24.6
	-	99.9	-

Table 4. Mobilized shear parameters at maximum displacement ($\approx 25\%$ strain) for selected synthetic wastes

Synthetic waste SW_		01_1	01_2	02	03	04	05	06	07	08	09
Mob. Friction Angle ϕ Φ	[°]	38.8	34.2	28.7	34.0	34.9	34.9	40.5	43.3	36.4	33.9
Mob. app. Cohesion c	[kPa]	28.5	30.8	11.5	12.1	5.8	6.2	12.3	16.0	15.0	0.0

Table 5. Mobilized shear parameters at $\approx 20\%$ strain for real wastes reported by Gotteland *et al.* (2000)

Real Waste		NHIW_1	NHIW_2	DW_1	DW_2	DW_3
Mob. Friction Angle Φ	[°]	29.6	34.0	33.0	29.5	39.2
Mob. Cohesion c	[kPa]	23.4	52.5	75.0	40.0	21.5

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