UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

School of Civil Engineering and the Environment

Shear Strength Characteristics of Mechanically Biologically Treated (MBT) Waste

by

V.I. Sudarshana C.K. Fernando

Thesis for the degree of Doctor of Philosophy

November 2011

Acknowledgements

I would like to acknowledge and thank all people for their help and support that make this thesis possible.

Firstly, I am deeply indebted to my main supervisor Prof. William Powrie, secondary supervisor Prof. David Richards and mentor Geoff Watson for providing the opportunity to join this research project and for providing clear direction, motivation, guidance and constructive criticisms during this research. Completion of the work required for this degree would have been impossible without them.

I would like to thank Harvey Skinner for helping during laboratory works, in setting up instruments and in troubleshooting various technical problems.

The financial support for this study was provided by the Engineering and Physical Sciences Research Council (EPSRC) is gratefully acknowledged.

I thank all my colleagues for their friendly help and for the pleasant years working together.

My wife Melanthi & my sons (Dineth and Salitha) are always a great source of inspiration for me and provided great accompany and support.

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

Doctor of Philosophy

SHEAR STRENGTH CHARACTERISTICS OF MECHANICALLY BIOLOGICALLY TREATED WASTE (MBT)

By Sudarshana Fernando

Mechanical biological treatment (MBT) is the generic name for a group of processes which have been used to reduce the biodegradable content of municipal solid waste (MSW) in order to aid compliance with the Landfill Directive. As a result of mechanical biological treatment, MSW is converted to a material which has different properties to its parent material, including changes to its mechanical properties.

The aims of this research were to identify:

- The shear strength characteristics of aerobically treated MBT, processed at New Earth Solutions (NES) in the UK
- Changes to the properties of the reinforcing elements due to the MBT process and its impact to the shear strength

NES produced two fractions of MBT residue (0-10 mm and 0-20 mm) which were tested using direct shear equipment in order to identify the shear strength characteristic of the MBT residues. It was thought MBT might be a weak material compared to MSW due to the significant reduction of the reinforcing particles size and content, the results confirmed that MBT is a strong material (mobilizes its strength rapidly with displacement) compared to MSW.

MBT processes lead to changes in both the content of reinforcing particles and their properties. The reinforcing effect and its impact on the shear strength of MBT waste was tested using direct shear. To an unreinforced basic matrix of either MBT or compost were added reinforcing elements in a controlled way to investigate the impact on shear strength from each identified reinforcement property.

DECLARATION OF AUTHORSHIP

I, Sudarshana Fernando, declare that the thesis entitled Shear Strength Characteristic of Mechanically Biologically Treated (MBT) Waste and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this works have been published as

Fernando, S., Powrie W., Watson G., Richards D.J., (2008). The Impact of the Reinforcing Content on the Shear Strength of Mechanically Biologically Treated Waste. Hydro-Physico-Mechanics of landfills. Braunschweig, Germany.

Signed: ……………………………………Date: …………………………….

TABLE OF CONTENTS

CHAPTER 3

WASTE CHARACTERISATION, MATERIALS AND METHODS

List of Figures

List of Tables

Chapter 1

Introduction

The shear stress characteristics of waste are one of the most important factors in landfill engineering including infrastructure designs, stability calculations and landfill maintenance. Waste is the major component in a landfill system. The shear strength of the waste plays a major role in the stability and integrity of various landfill components including the subgrade, lining and cover system as well as the drainage system integrity and leachate/gas well integrity and waste slope stability (Dixon & Jones, 2005).

The shear stress characteristics and behaviour of the waste are still not fully understood. Though the UK has not been experienced, large scale landfill failures, disasters in other countries show the lack of understanding of waste strength and its consequences to the environment and even to the human lives (e.g. Eid *et al*. 2000).

The heterogeneous nature of waste and changing composition have created difficulties in determination of general strength characteristic values.

The role of reinforcing elements on shear strength is one of the main areas which is poorly understood. In reinforced sand studies, attempts have been made to understand the role of the reinforcements in shear strength. There are huge property differences between reinforced sand and waste, though both show similar structures. How the reinforced sand findings are applicable for waste have not yet been investigated in depth.

In near future, post-Landfill Directive wastes, probably Mechanically Biologically Treated waste (MBT) will replace Municipal Solid Waste (MSW). MBT will differ from MSW in terms of its reinforcement properties and content and the waste matrix properties, as a result, the strength characteristics of MBT waste will not be the same. To understand the strength characteristics and properties of this new type of residual waste is vital for landfill engineering.

Geotechnical strength determination methods are widely used to determine the waste shear strength (such as direct shear, triaxial, etc). In this research direct shear test was used to determine the MBT strength characteristics.

Aims and objectives

In light of the above, the main aims of the research are to,

a) Identify the shear strength characteristics of aerobically treated 0-10 mm and 0-20 mm New Earth Solutions (NES) MBT using direct shear equipment
b) Identify the impact of the reinforcing elements on the shear strength of the MBT using direct shear equipment

The objectives of this research are to understand;

- The changes to the shear strength characteristics of the MBT waste, as a result of the MBT process;
- The changes to the reinforcement (e.g. content and size) in the MBT and its effect on the strength;

- How the field condition changes (such as moisture content, unit weight) impact on the strength of the MBT and
- The impact of reinforcement on shear strength of MBT, considering reinforced sand as an analogue material

Organisation of this thesis

This thesis consists of six chapters as follows,

Chapter 1 - Summarises the context of the work and defines the aims and objective of the research

Chapter 2 – Explains the background to this research work in detail

Chapter 3 – Characterisation of the MBT waste used in this research. The MBT waste was analysed using MSW waste classification methods. Proctor compaction test (using the BS 1377:4), interface strength of the reinforcements and MBT matrix, particle density of the MBT and each waste component were conducted as a part of the classification.
Methodology used in this research, including description to the equipment and setups to the equipment and sample preparation method.

Chapter 4 – The strength characteristics of the MBT residuals were assessed using direct shear tests. The effects of moisture content and unit weight on strength were investigated. Volume change of the sample with shear displacement was measured accurately, using 4 LVDTs. Shear strength and its relation to shear displacement was assessed using two different size shear boxes.

Chapter 5 – Reinforcing element properties and their impact on the shear strength of MBT was determined using 0-2.8 mm fraction as a basic matrix with reinforcements introduced in a controlled way.

Chapter 6 – Conclusions and recommendations for future work

Chapter 2

Background

Soil is considered as a comparatively heterogeneous material, but MSW is far more heterogeneous. Soil comprises particles of different mineralogy (Barnes, 2000), but the material as a whole is homogeneous compared to waste. Waste mechanics is derived from soil mechanics, which was originally aimed at a relatively homogeneous, incompressible material.

MSW comes from domestic and commercial sources. The composition of MSW is likely to depend on various local social and economic factors as well as changing with the seasons and legislation. As a result of this, the composition of the waste within a landfill will also change over time. As the strength of a material depends on other material properties, the strength characteristics of the waste are likely to change with composition. Grisolia *et al*. (1995) conducted waste analysis on seven different truck loads of waste, summarised in Table 2., which showed heterogeneity over even a relatively small area and timescale.

Table 2. 1 - Waste composition summary for seven truck loads (from Grisolia et al 1995)

Waste categories	% of wet weight		
	Minimum	**Maximum**	**Average**
Food	24.53	36.08	28.15
Green yard	0.00	5.51	1.87
Paper/cardboard	26.76	37.25	30.63
Light plastic	7.54	10.86	9.02
Hard plastic	2.07	4.81	3.13
Textiles/rugs	2.36	4.84	3.57
Diapers	2.67	4.50	3.59
Glass & soils	3.77	13.90	7.30
Metals	2.27	2.84	2.42

MSW generally consists of different components such as glass, paper, plastics, textiles, rubber, stones, garden waste, food waste as shown in Table 2.1. As well as variations in composition, there is also a significant variation in particle size from clay to mattresses and different particle shapes.

Due to the variation of composition as well as the particle size and shape, it is very difficult to predict the mechanical properties of waste essential to landfill engineering. (Kavazanjian (2001) found friction angle and cohesion varying respectively 10°-53° and 0-67 kPa in waste)

In the light of this, waste classification systems have been developed.

2. 1 Waste classification

Many researches have developed waste classification systems including Landva & Clark (1990), Grisolia et al. (1995), Kolsch (1995) and Dixon & Langer (2006).

Landva & Clark (1990) classification

Landva & Clark (1990) classified waste components into two major categories and each major category into two sub-categories as follows;

- Organic
  - Putrescible (OP) – readily degradable such as food and garden waste
  - Non-putrescible (ON) – slowly biodegradable such as paper and wood

- Inorganic
  - Degradable (ID) – corrodible such as metals
  - Non-degradable (IN) – such as glass, ceramic, ash

ON, ID and IN were categorised into three further categories;

1) Hollow containers (e.g. bottles, pipes, cans, etc.)
2) Platy or elongated items (e.g. beams, sheets, etc.)
3) Bulky items (e.g. furniture, appliances, auto bodies, etc.)

Landva & Clark (1990) also classified under a further four areas;

1) water content
2) organic content
3) specific gravity

4) particle size analysis

Grisolia *et al*. (1995) classification

Grisolia *et al*. (1995) developed their classification from the perspective of mechanical behaviour and divided MSW into the following classes:

- Class A (inert stable elements) – materials that do not modify their initial composition in the medium term such as soil, glass, ceramic, etc.
- Class B (highly deformable elements) –materials that tend to provide high initial settlement under stress such as paper, plastic, rubber, etc.
- Class C (readily biodegradable elements) – material such as food waste that change significantly due to biodegradation.

Kölsch (1995) classification

Kölsch (1995) classification added two new classification areas namely material group and particle dimension. Under this classification, waste components were placed into one of seven material groups probably based on the stiffness and the strength of the waste components.

- Material (7 groups)
  - Paper (including cardboard)
  - Smooth synthetic (foils, rubber, textile, etc.)
  - Hard synthetics (plastics, hard leather, etc.)
  - Metals

- Minerals (glass, ceramic, soil, etc.)
- Wood
- Organics (biowaste, grass, etc.)

- Particle size
  - 0 - 8 mm
  - 8 - 40 mm
  - 40 – 120 mm
  - 120 – 500 mm
  - 500 – 1000 mm

The latter two groups were sorted manually, the others by sieving .

Under Kölsch (1995) waste particles were categorised into four dimensions.

- 0 Dimension – grain
- 1 Dimension – fibres
- 2 Dimension – foils
- 3 Dimension – box

Dixon & Langer (2006)

Dixon & Langer (2006) expanded on earlier classification systems and used four major sub-divisions,

- Material groups (based on engineering properties compatible with Kölsch (1995))
- Shape related subdivisions following Kölsch's earlier work and expanding on it to include behavioural components:
  - 1D

    - 2D which would act as reinforcing components increasing the strength of the material
    - 3D which was split into compressible & incompressible
- Particle size (as Kölsch (1995))
- Degradation potential

A classification system for MBT waste is discussed and implemented in Section 3.1 by considering the above classifications.

2. 2 Waste structure

Jessberger *et al*. (1995) considered MSW as a compound material consisting of a basic matrix of granular materials and a fibre matrix of 1 and 2D particles which increase the strength of the material by providing reinforcement as shown in Figure 2. 1.

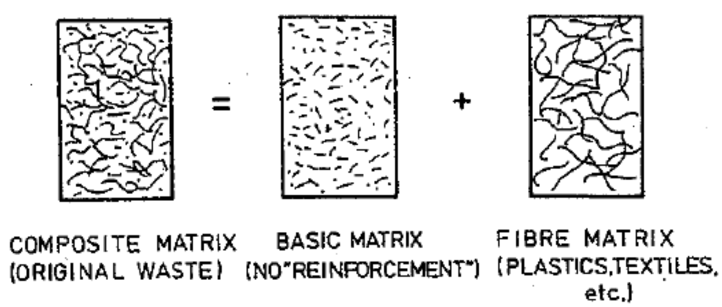


Figure 2. 1 - Waste as a compound matrix with non reinforced basic matrix and a fiber compound matrix (after Jessberger et al. 1995)

The model for waste proposed by Jessberger *et al.* (1995) is similar to reinforced sand with randomly distributed reinforcing elements, mostly fibres. Sand can be considered as the basic matrix. There are differences between the two materials, for instance soil particles are denser and harder than most of the materials found in waste. Soil particles are usually considered to be incompressible which is not the case for some of the components of MSW (e.g. plastic bottles, tin cans). Reinforcements in waste are mainly 2D particles (Chapter 3) whereas the reinforcing particles added into soils are typically fibres (i.e. 1D). Reinforced soil (as an analogue material) can help in enable understanding of waste behaviour; however, comparisons of the two materials need to be treated with care due to the differences in properties.

2. 3 Shear strength of waste and concepts

The mechanical properties of waste are different to those of soils due from the different properties of the two materials as discussed. However, most of the mechanical testing of wastes has been carried out using geotechnical testing methods. Researchers have raised concerns about applying the concept of soil mechanics to waste due to the significant differences between the properties of the two materials (e.g. Dixon & Jones, 2005).

Researchers have attempted to explain the strength of waste using different concepts including Kölsch (1995), Powrie *et al*. (1999). Kölsch's and Powrie's concepts are discussed in detail in this chapter and the results are discussed according to these concepts in Chapter 4 & 5.

Kölsch (1995)

Kölsch (1995) provided a model of normal stress and its relationship to the shear stress in waste shear tests. Kölsch (1995) explained that waste strength has two components - friction and tension and that shear stress was dependent on sample deformation and the applied normal stress.
As shown in Figure 2. 2, the shear test was divided in to four major phases.

Phase 1 – in the initial stage, the shear resistance is due mainly to friction as reinforcements within the waste have not been yet had their tensile capacity mobilised

Phase 2 - Shear resistance consists of friction and tension. During this phase tension in the reinforcing particles starts to contribute and increases to its maximum

Phase 3 - Shear resistance is again made up of friction and tension in the reinforcements. As a result of slipping or tearing of the reinforcement, the tensile component reduces from the maximum to zero during this phase.

Phase 4 – Under larger deformations as reinforcements are not creating any reinforcement effect, the shear stress in purely frictional

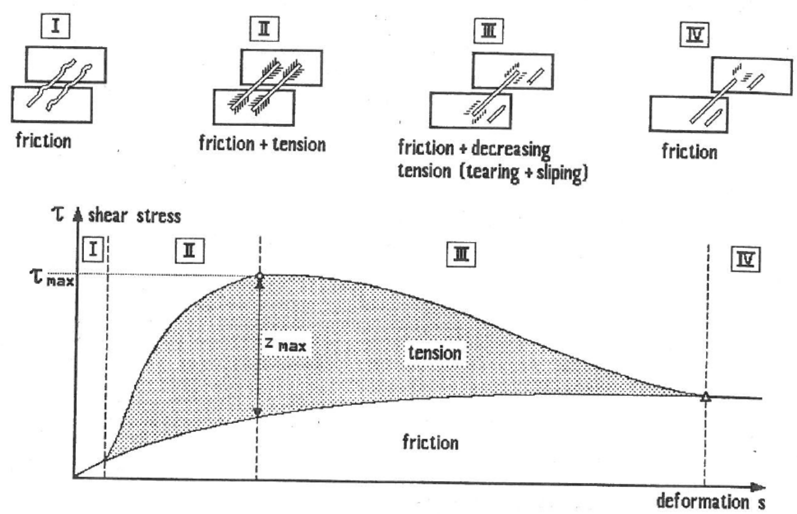


Figure 2. 2 - Behaviour of the reinforcement during the shear stage (after Kölsch, 1995)

Kölsch (1995) model showed how the tensile stress in the reinforcements depends on the normal stress (Figure 2. 3). Under low normal stresses ($\sigma<\sigma_1$) and high normal stresses ($\sigma>\sigma_4$), there is no significant reinforcing effect. At intermediate stresses ($\sigma_1<\sigma<\sigma_4$), there is a reinforcing effect

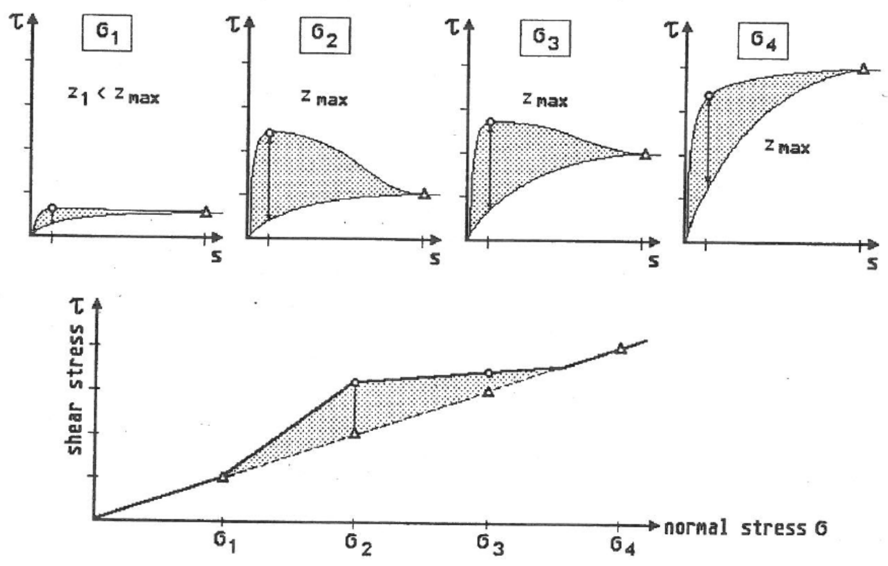


Figure 2. 3 - Behaviour of the reinforcement with the normal stress (after Kölsch, 1995)

Powrie *et al*. (1999)

Powrie *et al*. (1999) examined the validity of the Mohr-Coulomb failure criteria (which conventionally describes the shear strength of soil) for waste and argued that cohesion and angle of friction are inappropriate for wastes as:

- Cohesion is due only to the reinforcing effect and as discussed in Kölsch (1995) at low confiningr stresses, the reinforcing effect is negligible or non- existent
- φ as friction angle is not correct regarding the waste. When cohesion is omitted, Ø represents both the frictional and tensile components. Powrie *et al*. (1999) suggested it would be better referred as "angle of shearing resistance".
- Angle of shearing resistance under higher stresses cannot be applied under the lower normal stress due to the relationship between tension (due to the reinforcing effect) and normal stress (as discussed in Kölsch (1995))

The concepts developed by Powrie *et al*. (1999) and their applicability will be discussed in detail in Chapter 5.

2. 4 Major factors affecting the shear stress of waste

MSW is a highly heterogeneous material (because of its changing composition and component range). The most appropriate way to study waste strength is to investigate how changes in the waste affects the strength characteristics.

The factors likely to have an effect on the shear strength of waste are reinforcement content, orientation and interface properties; particle size, dimension, and stiffness; decomposition/age; basic matrix properties; and normal stress. Unit weight and moisture content will also have an effect and these are discussed in Chapter 4.

2.4. 1 Reinforcement content and its impact on shear strength

Reinforcement content and its impact on the strength of the compound material has been investigated in waste and reinforced sand by many researchers (including Fucale *et al*. (2007); Tang *et al*. (2007); Dixon & Langer (2008); Shewbridge & Sitar (1989 & 1996); and Benson & Khire (1992)). Studies show that the inclusion of the reinforcements has a positive impact in increasing the strength of the material. i.e. in general when the reinforcement content is increased, the strength of the material is increased.

Santoni *et al*. (2001) reported;

- sub-optimal reinforcing content in sand results in strain softening characteristics
- optimal reinforcing content results in strain hardening characteristics

- super-optimal reinforcing results in excessive deformations to create load support capabilities

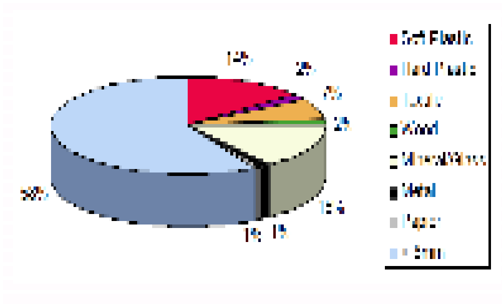


Fig 2.4

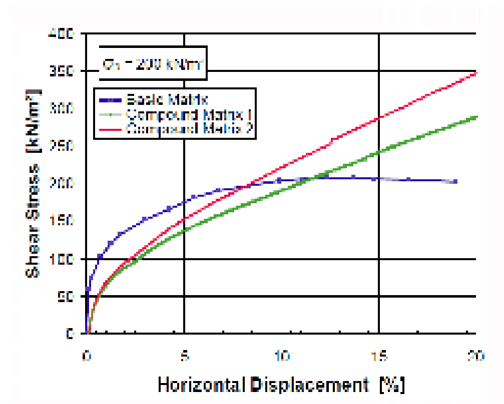


Fig 2.5

Figure 2. 4 - MBT composition
Figure 2. 5 - Direct shear results for the basic matrix, matrix 1(20% >8mm) and matrix 2 (10% >8mm) in 0-8 mm basic matrix under 200kPa normal stress using a 300mm shear box (after Fucale et al. 2007)

Figure 2. 5 shows that the unreinforced (basic) matrix has lower shear trength than the two compound matrices. There is clear evidence that the waste components larger than 8 mm (i.e. reinforcing elements) have the ability to increase the shear strength of the material. The material with the lower reinforcing content (matrix 2) has a higher strength than the material with 20% reinforcement (matrix 1). The basic matrix shows higher stiffness and lower strength with displacement. This result clearly shows that changes to the reinforcing content affect the shear strength of MBT and a greater amount of reinforcements than an optimum reduce rather than enhance the shear strength of the waste.

Tang *et al*. (2006) used sand (with a D_{60} of 0.0117mm) reinforced with different percentages by mass (0.05%, 0.15%, 0.25%) of polypropylene fibre (12mm length and 0.034mm diameter) and determined the unconfined compressive strength with the changing fibre content. When 0.05% of fibre was added to the soil it showed a significant increase in the peak strength, and with increased fibre content (0.15% and 0.25%) both peak and post peak strengths were increased as shown in Figure 2. 6.

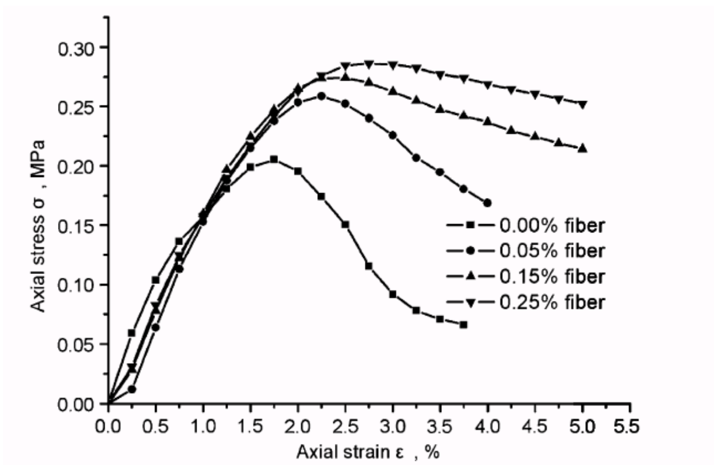


Figure 2. 6 - Strength increase with increasing fibre contents under unconfined compressive strength test (after Tang et al. 2007)

Tang *et al*. (2007) did not observe a reduction in strength with increasing fibre content as reported in Fucale *et al*. (2007), probably due to the significantly lower fibre contents used in their study. Fucale *et al*. (2007) may have had a reinforcing content greater than the optimum range (Fucale had 20% >8 mm content) to find the same as Santoni *et al*. (2001) with high fibre content (i.e. higher than optimum).

Chapter 3 Section 3.3 shows that the plastic/plastic interface strength is weaker than the MBT matrix/plastic interface strength. A higher reinforcing content leads to more plastic/plastic interactions and hence lower strength characteristics can be expected.

2.4. 2 Waste basic matrix and its impact on shear strength

How the basic matrix affects the strength has been investigated in reinforced sand studies as well as in waste (e.g. Santoni *et al*. (2001); Kaniraj & Gayathri (2003) and Kaniraj & Havanagi (2001)- sand and Dixon & Langer (2008) - waste).

In reinforced sand studies the preparation of fine soil particles affects the unconfined compressive strength. Santoni *et al*. (2001) used 1% by mass of 51 mm fibres in unconfined compression tests using sand as the matrix. In these tests, the silt content in the sand was varied from 1% to 12%. The results showed that the maximum strength was achieved with a 1% silt content but the strength with a silt content of 8% was still greater than that of the silt-free material. However, when the silt content was increased further to 12%, the final strength of the material decreased below that of the silt-free material as shown in Figure 2. 7.

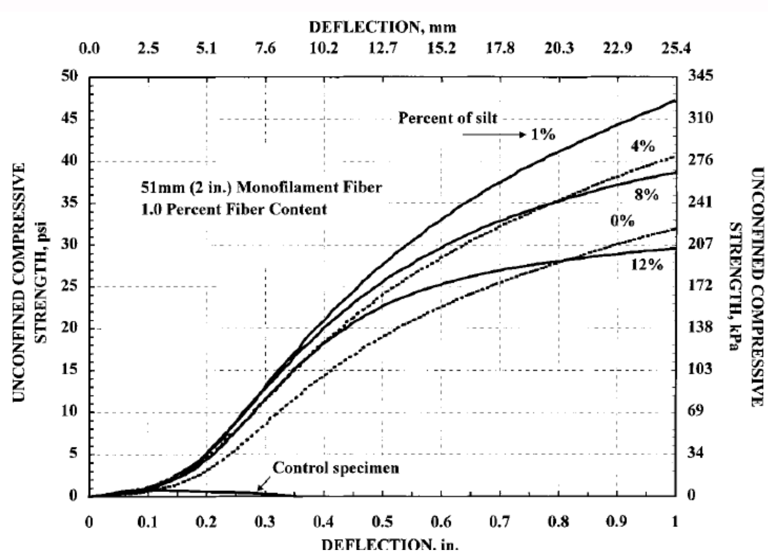


Figure 2. 7 - Shear strength change with the changes to the silt content in reinforced sand determined using unconfined compression tests (after Santoni et al. 2001)

These results show that changes to the basic matrix (in this case, the amount of fines) have a significant impact on the strength characteristics. This would suggest that the shear strength of waste may change over time due to biological degradation.

2.4. 3 Decomposition and its impact on shear strength

Unlike soils, waste changes its composition with time, due primarily to biological and chemical degradation (e.g. rusting). However, strength tests on degraded waste suggest on similar shear strength to undegraded waste (i.e. aged wastes seem unaffected by degradation) (Kavazanjian, 2001).

However degradation of the waste is likely to change the properties of the material;

- Due to the breakdown of the organic material, a finer matrix material can be expected in aged waste compared with raw MSW
- Although reinforcing materials such as flexible and stiff plastics are unlikely to be significantly affected by decomposition, other reinforcing materials such as paper and wood are likely to be weakened or removed by biodegradation
- Heating during aerobic degradation may lead to increased brittleness and reduced strength in some plastics.

The shear behaviour of waste as it ages (decomposes) was investigated by Kuehle-Weidemeier (2006). As shown in Table 2. 2 the average friction angle of the aged waste was the same as fresh waste. The cohesion of aged waste is lower (4 kPa) than that of fresh MSW but the difference is less than 10% so is unlikely to be significant. These results show that the age of the waste has only a small influence on the strength parameters. However, as these studies were conducted on different waste samples (aged and fresh), the sample composition was probably not the same, making comparisons between the two waste types difficult.

Table 2. 2 - Shear strength properties of fresh and old waste (Kuehle-Weidemeier, 2006)

Waste type	**Avg. friction angle (°)**	**Cohesion (kN/m^2)**
Fresh MSW	29	50
Old or composted MSW	29	46

Waste composition is highly dependent on social and economic conditions in the collection area, which may change over time. For example, significant increases in rates of recycling over the last decade or so have changed the composition of residual waste. The results obtained from fresh and old waste samples not easy to compare due to the heterogeneous nature of the waste, which changes with time as explained.

It is clear that properties of the waste are likely to change with the degradation, which likely leads to an impact on shear strength. However it is difficult to draw conclusions on the level of degradation and its impact on the shear strength from the available data.

2.4. 4 Particle size and its impact on shear strength

Reinforcement particle size and its impact on strength has been studied by many researchers including Jessberger (1995); Consoli *et al*. (2007); Santoni *et al*. (2001); Foose *et al*. (1996); Consoli *et al.* (2002) and Casagrande *et al*. (2006). Jessberger (1995) conducted large (540 mm diameter) uniaxial compression tests on two different waste types - as-received MSW and the MSW fraction passing a 120 mm sieve (85% MSW is smaller than 120 mm). The compression testing results showed that the sample with <120 mm material failed with a peak at 20% strain. The

MSW sample increased its compressive strength with strain without reaching a peak or a failure in contrast to the sieved sample as can be seen in Figure 2. 8. This may be an indication that the particle size has an impact on the compressive strength of the waste.

Note: As about 15% of the waste was removed by sieving, it is likely that composition of the waste was changed

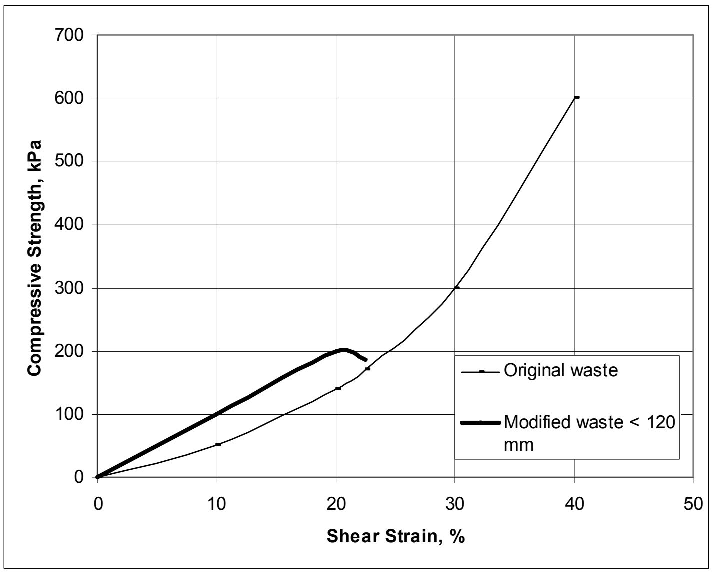


Figure 2. 8 - Unconfined compression test on as received MSW and >120mm components separated MSW (after Jessberger *et al*. 1995)

Consoli *et al*. (2007) used a ring shear apparatus to investigate the residual strength of reinforced sand at large shear strains. Sand with an effective diameter (D_{10}) of 0.16 mm was used with 0.023 mm diameter polypropylene fibres of 6, 12 and 24 mm length. The fibre content was 0.5% by dry soil mass. The displacement rate used was 0.17 mm/min in all tests. The results of these tests are shown in Figure 2. 9 and indicate that:

- Fibre length has a strong influence in increasing the residual strength. The sand with 6 mm fibres showed a slight increase in residual strength compared with the unreinforced material. Sand reinforced with the 12 and 24 mm fibres showed the same residual strength – in both cases higher than that achieved by the sand reinforced with 6 mm fibres.

- under lower normal stresses such as 20 kPa and 100 kPa, the shear strengths were not much different in reinforced sand samples regardless of the reinforcement length.
- at higher normal stresses higher differences in shear strength can be observed as shown in Figure 2. 10 (a).

After about 3000% strain, the length of the fibres was measured and it was found that the fibre length was 4 mm – 6 mm in each case. This indicates the fibres less longer than 4 - 6 mm tend to fail by pull-out rather than elongation or breakage with the sand used in these tests. It can be assumed there is a minimum length for the fibres to act as reinforcement in order to provide the tensile strength (equally fibres greater than 4-6 mm length may be in tension). All of the specimens studied by Consoli *et al.* (2007) contained 0.5% fibres with 0.23mm diameter. After breaking the fibres at large strains it was evident that strengths were higher in the samples with the greater initial fibre length. As longer reinforcements elongated to a great extent (Fig. 2.10(b)), the contact surface area of the fibres has probably increased.

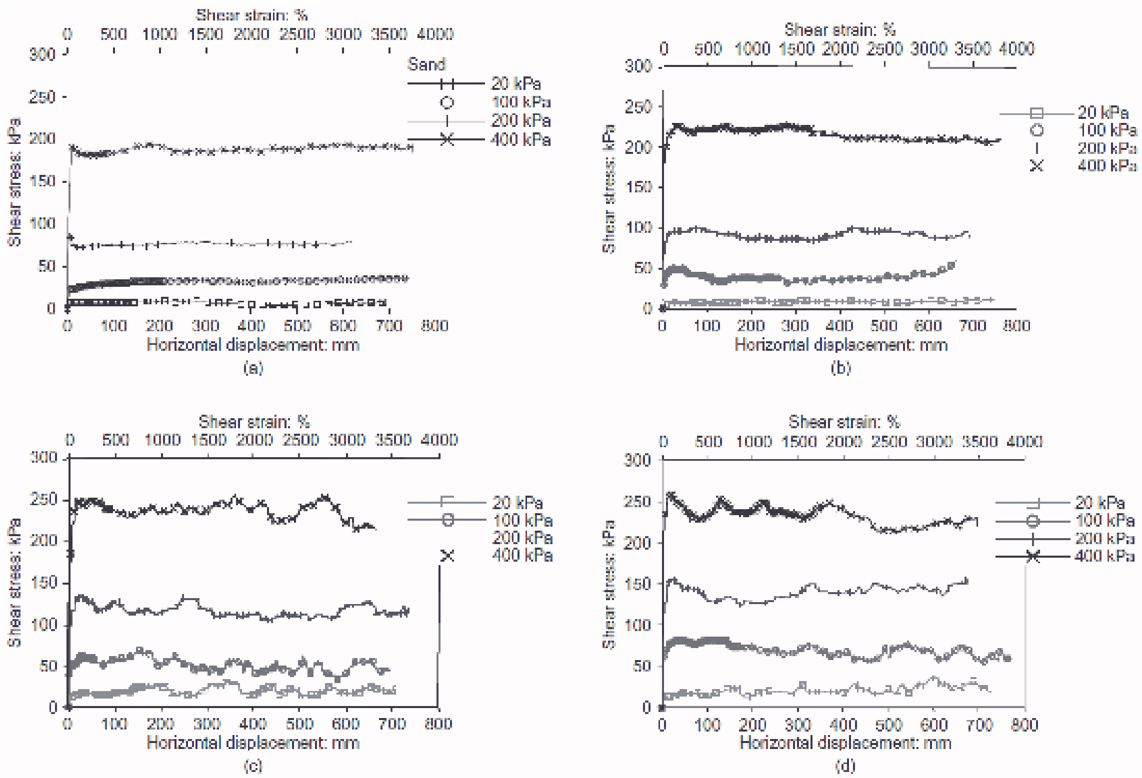
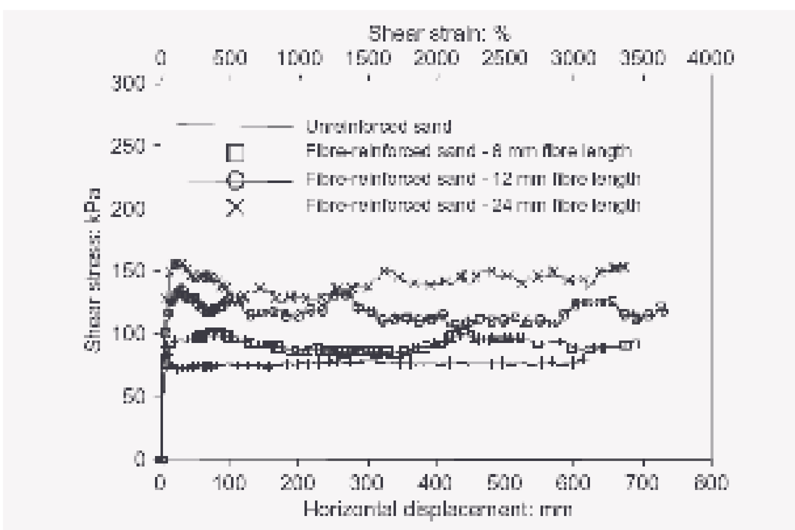
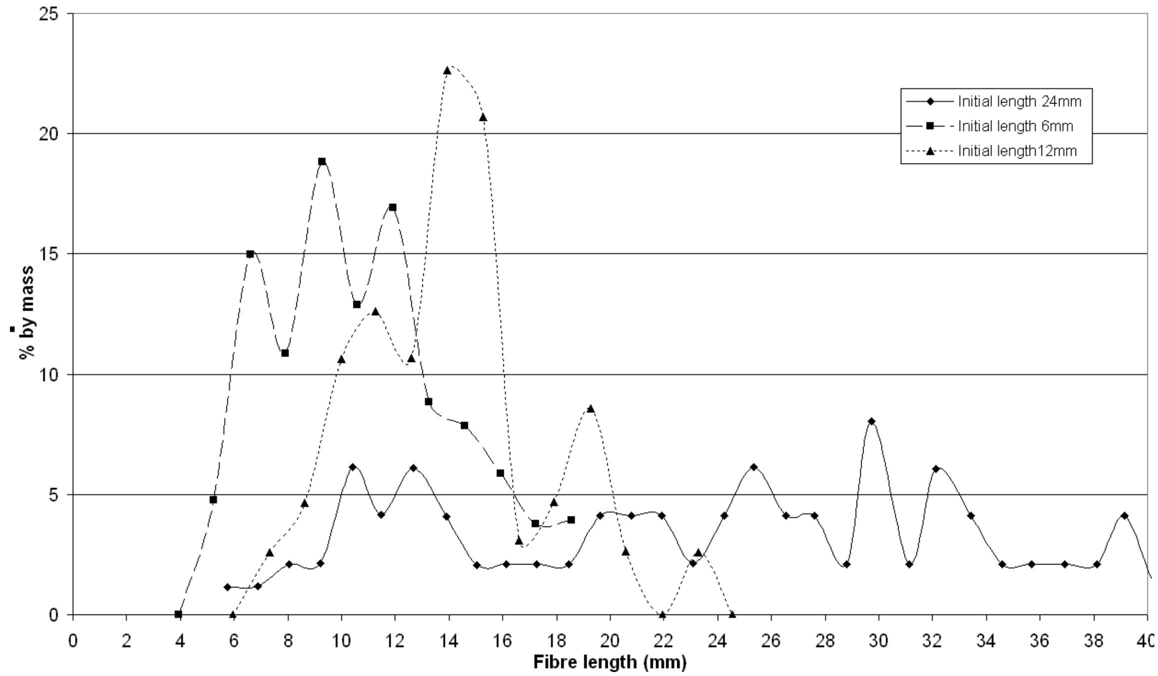


Figure 2. 9 - Ring shear results on reinforced sand - fibre content of 0.5% and diameter of 0.023mm, sand effective diameter 0.16mm. Sand mixed witha) no fibres b) 6 mm fibres c) 12 mm fibres d) 24 mm fibres (after Consoli et al. 2007)



(a)



(b)

Figure 2. 10 - (a) Comparison between specimens with different fibre lengths under normal stress 200 kPa with ring shear (after Consoli et al. 2007) (b) Fibre length variation with strain under 200 kPa, showing fibre stretching and breakage (Consoli et al. 2005)

It seems that reinforcement length has an influence on the shear strength and there is a minimum length for a reinforcing particle to provide a significant tensile strength.

2.4. 5 Particle dimension and its impact on shear strength

The impact of particle dimension on the strength has been studied by researchers including Santoni *et al.* (2001); and Michalowski & Cermác, (2003). Most reinforced sand studies used 1D reinforcement with relatively few using 2D reinforcement (e.g. Foose *et al*. 1996). However most of the reinforcing particles in waste are likely to be two dimensional (2D) and this is discussed in detail in Chapter 3.

Santoni *et al.* (2001) conducted unconfined compression tests on sand reinforced with 1% by mass of different types of fibres with different lengths and dimensions (1D and 2D). Because of the cohesionless nature of the reinforced sand, water was added to enable moulding of specimens. A moisture control study on the sand had been conducted prior to the each test to determine the target moisture content. The unconfined compressive strength increased with the length of the fibres until the length reached 2” (50.8mm). When the fibre length was increased to 3” (76.2mm) the strength was reduced as shown in Figure 2. 11.

In contrast to the fibre reinforced sands, when the tests were repeated using reinforcing tapes (i.e. 2D rather than 1D), the strength was seen to increase with increasing reinforcement length as shown in Figure 2. 11.

The results of Santoni *et al.* (2001) suggest that there is an optimum fibre length and that this is dependent on fibre dimension; probably related to the contact area between the fibre and the matrix.

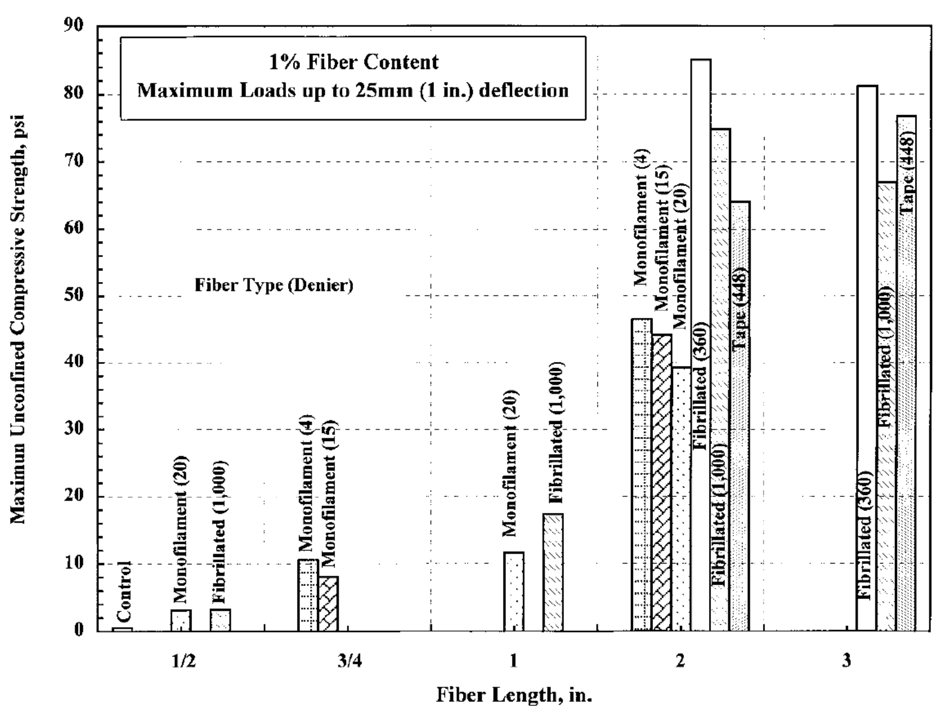


Figure 2. 11 - The impact of the fiber shape and length on the strength (after Santoni et al. 2001)

2.4. 6 Orientation of reinforcement and its impact on shear strength

The impact of reinforcement orientation on the strength of reinforced soils and waste has been investigated by Rajan *et al.* (1996); Jewell & Wroth (1987); Gray & Al-Refeai (1986) – sand, Zekkos (2005); Athanasopoulos *et al*. (2008) - waste.

Rajan *et al.* (1996) and Jewell & Wroth (1987) attempted to identify the impact of fibre orientation in direct shear tests on reinforced sand. Zekkos (2005) and Athanasopoulos *et al*. (2008) studied reinforcement orientation and its impact on waste strength. These researchers focussed on the reinforcements which had been prearranged to a known orientation. Rajan *et al*, (1996) explained that the tensile stress in a fibre can be resolved into components normal and tangential to the shear plane. Normal components cause an increase in normal stress on the failure surface while the tangential component directly resists the shear.

Jewell & Wroth (1987) showed that the highest reinforcement impact can be achieved when the reinforcement is oriented at 30° vertical to the shear plane as shown in Figure 2. 12. Reinforcements have an adverse impact on strength when the reinforcement is in compression as shown Figure 2. 12.

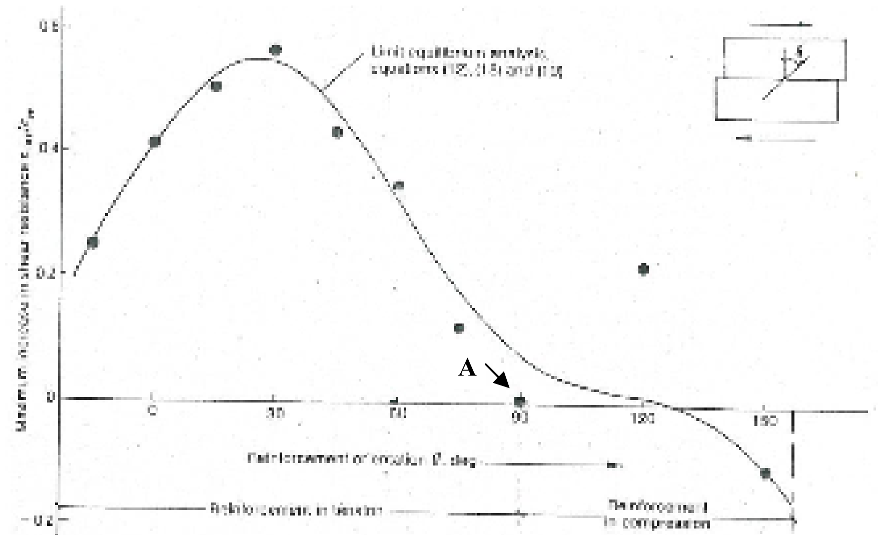


Figure 2. 12 - The impact of the fiber orientation and impact on the strength (after Jewell & Wroth (1987))

Zekkos *et al.* (2007) investigated the effect of reinforcement orientation in MSW using a waste sample which had 62% of particles passing a 20 mm sieve. This research found that the sample with reinforcements parallel to the shear plane reached a constant shear strength in a direct shear test. The best-fit curve in Figure 2.12 implies that there is some reinforcing effect from horizontally aligned reinforcements. However the data Point A in Figure 2.12 shows clearly there is no reinforcement effect from horizontally aligned reinforcements. The sample where the reinforcement was aligned perpendicularly to the shear plane did not achieve a peak and strength increased with displacement until the end of the test as shown in Figure 2.13.

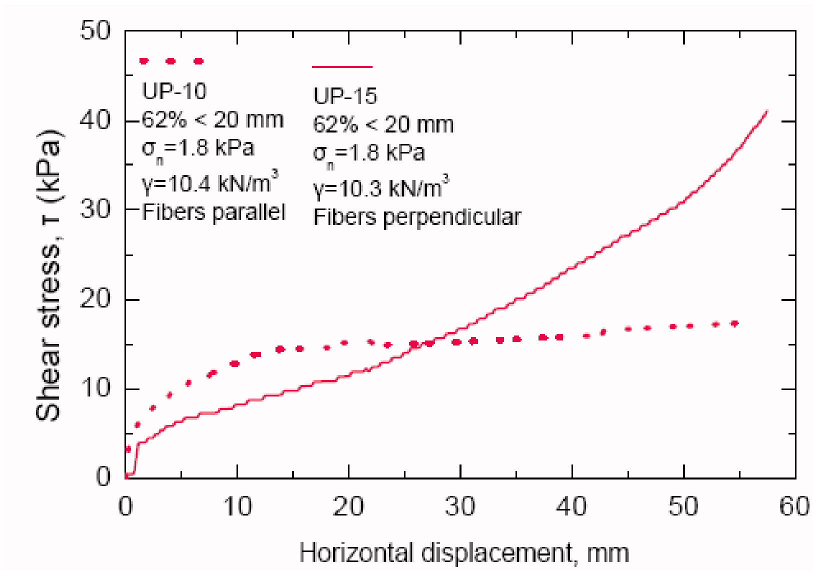


Figure 2. 13 - Comparison of the responses of MSW in direct shear testing for specimens in which the reinforcement is parallel and normal to the shear surface (after Zekkos et al. 2007)

These results confirm that the orientation of the reinforcement has a significant impact on the shear strength.

2.4. 7 Interface frictional properties of the reinforcement and their impact on the shear strength

Interface frictional properties and their impact on the compound material have been investigated by Michalowski & Cermác, (2003); Gray & Ohashi (1983) and Sewbridge & Sitrar (1996).

Michalowski & Cermác, (2003) studied the interface friction angle of steel fibres, polyamide fibres and polyamide sheets with fine and coarse sands. The aim of this experiment was to identify the interface frictional properties of the reinforcement when pulled out using modified direct shear equipment.

A 100mm length fibre with 0.3mm diameter were used and pulled out at a speed of 0.2mm/min.. The steel fibre showed higher interface frictional characteristics than the polyamide as shown in Figure 2. 14.

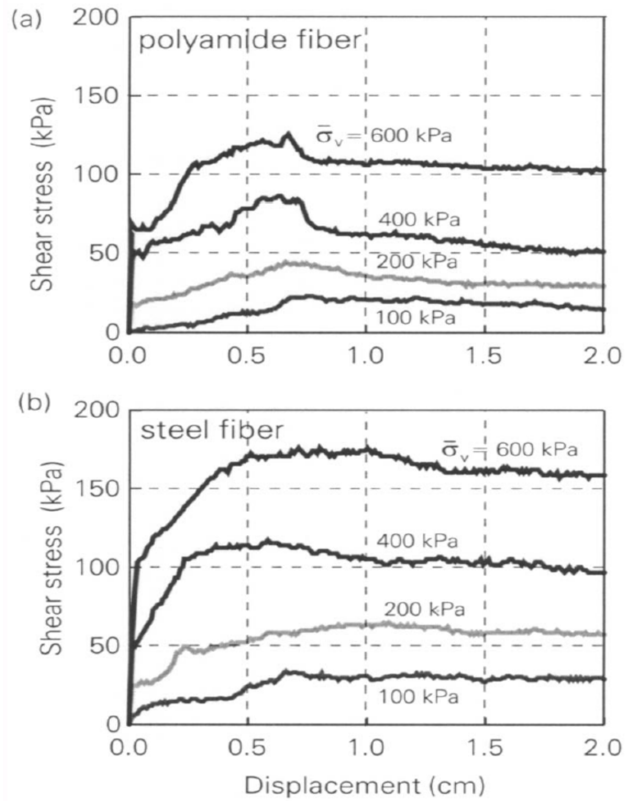


Figure 2. 14 - Fibre pullout strength (a) polyamide (b) steel (after Michalowski & Cermác, 2003)

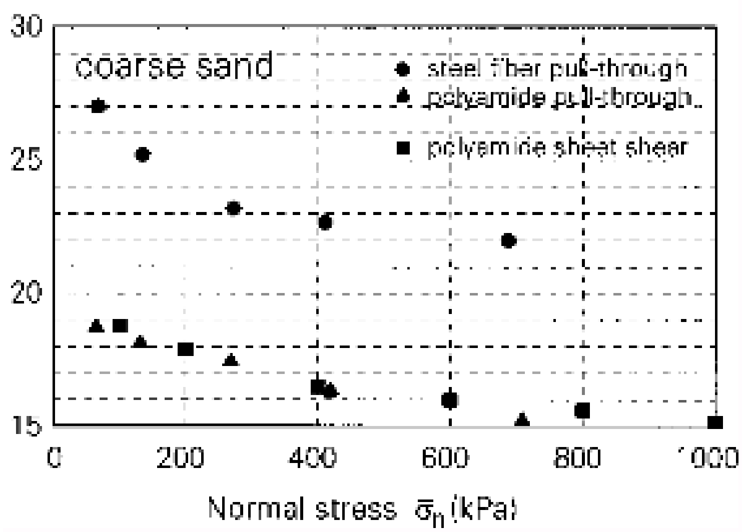


Figure 2. 15 – Peak fibre interface properties polyamide fibres, steel fibres and polyamide sheets (after Michalowski & Cermác, 2003)

These results showed that the use of 1D or 2D material from the polyamide sheet (same material) did not make much difference to interface friction angle. This would expected due to they having the same interface properties. Fibre pullout tests proved that the interaction between fibre and the matrix is mainly frictional.

Figure 2. 14 & Figure 2. 15 show that reinforcement with a high interface friction is likely to increase the shear strength of the material more than low friction reinforcement.

2.4. 8 Normal Stress and its impact on shear stress

Kölsch (1995) introduced a model to explain how the normal stress influences the shear strength of the waste as discussed previously in Section 2.3.

Borgatto *et al*. 2009 conducted a direct shear testing programme using a 300 mm shear box on MBT waste (0-60 mm). The classification of the material is shown in Figure 2. 16 and Figure 2. 17. To identify the impact of the reinforcement, the MBT waste was modified by eliminating the soft plastics and direct shear tests were conducted on both the as-received and modified samples under 25 and 300 kPa normal stresses as shown in Figure 2. 18 and Figure 2. 19.

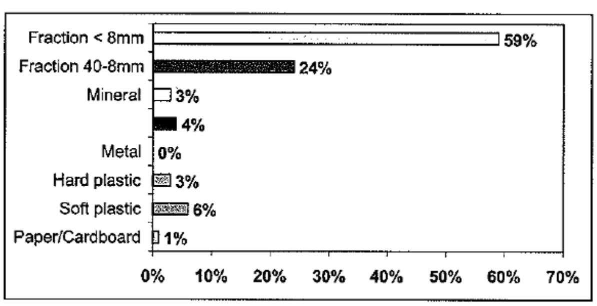


Figure 2. 16 -Classification of the waste material tested (after Borgatto et al. 2009)

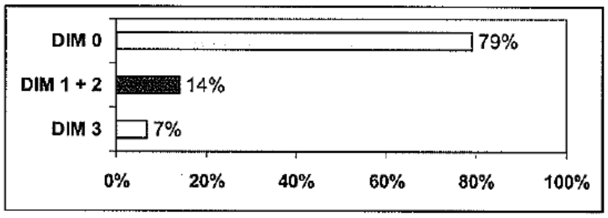


Figure 2. 17 - Classification of the waste material according to the dimension (after Borgatto et al. 2009)

The test with a 25 kPa normal stress showed that the original MBT material had a higher shear strength than the modified MBT as shown in Figure 2. 18. On increasing the normal stress the impact of the soft plastic was reduced. The final test at 300 kPa shows the shear stress curves of the MBT and modified MBT are almost the same, complying with the behaviour suggested by Kölsch (1995) at higher stresses.

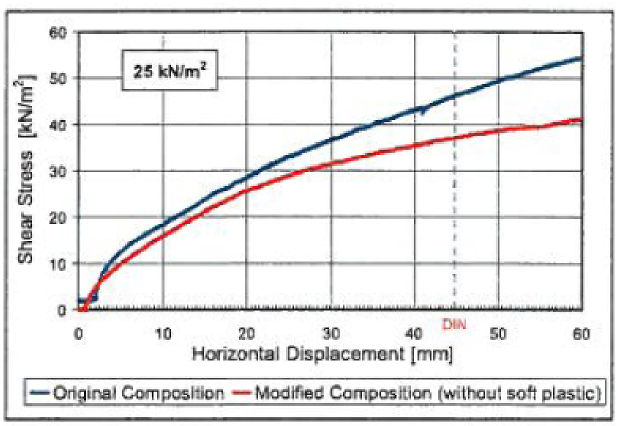


Figure 2. 18 - Shear displacement under 25 kPa using 300 mm shear box (after Borgatto et al. 2009)

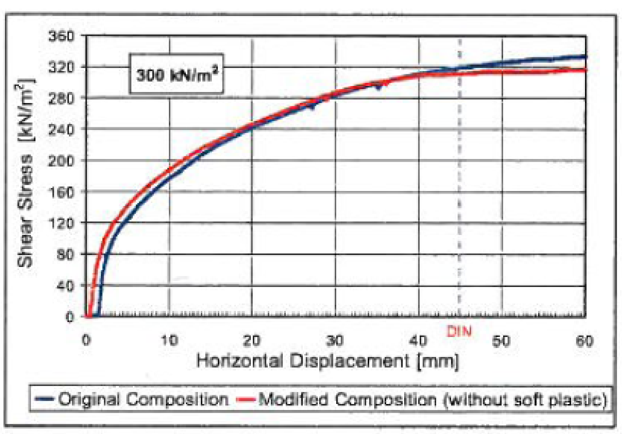


Figure 2. 19 - Shear displacement under 300 kPa 300 mm shear box (after Borgatto et al. 2009)

Zekkos *et al*. (2007) conducted direct shear tests on MSW specimens which included 100%, 62%, and 12% material with particles smaller than 20 mm. This suggests that Zekkos' basic matrix was 0-20 mm. Tests were performed at 5 normal stresses with the results summarized in Figure 2. 20.

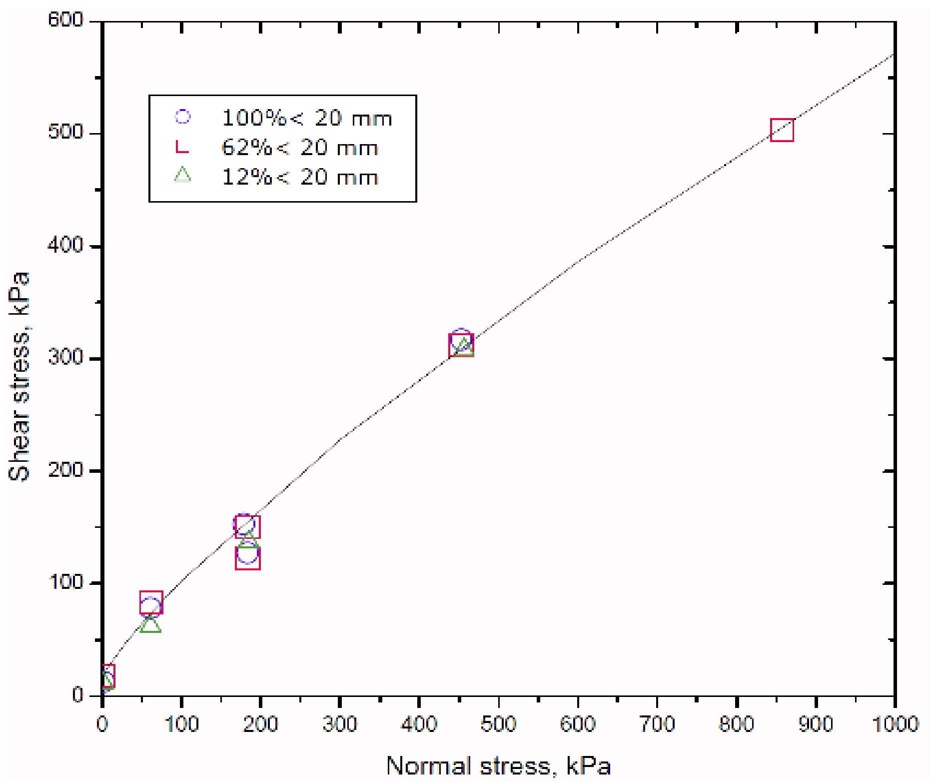


Figure 2. 20 Shear strength change with composition (after Zekkos et al. 2007)

The results do not show any significant difference in shear strength throughout the normal stress range. (i.e. the increased amount of fibrous material does not appear to be influencing any increase of the shear stress of MSW in direct shear). The reasons for this are probably due to sub-horizontal alignment of the reinforcing material caused by the sample preparation technique (tamping), which would have led to the reinforcing having very little effect as shown by Zekkos *et al*. (2007). The high reinforcement content may be greater than the optimum content range and the 0-20 mm fraction may have contained a high amount of reinforcing elements, which is used as the basic matrix in this testing programme.

2.4. 9 Reinforcement stiffness and its impact on shear strength

The stiffness of the reinforcements and its impact on the shear strength has been investigated by Shewbridge & Sitar (1996); Gray & Ohashi (1983); Shewbridge & Sitar (1989) and Jewell & Wroth (1987).

Jewell & Wroth (1987) found that the higher the stiffness of the reinforcing, the greater the contribution to the shear strength (Figure 2. 21).

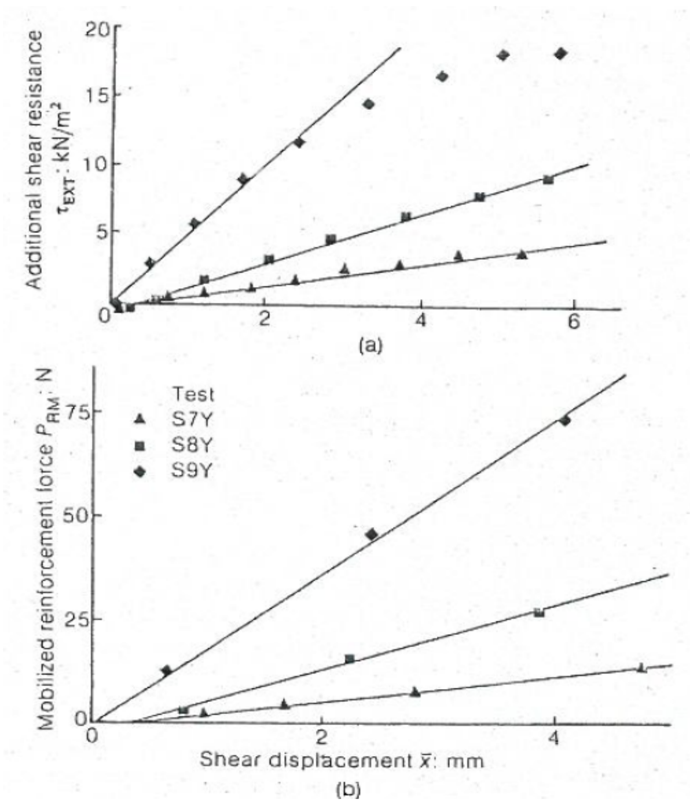


Figure 2. 21 - Shear strength change with stiffness of the reinforcements (after Jewell & Wroth, 1987) (stiffness S7Y – 0.107, S8Y-0.387, S9Y-1.5 kN)

Shewbridge & Sitar (1989) stated that reinforcements increase the strain hardening of the material and Shewbridge & Sitar (1996) stated that reinforcement stiffness increased the shear zone thickness while increasing the shear stress of the material.

2. 5 Shear strength of waste

Generally geotechnical testing methods are used to identify the shear strength of waste. Shear strength characteristics of waste have been studied by Grisolia *et al*., (2001); Kölsch (1995); Landva & Clark (1990); Zekkos (2005) and Kölsch (2009). The most common test methods are direct shear, triaxial and less commonly, unconfined compression. Some researches have made efforts to introduce other soil testing methods to waste. For example, Dixon & Jones (1999) carried out pressure meter tests on a landfill; Kavazanjian Jr., (1999) used simple shear tests on MSW and Kölsch (1995) developed a tensile test apparatus for use on MSW.

Consoli *et al*. (2007) and Yetimoglu *et al*. (2005) introduced the ring shear and CBR (California Bearing Ratio) test respectively for reinforced sand, but no attempts to apply these to wastes have been discussed.

2.5.1 Using direct shear equipment

Thomas *et al*. (1999) conducted direct shear tests on MSW using a 1 m x 1 m shear box and displacement rate of 3 mm/min. The composition of these samples I2 and I3 are shown in Table 2. 3;

Table 2. 3 - Composition of the waste samples (Thomas et al. 1999)

Component	**I2** **Unit Weight = 15.9 kN/m^3**	**I3** **Unit Weight = 11.9 kN/m^3**
Plastic	18.4	22.4
Paper	17.1	25.8
Textile	6.6	15.2
Inert	11.3	2.7
Metal	5.0	1.8
Fine	37.4	24.2
Wood	4.2	7.9

Sample I3 shows a higher content of reinforcements such as plastic, paper, textile and wood than I2. I2 was tested under two different normal stresses (two tests were conducted at 50 kPa and one at 100 kPa) and I3 was tested under one normal stress (75 kPa). The results are shown in the Table 2. 4. Sample I-3 with a higher reinforcement content shows lower stress ratio than sample I-2. This may be due to a higher than optimal reinforcing content.

Table 2. 4 - Summarised Shear Stress Ratios

Sample	**Normal Stress**	**Stress Ratio at 180mm displacement**
I2	50 kPa	0.986 and 1.222
	100 kPa	0.835
I3	75 kPa	0.795

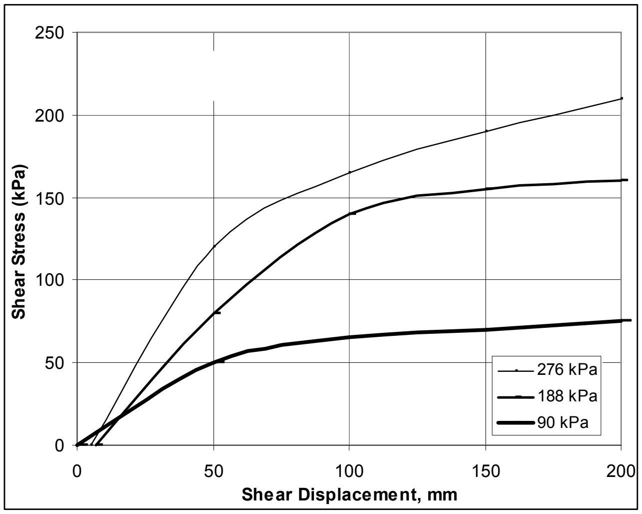


Figure 2. 22 - Direct shear results for MSW (after Kölsch, 2009)

Kölsch (2009) shows the shear strength continuing to rise with larger displacements until the end of the test using direct shear as in Figure 2. 22 - Direct shear results for MSW (after Kölsch, 2009)

Maher (2009) conducted a direct shear test programme on pre-treated MSW using a shear box with dimensions of 400 x 250 mm. The waste was shredded and aerobically treated in windrows. Results from the direct shear tests are shown in Figure 2. 23.

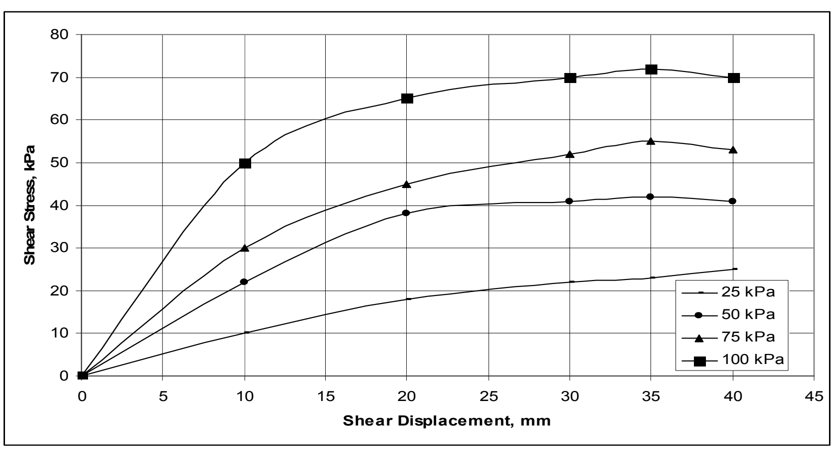


Figure 2. 23 - Shear strength plot for MSW using 400mm x 200mm shear box under 25, 50. 75, 100 kPa (after Maher, 2009)

The direct shear tests were conducted under normal stresses of 25, 50, 75, 100 kPa. At about 45 mm displacement, the direct shear curves at the two highest normal loads (100 kPa and 75 kPa) have achieved clear peak strengths while the 50 kPa direct shear test has achieved a constant shear stress. However the direct shear result at 25 kPa showed the shear strength is still slightly increasing after 45mm displacement.

The direct shear results of Maher (2009), Kölsch (2009) and Thomas *et al.*(1999) show:

- Reduction of the particle size may aid the achievement of a peak or constant shear stress with larger displacement (i.e. leads to observe failure in waste)
- Under high normal stresses, peak strength or failure is more likely to be observed.

2.5.2 Using triaxial equipment

Triaxial tests on waste (eg. Kavazanjian (2001), and Grisolia *et al.* (1995)) have shown that it can withstand very high strains without reaching failure as can be seen in Figure 2. 24. The reinforcements within waste may be elongating, providing a tensile component of strength without failing within the strain limits of the test.

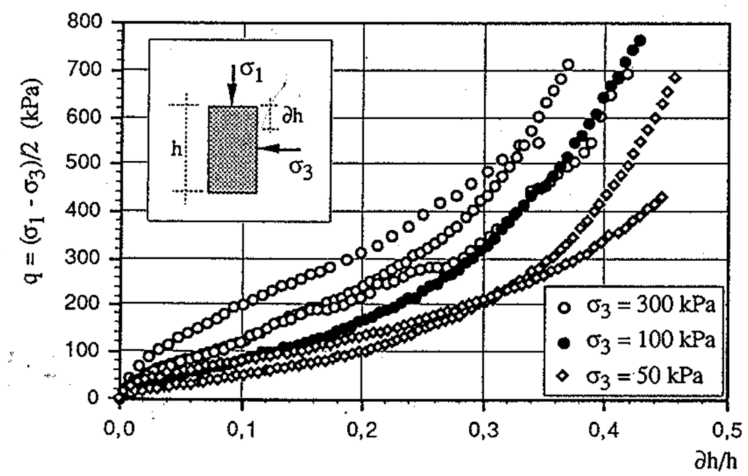


Figure 2. 24 - Triaxial tests: typical stress- strain curves (from Grisolia et al. 1995)

The increasing stiffness at higher displacement can be explained by the higher tensile forces in the reinforcements.

Zekkos *et al*. (2007) conducted triaxial tests on waste,

- Specimen < 20 mm (i.e. A3-2L)reached peak shear stress conditions at an axial strain of about 22% and then exhibited a post-peak reduction in shear resistance.
- When fibrous, >20 mm material was included (i.e., Specimen A3-7L with 62% < 20 mm) the specimen exhibited a lower stiffness initially , but at larger strains exhibited a progressive upward curvature without reaching a peak shear stress . Similarly specimen included 14% <20 mm (i.e. specimen A3-12L) material by weight, exhibited a more pronounced upward curvature.

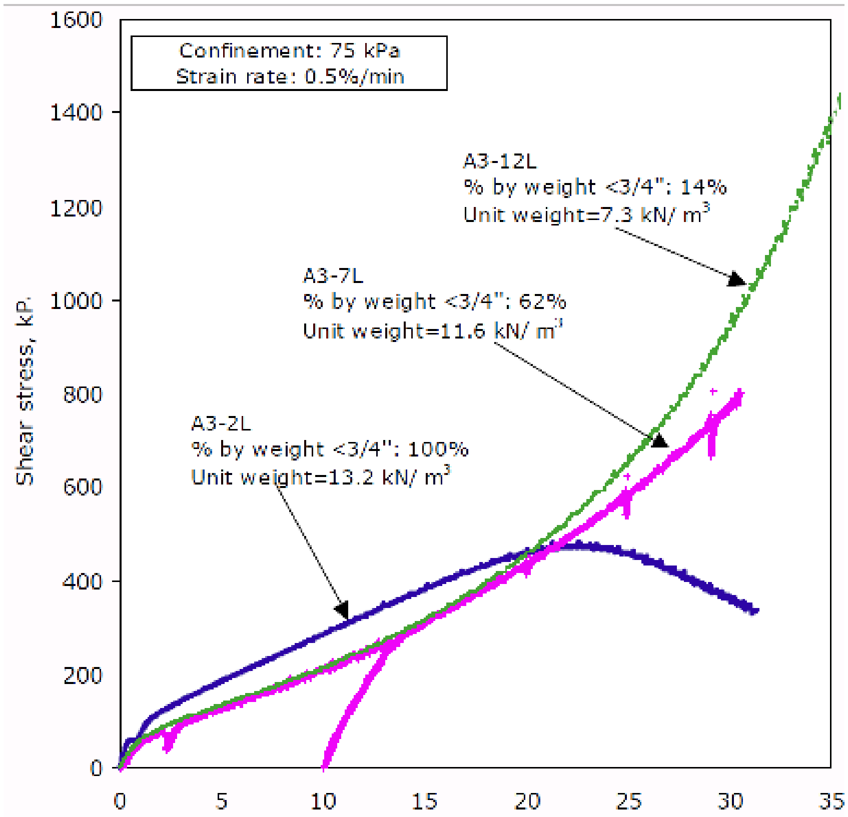


Figure 2. 25 - The effects of reinforcement content on shear stress and axial strain on 300 mm dia. triaxial tests on MSW (after Zekkos et al. 2007)

Triaxial results show,

- Reinforcement content increase the strength increases
- Upwards curvature with strain (compare to direct shear)

That it is hard to find triaxial and direct shear results conducted on the same waste samples. Zekkos (2005) conducted a study using a 300 mm direct shear apparatus on waste samples with different reinforcement contents similar to the triaxial tests shown in Figure 2. 25. For this study samples with 100%, 62% and 12% (instead of 14% in the triaxial test) of particles smaller than 20 mm were used. The results of these tests are shown in Figure 2. 26.

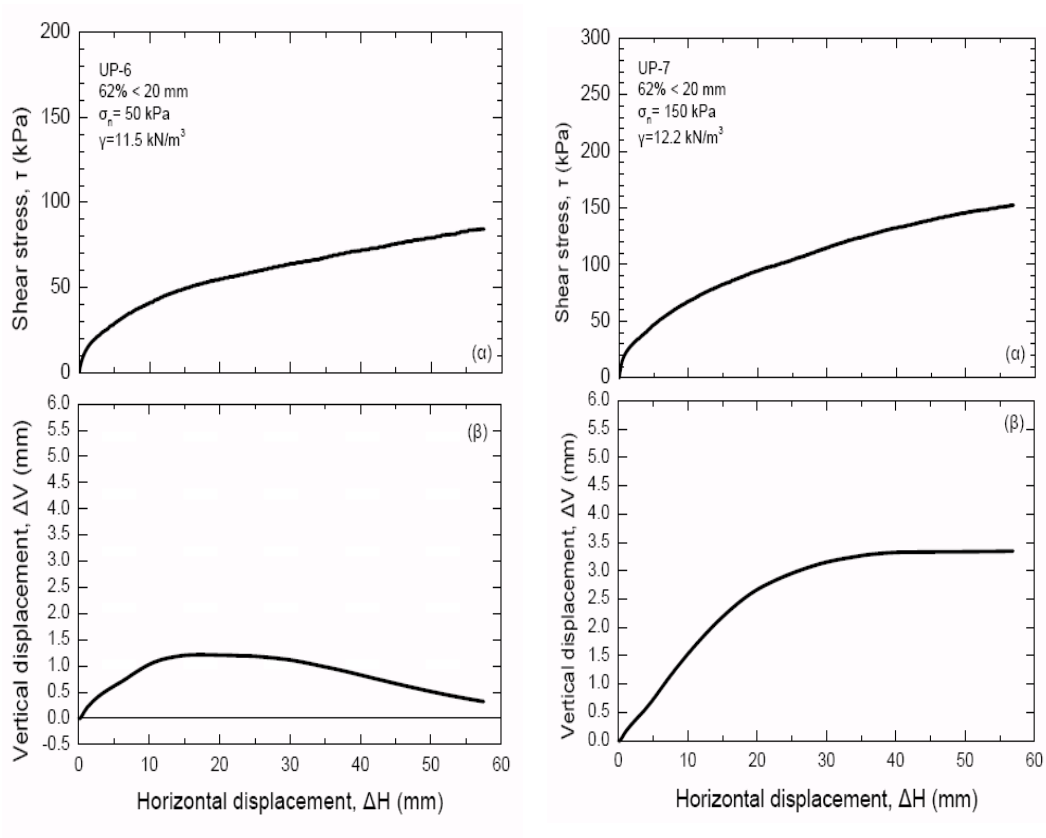


Figure 2. 26 - Direct shear tests on 62%<20mm waste using 300mm shear box (after Zekkos, 2005)

- Sample content 62% < 20 mm shows increasing strength with displacement in both results using triaxial and direct shear (Figure 2. 26)

- Sample content 100% > 20 mm shows clear peak and reduces strength after peak with triaxial and increasing strength with displacement (without peak or constant strength) with direct shear (Figure 2. 27)

There is no clear explanation for the different behaviors of the same material in direct shear (Figure 2. 27) and triaxial tests. However it can be the confining stresses in the triaxial test may be mobilizing the reinforcements to a higher degree to achieve the upwards curvature.

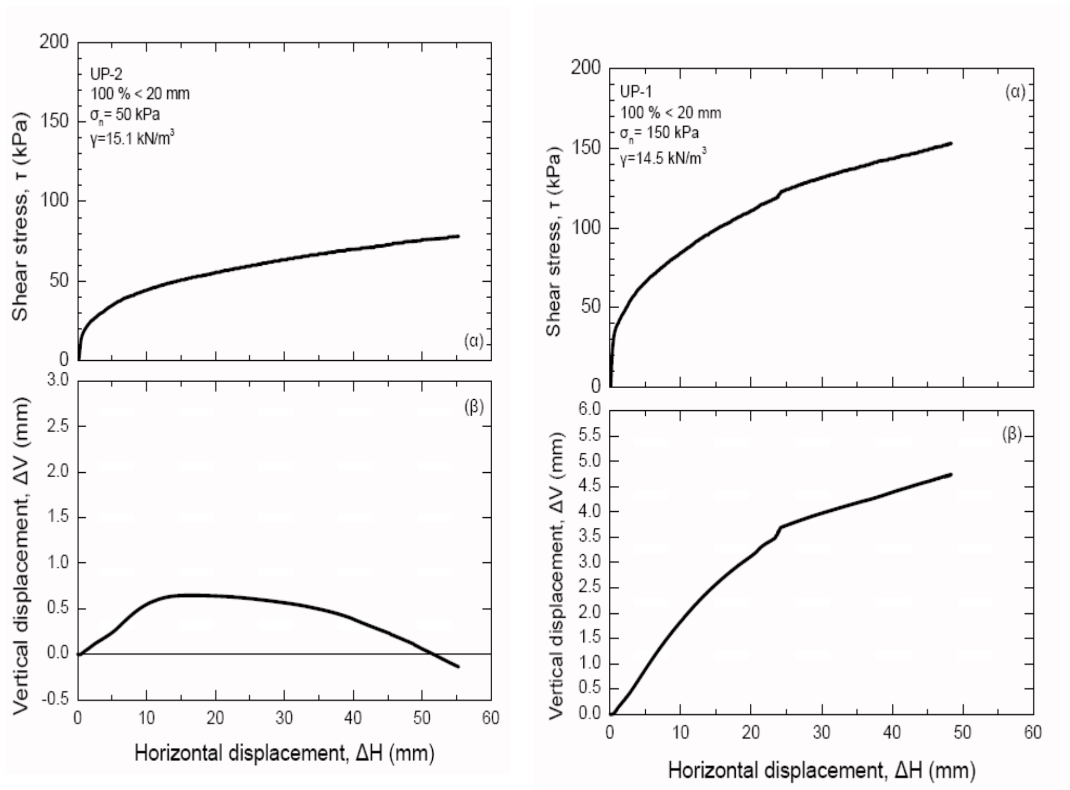


Figure 2. 27 - Direct shear test on <20mm waste using 300mm shear box (after Zekkos, 2005)

2. 6 European regulation and likely future landfill residual waste in the UK

The composition of future MSW is likely to change with the EU landfill directive. The EU landfill directive is focused on reducing uncontrolled emissions of methane from landfill by controlling the amount of biodegradable municipal waste (BMW) which may be disposed in landfill sites. According to the EU regulations in the UK, the amount of BMW being sent to landfill must be reduced to 50% of 1995 levels by 2013 and 35% of 1995 levels by 2020.

Experiences from other European countries, particularly Germany and Austria, has shown that MBT is an effective way of meeting the BMW diversion targets. As well as other European countries, the UK waste will probably be treated using MBT to reduce biological activity and organic content. MBT processes produce a residue which has a similar appearance to compost but based on the experience of other European countries and the findings of the Juniper report (Archer *et al*. 2005), it seems likely that much of this residue will be end up in landfills.

To discuss the effects of reinforcing on MBT, it is important to predict the likely residual waste or the MBT will be in the UK. The most appropriate way for this prediction seems considering the EU directive in place, considering existing standards for MBT from the countries such as Germany/Austria and by considering the likely approach by the UK regulating authorities.

As discussed earlier the EU directive is only focussed on reduction of the biodegradable waste content from the MSW. The Environment Agency (2005) draft guidance showed that UK regulation also focused on BMW reduction.

At present, Germany and Austria landfill much of the residual waste from MBT processes . German and Austrian standards have been set for the level of microbial activities and for the calorific value (Heiss-Ziegler & Fehrer, 2003). The German standards for the MBT to be landfilled are shown in Table 2. 5.

Table 2. 5 - German MBT boundary values for landfilling (From Kuehle-Weidemeier, 2006)

Parameter	**Upper limit**
BOD/AT4 (mgO2/gDM)	5
TOC (mg/L)	250
Gas production GB_{21} (*NL/kgDM*)	20
Calorific value (kJ/kg)	**6000**
TOC DM (mass % DM)	18

To achieve the calorific value requirement, present industrial practice in both countries is to reduce the plastic content (Heiss-Ziegler & Fehrer, 2003) as the calorific value of plastics can be as high as 32,000 kJ/kg. Plastics are also a major source of reinforcing, so eliminating them could have a detrimental affect on the strength of the waste.

To get rid of the plastics present Austrian and German practice is eliminating as much as plastics in the initial stage of the process and by post-treatment sieving, typically to 60mm (Kuehle-Weidemeier, 2006). Sorting of the White's MBT (Velkushanova *et al*. 2009) showed that the largest material (in this case greater than the nominal 20 mm particle size) contained large quantities of 2D reinforcing particles as shown in Figure 2. 28 - Waste analysis results of White's MBT >20mm fraction. These quantities are much larger than those found in the raw waste (38% plastics in the >20 mm fraction compared to 11% for 0-20 mm MBT).

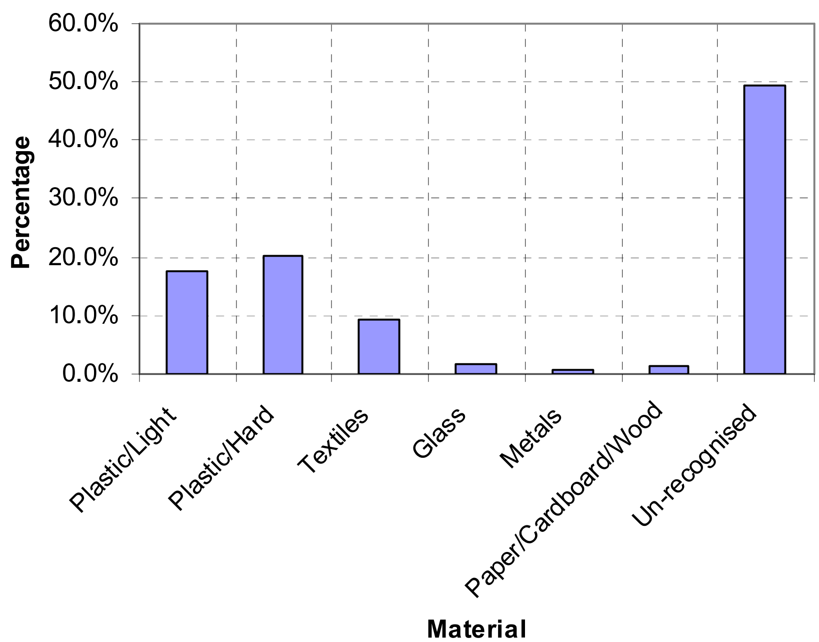


Figure 2. 28 - Waste analysis results of White's MBT >20mm fraction

At present there are no landfilling criteria based on calorific value in the UK. Reduction of the amount of larger particles with a concomitant effect on reinforcing content would probably only happen if:

- The operator had a market for refuse derived fueld (RDF)   or
- If a smaller particle size optimized the degradation process

2. 7 MBT and its impact on the shear stress of the waste

In order to comply with the requirements of the EU landfill directive (EC, 1999), the UK had to reduce the amount of BMW going to landfill and to ensure that all MSW pre treated prior to landfilling. The final BMW target is 35% of 1995 levels by 2020. Hence MBT may be the one of the main wastes being landfilled in near future. In order to meet these targets, it is likely that significant amount of MSW will to be treated using MBT processes. However at the moment there are no exclusively, MBT landfill sites in the UK.

The NES MBT is aerobically treated in forced air windrows as is shown more details in Figure 3.1. The maximum particle size of the NES MBT is 20mm. Particle size of the NES MBT is smaller compare to the most European MBT residuals (e.g. typical German MBT 0-40 mm to 0-60 mm).

The mechanical process typically leads to particle size reduction. Aerobic biological treatments may lead to weakening of the reinforcing particles as a result of the high temperatures experienced during aerobic degradation. The organic content and the properties of the reinforcing particles in MBT are both likely to be different in MSW. MBT treatment is likely to affect the reinforcing content, size and shape, as well as the basic matrix properties, consequently affecting the shear strength. However identifying the shear strength characteristics of the MBT is important in identifying the possible changes that may need to be made to the design and construction of future landfills, which may contain a significant percentage of MBT residual waste.

Studies on reinforced sand, MSW, European MBT show that;

(a) The addition of reinforcing particles may increase or reduce the strength of the compound material depending on the reinforcement content. If the reinforcement content is in the optimum range, shear strength increases and if the reinforcement content is greater than the optimum, shear strength may be reduced. (e.g. Santoni *et al.* 2001).

(b) Reinforcement particle size has an influence on the shear strength (e.g. Consoli *et al*. 2005). Reinforced sand studies show that increasing the reinforcement length, increases the reinforcement effect up to a limit and further increases in the reinforcement length reduce the reinforcing effect (e.g. Santoni *et al*. 2001).

(c) Changes to the basic matrix (e.g. Kaniraj *et al*. 2003) and reinforcement particle shape (e.g. Santoni *et al*. 2001) proved to have an influence on the reinforcing effect.

(d) The higher the reinforcement stiffness, the greater the reinforcing effect (e.g. Jewell & Wroth, 1987)

In the light of the above, the following will be investigated in this study;

- Shear strength characteristics of the NES MBT produced in the UK
- The effect of changes to reinforcement properties on the shear strength of the MBT
- The impact of reinforcement on shear strength of MBT, considering reinforced sand as an analogue material

Chapter 3

Waste Characterisation, Materials and Methods

Part 1 – Waste Characterisation

3.1 Waste Analysis

The aim of the waste analysis was to categorise the MBT waste according to a geotechnical classification system and identify the factors which have been changed by the MBT process which may affect the strength of the residues.

For this study about 600 kg of MBT waste from a single batch was obtained from NES MBT plant at White's Pit in the South of England. NES plant is one of the trial plants in the UK actively studying the BMW diversion trials. The facility consists of a fully enclosed windrow composting system, taking black bag MSW as a feedstock. The process has been show to lead to 80% of BMW diversion from landfill. The capacity of the plant is 500 tonnes per month.

In the MBT process (Fig. 3.1), the MSW was first screened and shredded. It then passed through an indoor active windrow composting process (aeration, irrigation and mixing) lasting six weeks. Treated material was screened again and plastics and metals were separated. Finally the material was screened to either 20 mm or 10 mm, producing two residue types with different particle size ranges (i.e. 0 – 20 mm and 0 – 10 mm).

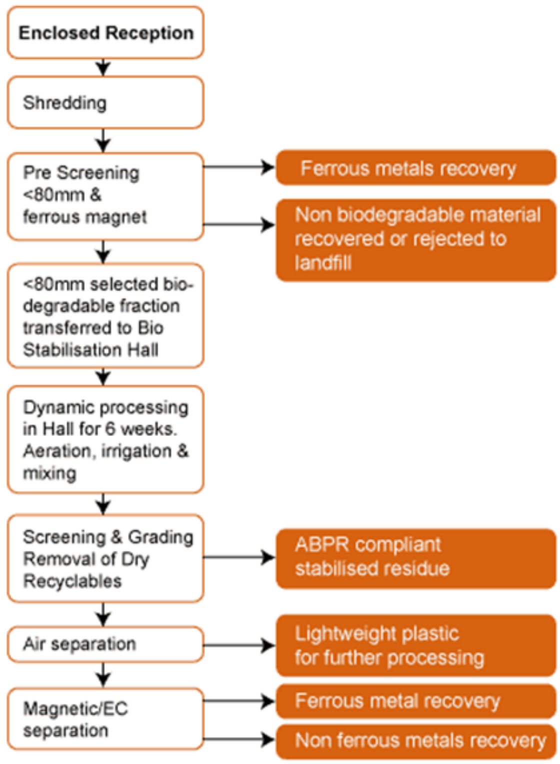


Figure 3. 1 - MBT Treatment Method for the obtained sample
(Source: http://www.newearthsolutions.co.uk/residual-waste-treatment/process-description/)

The material resulting from the process is less active than MSW but still has some pollution potential (Siddiqui *et al*. (2009)). The composted material standard (PAS100, 2011) requires the total glass, metal, plastic or any other non stone fragment > 2mm content by mass to be < 0.25%, with a maximum plastic content of not more than 0.12%. It seems that MBT residues are unlikely to satisfy this requirement for use as a compost. It is therefore likely that these and similar residues will end up being disposed of to landfill.

3.1.1 Determination of the Moisture Content

Two 5 kg samples of the MBT were oven dried at 65°C to determine the moisture content. The dried samples were allowed to cool at room temperature and the mass was determined at 24 hour intervals. When the weight difference between two consecutive readings was constant or less than

1% of the original mass, it was considered that the waste had achieved a dry state. The moisture content of the two samples was determined on the wet mass basis (i.e. mass of water divided by mass of wet solids), giving moisture content values of 26.1% and 26.9%. The average moisture content value 26.5% was used for calculations.

3.1.2 Analysis of 0-20mm MBT Waste

A detailed waste analysis was conducted on 18 kg of the 0-20 mm MBT sample. Each particle size band (retained on each sieve) was laid on a tray in a thin layer and each waste particle was picked by hand to categorise the waste into component materials. Some pictures of the components are shown in Fig. 3.5. The small nature of the particles made waste analysis a time consuming and difficult task. Some particles were found not to have been correctly identified in later tests - for example, clay lumps may have been categorised as stones.

Analysis was conducted based on the geotechnical classification by Langer (2005), modified as discussed below. Langer's classification consists of key five elements;

- Description of components (i.e. identifying the waste by material type)

Following existing methods (Dixon & Langer (2005), Kölsch (1995), Ivanova (2007), WRAP (2002)), waste was sorted into the following particles: flexible plastic, stiff plastic, textile/wool, glass, ceramic, stone, metal, paper, wood, bones and rubber. The categories of the material listed above give an indication of the mechanical properties (density, brittleness, flexibility) of the various material types.

- Shape related subdivision of components (dimensionality -1D & 2D reinforcing, 3D compressibility)

Following Kölsch (1995) and Langer (2005) the MBT was classified by dimensionality. It was possible to classify the bulk of the waste components larger than 5 mm by both material type and dimension (dimension 0 - each side of the piece short (in this case less than 5 mm) such as soil, dimension 1 - one side long, two sides short – such as wires , dimension 2 - two sides long, one short – such as sheets and dimension 3 - three sides long – such as stones) as shown in Table 3.1.

The aspects omitted from Langer's (2005) classification included the divisions into compressible/incompressible. The reason for this was that the MBT process has removed or destroyed (shredded) compressible components such as cans, plastic bottles. However this does not necessarily mean that the remaining waste particles are incompressible as assumed in soil mechanics.

- Size of components

The waste was sieved and sorted into > 20 mm, 12 mm – 20 mm, 7 mm – 12 mm, 5 mm – 7 mm size categories. As with all other waste classification systems, materials smaller than a certain size were classified as 'miscellaneous' (Material <8mm was considered as miscellaneous in Kölsch (1995)). 29% of the material was <5 mm, soil-like and therefore, classed as miscellaneous. However in this category a significant amount of waste components such as glass, plastics were still visible but difficult to sort manually.

- Degradability potential

The categorization of elements into degradable/non degradable was omitted, because the MBT process has already promoted degradation to a significant extent (Siddiqui *et al*. (2009)).

3.1.3 Waste analysis results

The waste components were categorised into dimensionality following Kölsch (1995) as shown in Table 3.1.

Table 3. 1 - Waste particles categorised by material type and dimensionality

Component	0D	1D	2D	3D
flexible plastic			x	
stiff plastic		x	x	x
Wool/ textile		x		
Glass				x
Ceramic				x
Stone				x
Metal				x
Paper/cardboard/wood[1]			x	x
Rubber				x
Miscellaneous[2]	x	x	x	x
Unidentifiables[3]		x	x	x

[1]most paper and cardboard was found as small balls instead of sheets.

[2] miscellaneous - defined as all material passing the 5 mm sieve

[3]unidentifiable - any other material which could not be identified >5mm

0D - almost all miscellaneous fall in to this dimension

1D - almost all wool/textile (approximately 1.3%) and very few hard plastic wires (0.37%) fall into this dimension.

2D - all the flexible plastic and most of the stiff plastic fall in to this dimension

3D – glass pieces, ceramic pieces were considered as 3D. However one dimension of these particles was small compared with the other two dimensions.

The dimensionality categorisation of the MBT waste shows that;
1D particle content is low in MBT waste and most of the 1D particles consist of low strength wools.
2D particle (flexible and stiff plastics) are the major reinforcing elements in MBT

The Particle Size Distribution (PSD) was determined for the waste at the as received water content, and then the waste analysis was conducted on the particles in each size range. Following Dixon and Langer (2006), the results from the waste sorting were plotted on a 3D chart (Fig 3.2), by particle size range for each component. Fig 3.2 shows that the majority of the identifiable MBT is made up of flexible plastic, stiff plastic, ceramic and glass components. Glass forms the pre dominant single identifiable particle by total weight.

Fig. 3.7 shows glass content in Ivanova's MSW was 3% by mass compare to 17% and 23% in 0-10 mm and 0-20 mm MBT respectively. Although some of the increase in glass content is due to concentration of the inert compounds by degradation, this would not occur for all the difference. According to the Parfitt (2002), the glass content in MSW is typically much higher (7% - 8%) than found by Ivanova. This high amount is broadly consistent with the glass content found in the MBT samples.

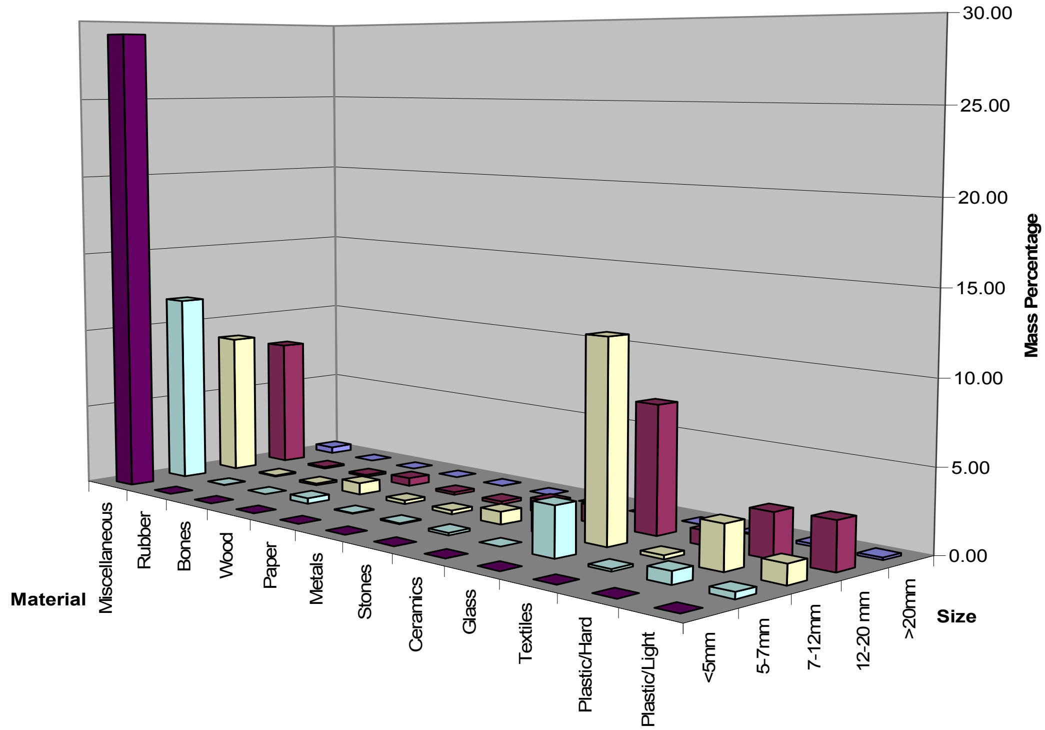


Figure 3. 2 - 3D graph of the 0-20mm MBT waste analysis results representing material, particle size and content

As the 0–10 mm and 0–20 mm MBT were obtained from the same batch (only difference is sieved through two different sieve sizes), it was assumed that the composition of the 0– 10 mm MBT could be determined by calculation from the 0–20 mm waste analysis results. The particle size distribution of the whole material (Fig 3.3) and each waste component of the 0-20 mm MBT are shown in Fig. 3.4.

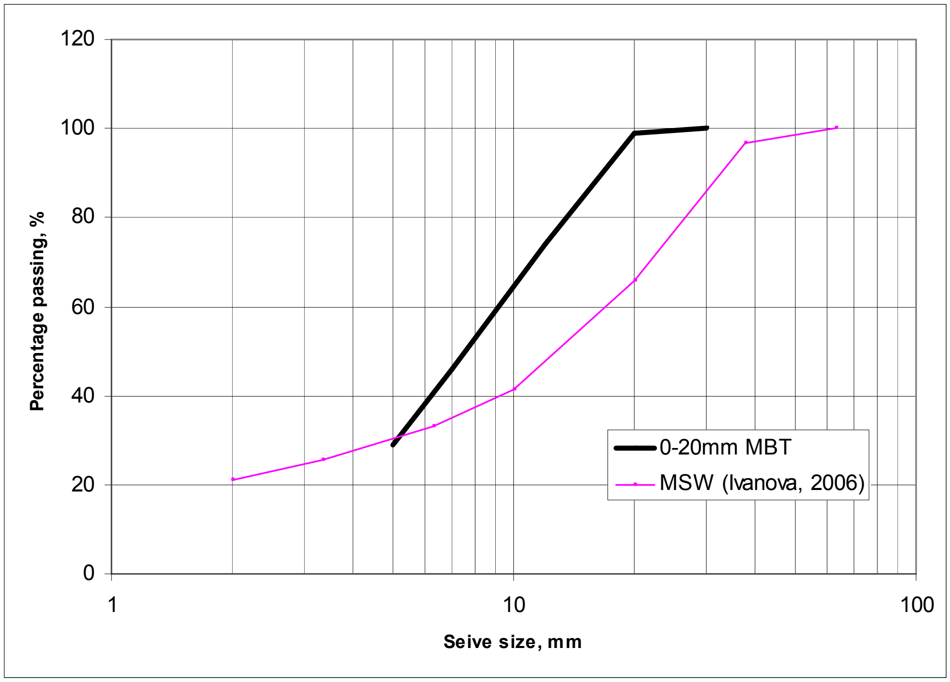


Figure 3. 3 - Particle size distributions on as received 5 – 20 mm MBT and MSW

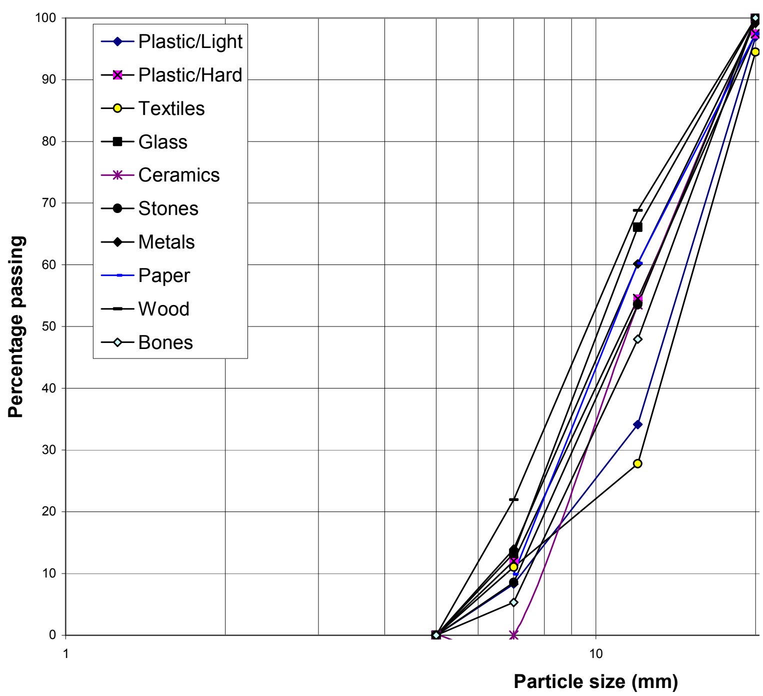


Figure 3. 4 - Particle size distributions of the waste components of 0-20mm MBT

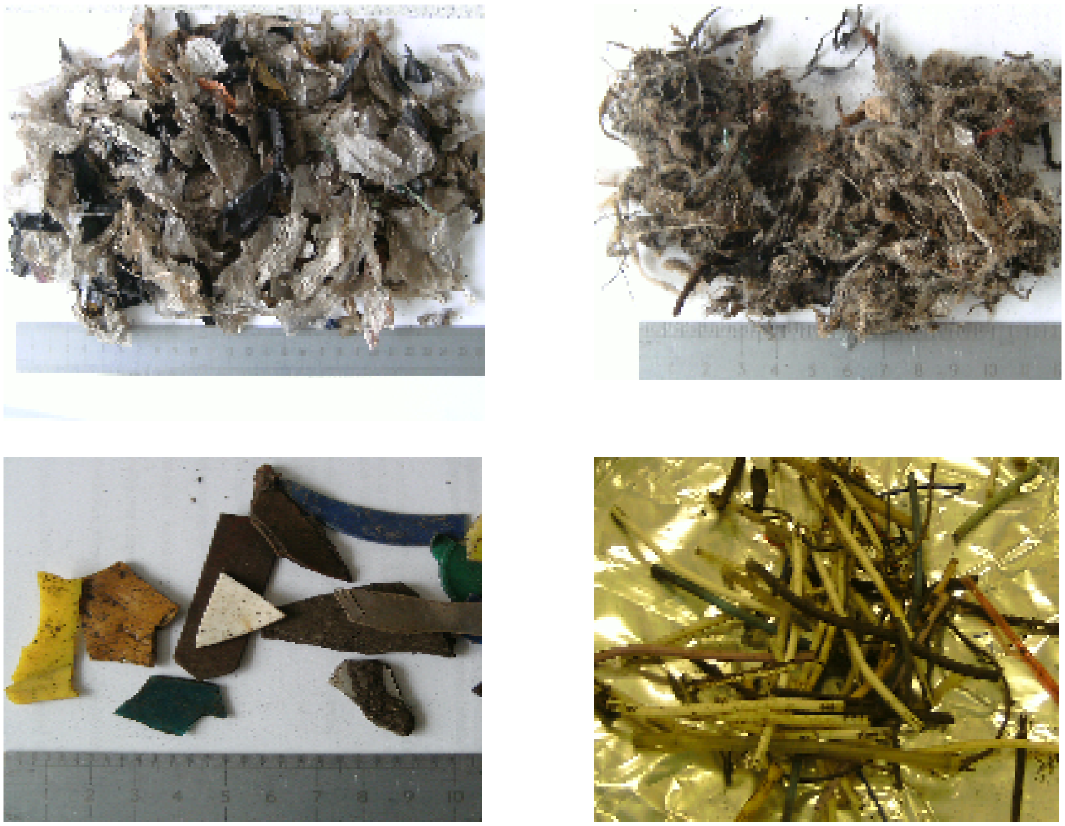
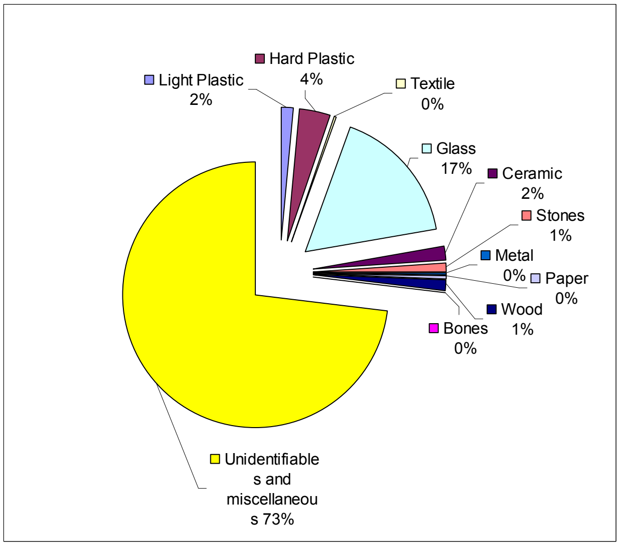
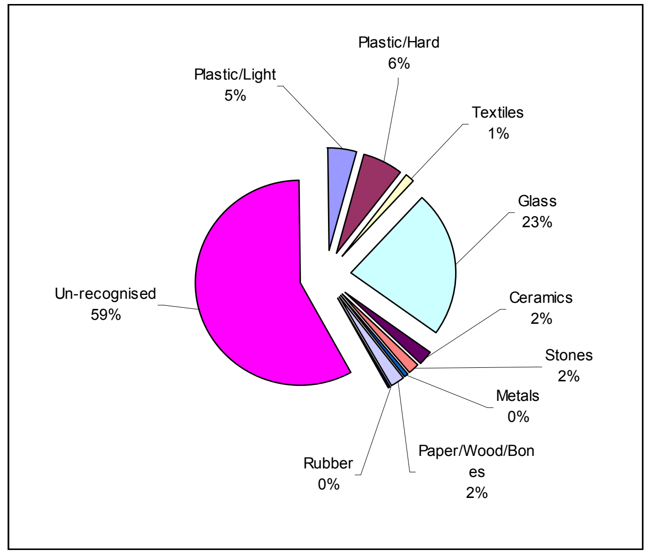


Figure 3. 5 - Pictures of MBT hand sorted particles (light plastics, wools, hard plastics, wires)

The calculated composition of the 0–10 mm MBT (using the Fig. 3.4) and the analysed composition of the 0-20mm MBT are shown in Fig. 3.6. The two compositions show that,

- A larger proportion of unidentifiable and miscellaneous materials can be found in 0–10 mm MBT (73% compared with 59% in the 0–20 mm)
- 0-10 mm MBT consists of hard plastic 4% by mass and 0-20 mm consists of 6% by mass
- 0-10 mm MBT consist of light plastic (2% by mass) compared with 5% in the 0 – 20 mm MBT
- The glass content has been reduced 23% to 17% in 0-10 mm MBT
- Other components do not show significant difference in content
- The larger particle size material shows higher reinforcement content





(a) **(b)**

Figure 3. 6 - MBT composition (a) 0-10 mm MBT- calculated (b) 0-20 mm MBT-analysed

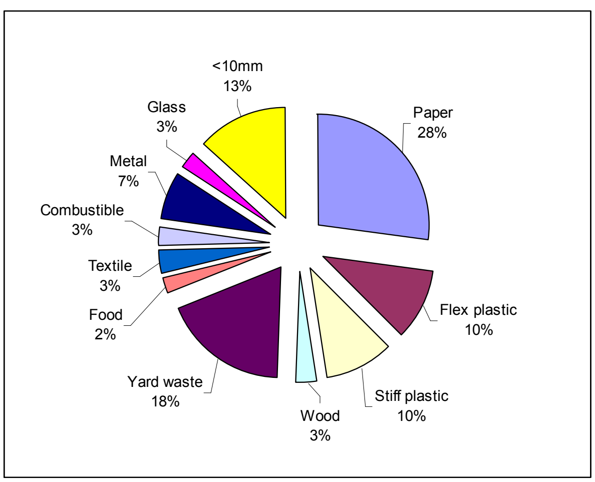


Figure 3. 7 - White's fresh MSW composition (Ivanova, 2006)

Table 3. 2 - Composition of 0-10 mm MBT, 0-20 mm BT and MSW

Waste Particle	0-10 mm	0-20 mm	MSW*
Plastic - flexible	2%	5%	10%
Plastic - stiff	4%	6%	10%
Glass	17%	23%	3%
Ceramic	2%	2%	[b]
Metal	[a]	[a]	7%
Paper	[a]	0.4%	28%
Stones	1%	2%	[b]
Yard Waste	[b]	2%	18%
Textiles	[a]	1%	3%
Miscellaneous (M) and unidentifiable (U)	73% (M<5mm-43%, U-30%)	59% (M<5mm-29%, U-29%)	13%(<10 mm)

[a] very small contents were presented

[b] not measured

*MSW from White's Pit (Fig. 3.7)

3.1.4 Errors Identified

Despite having been screened to 20 mm at the MBT plant, some of the particles in the MBT were larger than 20 mm. This can be explained as long particles with two measurements less than 20 mm and some of the larger flexible 2D items such as light plastics are able to pass through a 20 mm square mesh. 1% by mass of the 0-20 mm material was retained on the 20 mm sieve in the laboratory.

Separating the waste into components was a difficult task and some of the particles may not have been correctly identified. For example it was found that bones may have been categorised as wood after close examination of the sorted particles.

It was observed that a small amount of soil like material remained attached to many of the reinforcing components, probably leading to a slight overestimate of mass.

Particle sizes of the unidentifiable material were obtained by dry sieving method (BS 1377-2:1990 Section 9.3). Examination showed some were agglomerated, and likely to be broken down further under mechanical handling.

3.1.5 Conclusions

MBT processes lead to a significant decrease in particle size, a change in component contents (significant changes to the reinforcement content and 0D content) and increased homogeneity compared to the parent MSW.

3.2 Proctor Compaction Test on MBT

The aims of conducting the Proctor compaction test on MBT residues are,

- to understand the likely MBT placement density in landfill sites (in the UK) to use in this testing programme
- to identify the unit weight variation of the MBT to adopt a specimen preparation methodology
- to understand the compactability of the MBT compared with similar European residuals

It is well known that the bulk unit weight of waste has a significant effect on its mechanical properties (Zekkos, 2005). Dixon & Jones (2005) identified ten potential landfill infrastructure failure modes and unit weight was identified as an important property in designing in all of these modes highlighting the importance of the unit weight.

The unit weight of the MBT residue will not be the same as the MSW as there are differences in two materials. (e.g. (a) separating low density components such as plastics may lead to higher densities of the residual waste and, conversely, separation of metal, glass and other high density materials may lead to lower densities in the residual waste, and (b) changes to the composition and the particle sizes/shapes may lead to unit weight variations) However MBT residues are likely to have higher landfill densities than MSW as shown in Fig. 3.8(b).

European countries such as Germany have introduced regulations on minimum landfill emplacement densities (Münnich *et al*, 2005) to optimise the use of landfill space, giving an additional benefit of lower settlements. In Germany, to identify the emplacement density, laboratory (Proctor) and field tests have to be conducted to comply with the regulations. In the light of placement practices in Europe, it is possible that future UK regulations will seek to control placement densities in MBT landfills.

3.2.1 Approach to determine the likely UK landfilling MBT unit weight

As MBT landfills are not yet fully established in the UK, the likely placement unit weight of the MBT has to be predicted on the basis of laboratory tests and European practice. There can be differences with EU practices due to,

- The composition of the MBT waste (Siddiqui, 2011)
- Lower unit weights in the UK owing to the absence of placement density regulations
- Particle size differences (e.g. German MBT is sieved to achieve the regulated calorific value (Kuehle-Weidemeier, 2004))
- Differences in treatment methods (e.g. anaerobic/aerobic two phase treatment in Germany(Kuehle-Weidemeier, 2006) vs one phase treatment in the UK)

The unit weight of landfilled waste depends on many other factors including the initial compaction energy, overburden stress, compaction layer thickness, moisture content, age, properties of the particles such as ductility - compressibility, etc.

As many of these factors are constant for a given MBT waste stream sample, the factors that affect compaction can be identified as (a) compaction energy and (b) layer thickness.

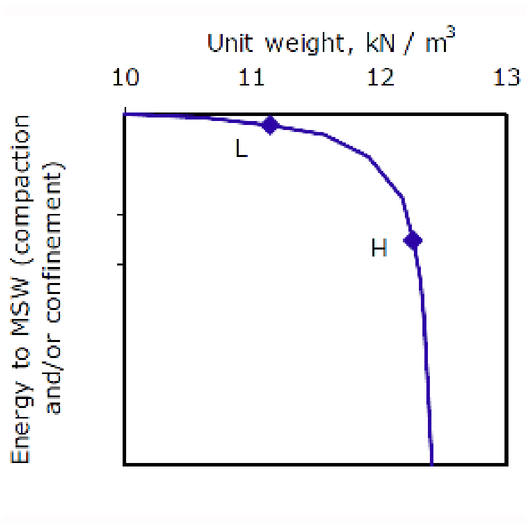
(a) Changes to the unit weight with the compaction energy

Kuehle-Weidemeier (2006)'s trial field compaction of MBT residues from the same plant with different compaction equipment (energy) showed that the unit weight of the waste is highly dependent on the compaction effort (Table 3.3).

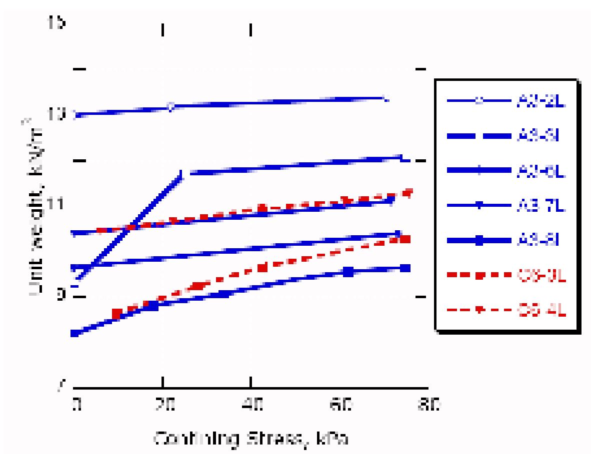
Table 3. 3 - Unit weights of MBT resulting from different degree of compaction effort (Kuehle-Weidemeier, 2006)

Parameter	Unit	Compactor 37 t	Roller 13 t	Compactor 28 t
Water content	% WM	35,1	33,3	32,9
Wet density	Mg_{WM} / m^3	2,19	1,22	1,75
Dry density	Mg_{DM} / m^3	1,45	0,81	1,17

Regardless of the small differences in initial moisture content and possible variations in the composition of the materials, the results clearly show that a higher compaction energy provides an enhanced unit weight.



(a) (L - light compaction/low confinement, H - high compaction/high confinement)



(b)

Figure 3. 8 - Conceptual model for MSW unit weight and energy input based on compaction or confinement (b) Unit weight change with stress, where A3-2L & A3-3L < 20mm and others close to MSW (after Zekkos, 2005)

The conceptual model presented by Zekkos (2005) shows the unit weight initially changing rapidly with compaction energy (Fig. 3.8(b)), and remaining unchanged with increasing energy (Fig. 3.8(a)) as with other geotechnical materials. Powrie & Beaven (1999)'s study shows the same relationship between normal stress and the density of MSW. Powrie & Beaven (1999) and Kavazanjian *et al*. (1999) show that increasing static stresses above 400 kPa do not significantly influence the unit weight. Zekkos (2005) showed that a > 30m overburden did not greatly influence the unit weight in moderately and highly compacted landfill sites in field tests, confirming Powrie and Beaven's results.

(b) Changes to the unit weight with the layer thickness

It is well known in geotechnical engineering that the layer thickness during compaction has a large influence on the density achieved. Layers with too high thickness lead to a non uniform compaction and low unit weights. The optimum layer thickness should be investigated for the type of compaction plant and the number of equipment passes over the waste. Dixon & Jones (2005) stated that MSW 0.5–1.0 m thick layers will facilitate a good compaction while 2-3 m thick layers provide poor to moderate compaction.

Kuehle-Weidemeier & Doedens (2003) carried out a compaction test on MBT 0.3 m and 0.5 m thick and found no significant influence due to this layer thickness change. Fig. 3.9 shows the same level of compaction in all field tests except one of the 0.3 m (low) layer thickness compaction which seems an anomalous result.

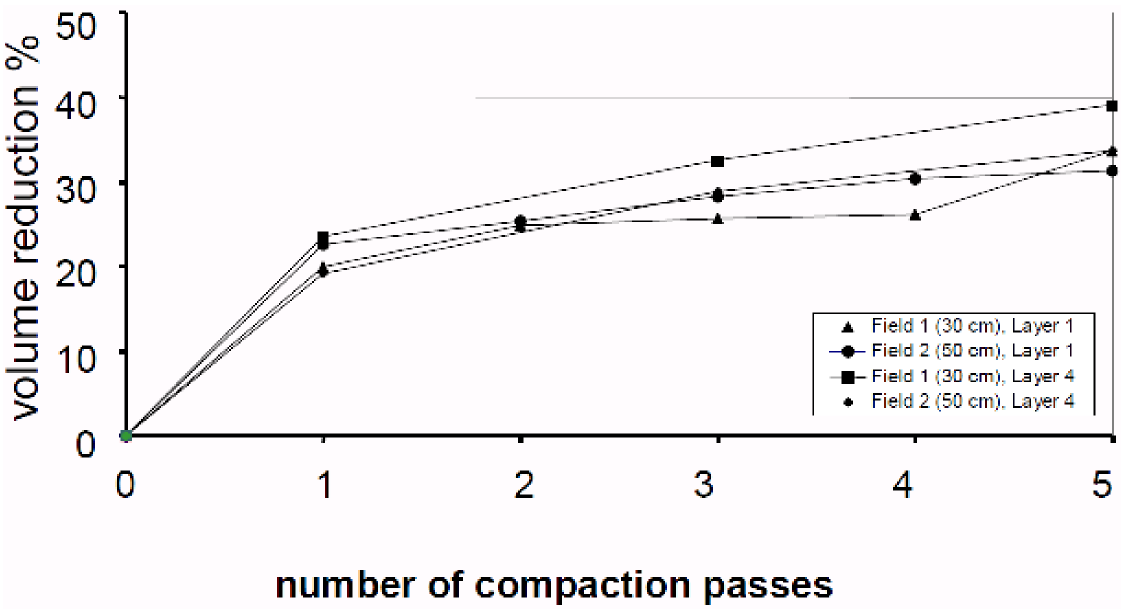


Figure 3. 9 - Compaction related to the layer thickness (after Kuehle-Weidemeier & Doedens, 2003)

As MSW generally has a higher void ratio and more compressible waste components than MBT, higher volume reductions would generally result. Thus thicker waste layers in the field might be possible with MSW than with MBT.

3.2.2 Proctor compaction test procedure and mould selection

The compaction test was carried out according to BS 1377-4:1990 part 4. The Proctor compaction test in a litre mould covers the determination of the dry density of a soil passing a 20 mm test sieve. Details of mould selection can be found as a note at the end of this section.

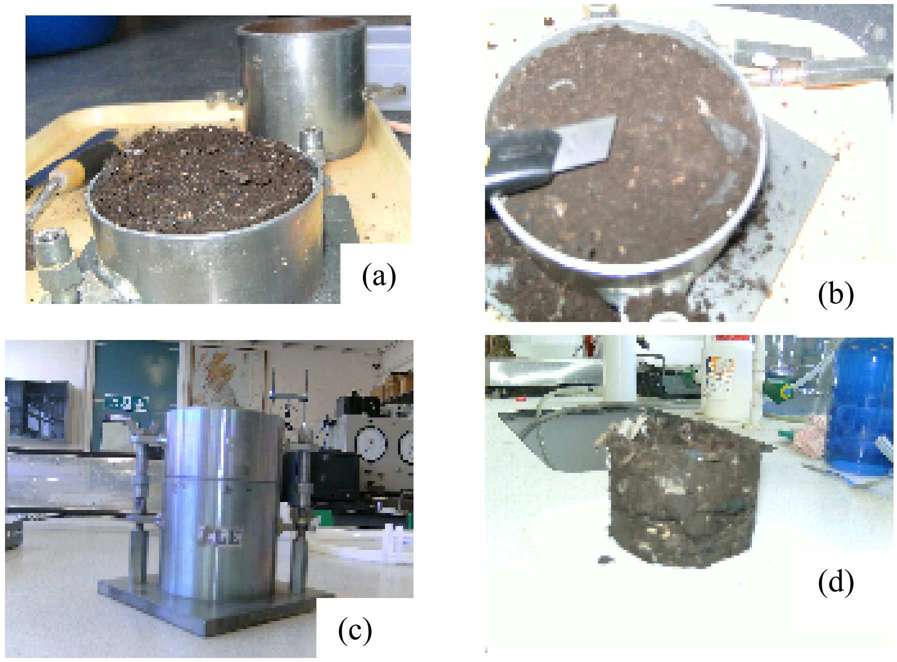


Figure 3. 10 - Proctor compaction test of MBT waste (a) Uneven surface after Proctor test (b) Trimming the surface to level it (c) Assembled proctor equipment (d) Compacted sample

3.2.3 Sample Preparation

The Proctor compaction tests were carried out on two MBT residues from the same batch which had been already sieved in the plant as a part of the process, 0-10 mm and 0-20 mm. Any remaining particles which were significantly larger than the nominal sieve size were removed manually (e.g. long wires, ball point pens etc.).

Using the quartering method (refer appendices), MBT samples of a suitable size were obtained from the both fractions. The moisture content of the material being tested was changed as follows. To achieve the predetermined moisture content, the required quantity of water was added using a hand sprayer and mixed thoroughly. The moist samples were placed in air tight containers/plastic bags and were allowed to absorb moisture for more than 24 hours. The sample was mixed again and then used for the compaction test.

All samples were oven dried after compaction to confirm the moisture content. The difference between the intended and the oven dried moisture content was about 1%. The most likely reason for this is air drying of the sample during compaction. Moisture contents are reported on a wet (total) mass basis (i.e. mass of water / mass of wet residues).

3.2.4 Modifications to the standard Proctor

- According to BS 1377:4, the height of the compacted sample should be 100mm. For this study the final height of the sample was modified to 60mm. Compared to soils, MBT residues are highly compressible and the Proctor mould is not tall enough to accommodate sufficient MBT residue to obtain a compacted height of 100mm. Hence the final compacted sample height was reduced to 60 mm. A 100mm high extension was used to accommodate material.
- The Proctor sample should be compacted in three layers with an equal amount of material in each layer. With the modification to the compacted sample height, the layer thickness was reduced accordingly.
- Texturing the upper surface before the new top layer (to increase the inter layer bonding) was omitted due to difficulties in achieving this with the MBT material.

3.2.5 Experimental Results

Two Proctor compaction tests were carried out on 0-10mm and 0-20mm MBT residues where particle densities are 1.69 & 1.929 Mg/m^3 respectively. The Proctor compaction curves obtained are shown in Fig 3.11 and 3.12. The dry density and the air void lines were calculated using Eqn. 3.1 and 3.2 respectively.

$$\rho_d = \frac{100_\rho}{100 + w} \qquad \textbf{Eqn. 3.1}$$

where

w is the moisture content of the soil (in %).

$$\rho_d = \frac{1 - \frac{V_a}{100}}{\frac{1}{\rho_s} + \frac{W}{100_{\rho w}}} \qquad \textbf{Eqn. 3.2}$$

where

ρ_d is the dry density (in Mg/m^3);

ρ_s is the particle density (in Mg/m^3);

ρ_w is the density of water (in Mg/m^3), assumed equal to 1;

V_a is the volume of air voids in the soil, expressed as a percentage of the total volume of the soil (equal to 0 %, 5 %, 10 % for the purpose of this plot);

w is the moisture content (in %).

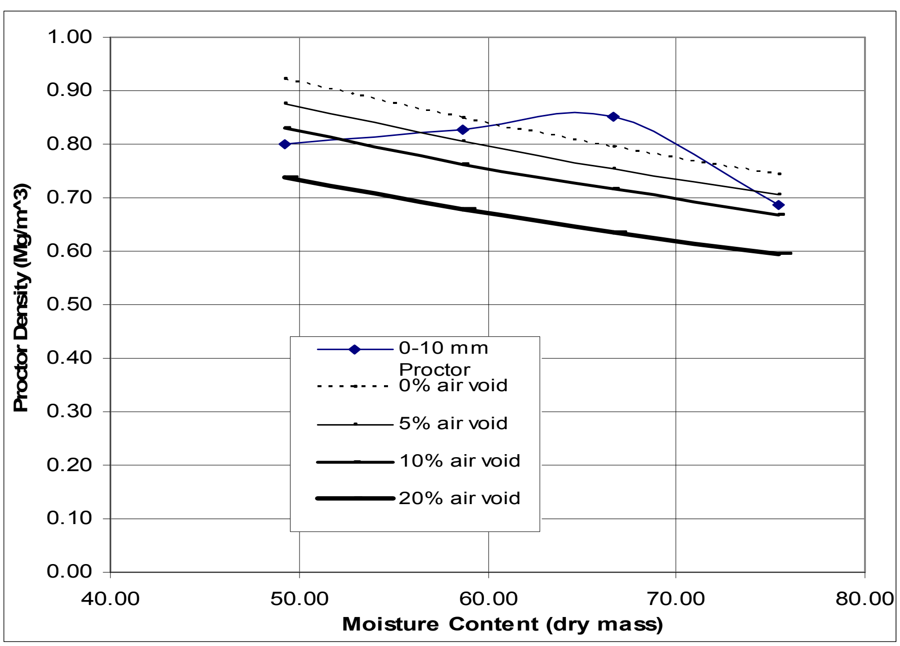


Figure 3. 11 - Proctor compaction on 0-10mm MBT

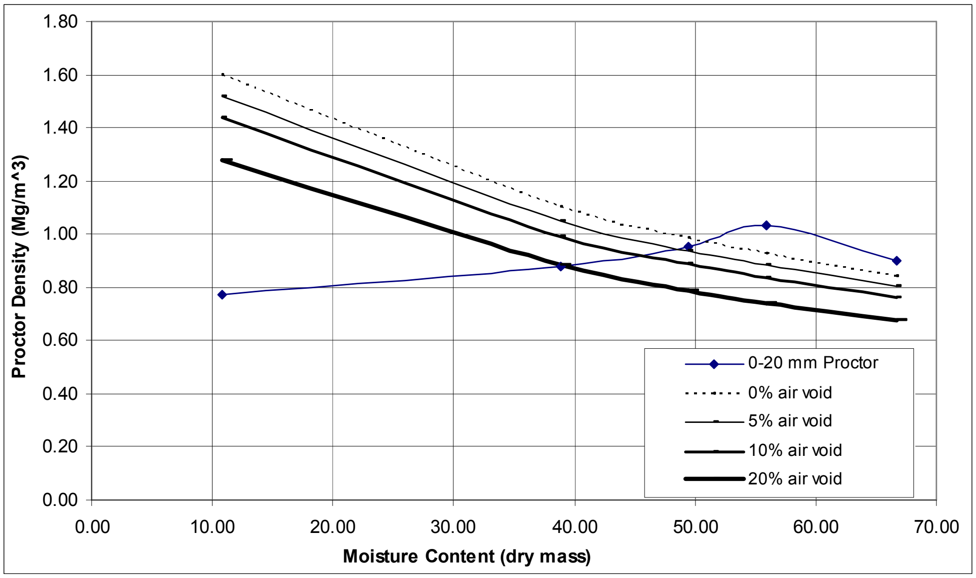


Figure 3. 12 - Proctor compaction on 0-20mm MBT

The 0-20 mm MBT material showed a higher maximum density (11.4 kN/m^3) than the 0-10 mm MBT (8.4 kN/m^3). As 0-20 mm MBT has a relatively high amount of reinforcing materials such as plastics (Fig. 3.6) it might have been expected to be of comparatively low compactability. This discrepancy can be explained as follows

- The glass content (high density material) is high in the 0-20 mm MBT as shown in Table 3.4. The average particle density of the 0-20 mm MBT material is greater than the 0-10 mm MBT and this will be discussed in Section 3.4.
- As MBT contains a high amount of fines, the 0-20 mm MBT waste might have provided more uniformly distributed material (compare with the 0-10 mm MBT) while increasing compactability

Table 3. 4 - Glass content according to the particle size range

MBT Fraction	**Glass percentage by mass (to the total mass)**
0-10 mm	17%
10-20 mm	23%

The Proctor curves for MBT show peak density values above the 0% air line, which is impossible. Whilst the compacted samples appear to be significantly denser than the initial samples, they did not appear to have no voids. The cause of the excess Proctor densities is not clear. It was assumed that the waste particles were incompressible (as in soil mechanics), while they are not incompressible. This may be the likely reason.

Münnich *et al.* (2005) studied 0-30 mm, 0-40 mm and 0-80 mm MBT, screening the same material using different sized sieves. The Proctor results show increasing density with increasing particle size as received and presented in Table 3.4.

Table 3. 5 - Storage density change with the particle size in MBT waste (Münnich et al, 2005)

Particle size (mm)	**Treated waste (Mg/m^3)**
< 30	0.67 – 0.76
< 40	0.70 – 0.90
< 80	0.97 – 1.00

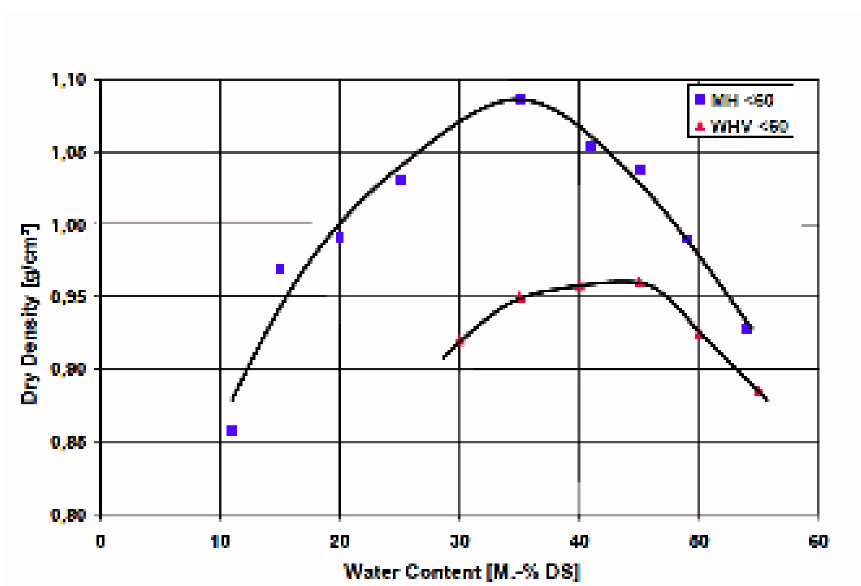


Figure 3. 13 - Proctor curves of two different 0-60 mm MBT using 250 mm dia. Proctor mould (Bauer et al. 2006)

Bauer *et al*. 2006's Proctor tests on 0-60 mm MBT (using a 250 mm diameter mould) achieved the maximum densities with moisture contents of approximately 35% (10.9 kN/m^3) and 45% (9.5 kN/m^3) as shown in Fig. 3.13. In the current study, the maximum dry densities and optimum moisture contents using dry mass are 11.4 kN/m^3 - 55% (0–20 mm) and 8.4 kN/m^3 - 65% (0-10 mm). The dry density figures obtained are close to those reported by Bauer *et al.* (2006) but the moisture content (using dry mass) are higher than those found by Bauer *et al*. (2006). However this is not surprising as the lower nominal size of the MBT fraction, the greater the soil like and organic particles (e.g. 73% in 0-10 mm and 59% in 0-20 mm), which are likely to be more absorptive.

3.2.6 Possible sources of error

During compaction, it was observed that some fine MBT material stuck to the rammer face. The compacting MBT surface was uneven due to high compressibility of the material. These may lead to an uneven distribution of the impact force

The MBT was compacted in three layers. Bonding between the layers seems weak and it was not possible to create textures on the surface to increase bonding, owing to the nature of the material. Compaction between layers may not have been even as can be seen in Fig. 3.10(d).

As the moisture content increased, it was increasingly difficult to compact the MBT. The MBT residues were likely to squeeze with the blows instead of compacting. At higher moisture contents, some of the water seeped out. Münnich *et al*, (2005) suggested that field compaction may have to be carried out on the dry side of the Proctor optimum in landfill operations.

The excess MBT was trimmed using a knife to level the surface as shown in Fig. 3.10 (b), as allowed in the BS (British Standards). Coarse materials such as glass and stones were removed during leveling and the holes created were filled with trimmed compacted fines. However there is a significant difference between the densities of the removed and filled materials.

When the Proctor mould height was reduced, it was assumed that the maximum particle size is related to the diameter of the proctor mould instead of the volume as stated in Bauer *et al*. (2006) according to the German standard.

3.2.7 Conclusions

Proctor compaction can be conducted on the MBT waste using soil testing methods. However, modifications to the compaction equipment and BS 1377:4 may be needed as discussed.

The MBT material tested behaves similarly to clay soils with varying moisture content and constant compaction effort leading to a maximum density at optimum moisture content.

Due to the difficulties in compacting at higher moisture contents, MBT residues need to compact at dry to optimum moisture contents, probably resulting landfilling at the as received moisture content in the UK.

3.3 Interface Properties of the Reinforcements and Basic Matrix

The aim of testing the interface properties between waste matrix and reinforcing materials was:

- to investigate the interface friction, in order to understand the impact of the reinforcements on strength (by considering the interface characteristics)

To understand the reinforcing effect which enhances the shear strength of a reinforced material, it is necessary to know the interface properties between the reinforcements and the waste. The interface properties depend on the both the surface frictional properties of the reinforcement and the properties of the material around it (i.e. skin friction between the reinforcement and the basic matrix) as discussed in Chapter 2. The interface properties were investigated in this study by sliding one material over the other (Fig. 3.14).

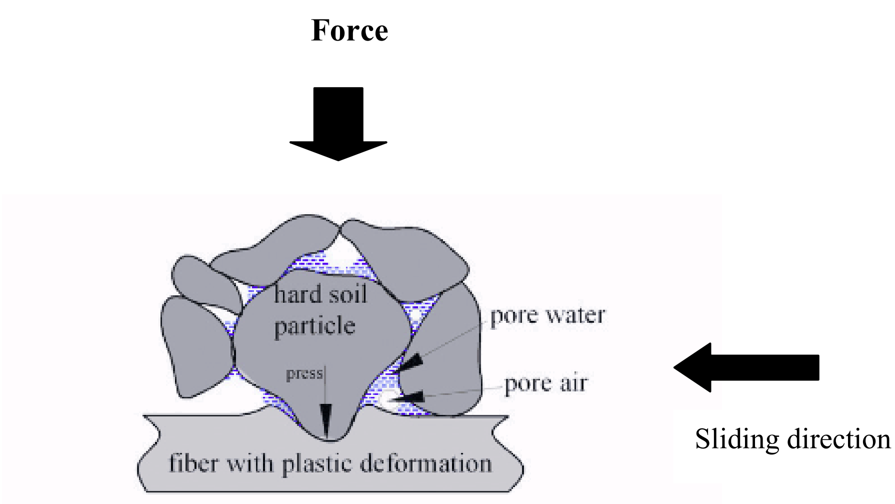


Figure 3. 14 - Contact condition between hard grains and reinforcing surface (Source: Tang et al., 2010)

The behaviour of reinforcement has been investigated in reinforced sand studies (e.g. Michalowski *et al*. (2003), Srinivasa Murthy *et al.* (1993), Tang *et al*. (2010)), and is more complex than the matrix simply sliding over the reinforcement, involving indentation and elongation. Fig. 3.16 shows this.

Michalowski *et al*. (2003) found that the coarse sand in their study was involved in bending fibres, which in turn enhances the interaction between sand matrix and fibres as shown in Fig. 3.15 and 3.16. Bending deformation of fibres associated with fine sand was smaller than that associated with the coarse grains.

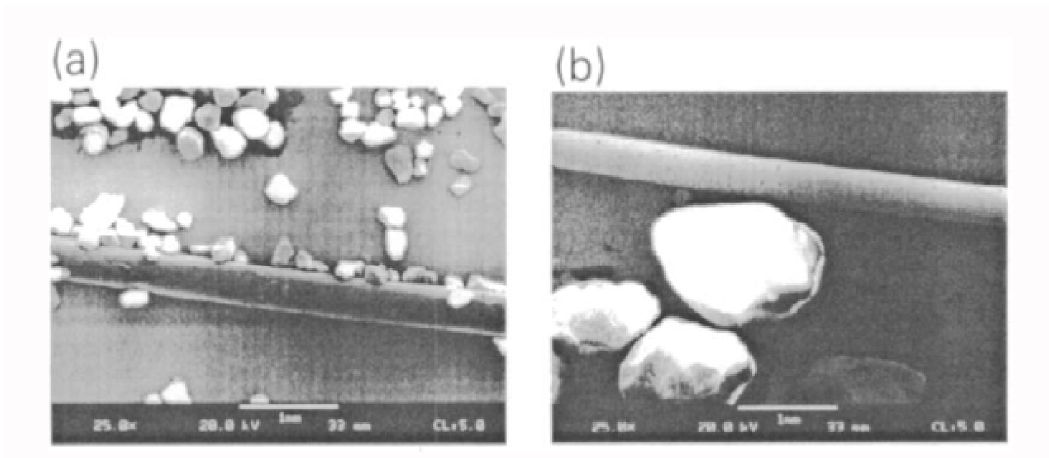


Figure 3. 15 - Sand grains and fibres (a) fine grains (b) coarse grains (Michalowski et al., 2003)

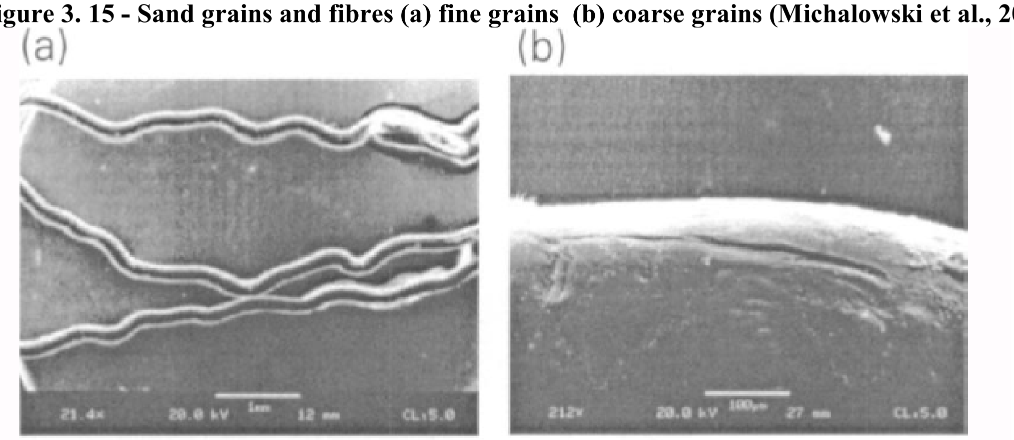


Figure 3. 16 - (a) twisted fibres result of coarse grains (b) local damage on a fibre (Michalowski et al. 2003)

Gripping of the reinforcement elements by sand particles may provide an extra influence resulting in elongation and local strains in reinforcements as seen in Fig. 3.16(b), which does not occur in simple sliding of one material over an other.

However, in the present case, examination of the reinforcements (also called inclusions) after each test revealed no identifiable deformation. As the particles making up the MBT matrix are generally soft and there is a lack of hard, angular, incompressible grains, it can be assumed that the materials slide over each other. The testing conducted in this programme gives a close to that behaviour of the reinforcements in the MBT residues.

3.3.1 Method

- Material interface properties were tested using the 100 mm direct shear apparatus, under three normal stresses; 50 kPa, 100 kPa and 200 kPa.
- Plastic blocks were prepared to the exact size of a shear box half and a hard plastic film (of the same material as the 2D stiff plastic inclusions used in this study as discussed in Chapter 5) was bonded to the surface (as shown in Fig. 3.17)
- When the MBT matrix/plastic interface was tested, the upper half of the shear box was filled with MBT matrix material
- BS 1377-7:1990 test procedure was followed with modifications

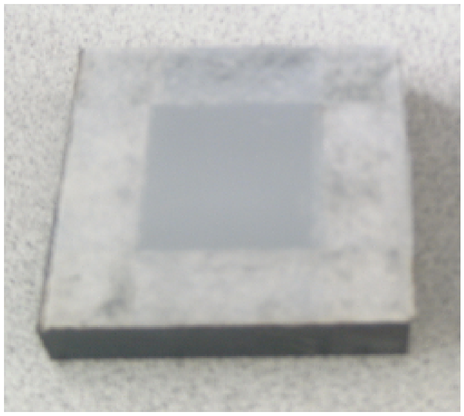


Figure 3. 17 - Plastic block with fixed plastic on its surface to measure interface characteristics

3.3.2 Results

Tests were conducted on three interfaces

a) textured plastic / textured plastic

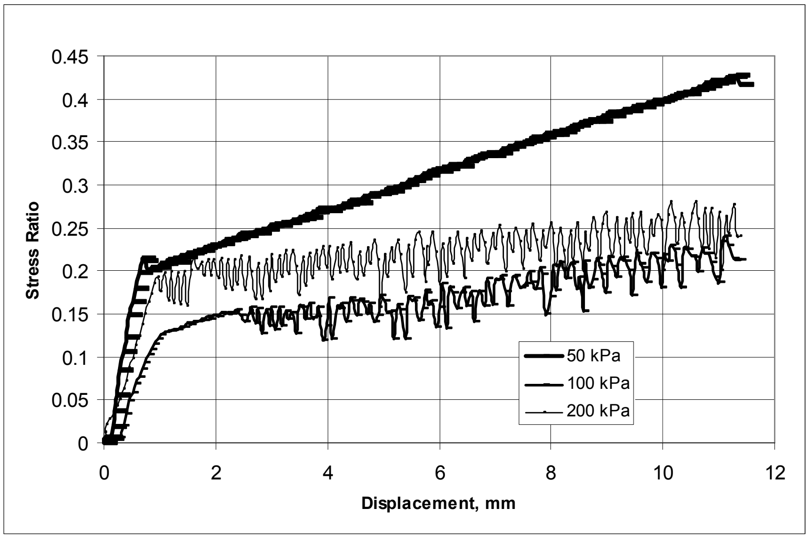
b) smooth plastic / smooth plastic

c) MBT basic matrix (0-2.8 mm MBT) / textured plastic

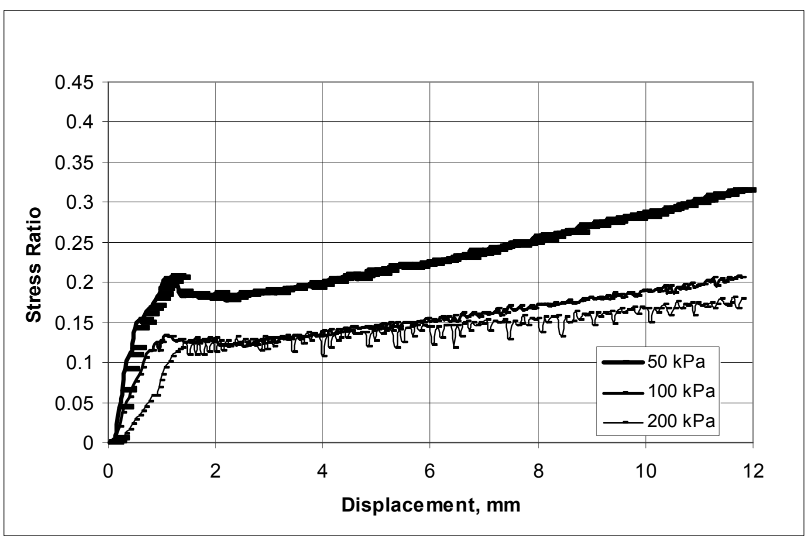
All plastics were obtained from the same type of waste bottles which were used as inclusions (Chapter 5) and the plastic type was HDPE. The smooth plastic was obtained from waste bottles without any texture surface and textured plastics from textured bottles.

a) & b) Plastic / plastic interface

Fig 3.18 shows the direct shear results for the textured and smooth plastic interfaces. Results at 50 kPa normal stress show a comparatively smooth curve but the higher the normal stress, the less smooth the curve. The uneven nature of the plastic surface may affect the smooth displacement at increased normal loads. The textured plastic interface has produced jumps in the stress strain curve. With both materials the stress ratio increases rapidly during the initial (appox. 1.5 mm) displacement. The stress ratio then continued to increase with displacement at a lower rate, until the test was terminated.



(a)



(b)

Figure 3. 18 - Interface characteristics using 100mm shear box (a) textured plastic/textured plastic (b) smooth plastic/smooth plastic

The textured plastic to textured plastic interface has a higher friction angle than that for the untextured plastics.

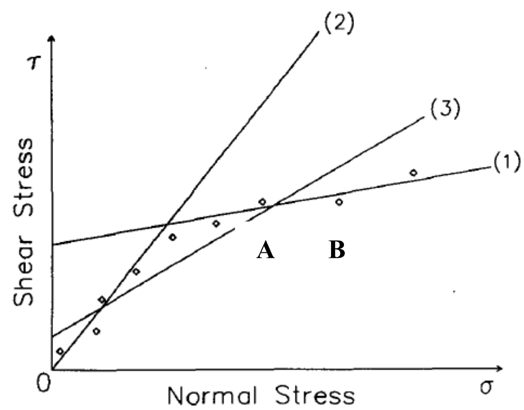


Figure 3. 19 - Interface shear strength (1) high normal stresses (2) low normal stresses (3) all laboratory data points (Giroud et al, 1993)

Giroud *et al* (1993) showed for synthetics/synthetics and synthetics/soil interface (as shown in Fig 3.19),

a) Rapid initial increase of the shear stress with normal stress (apparent friction angle) at low normal stresses (line 2), Shear stress < A

b) A lower rate of shear stress increase (line 1) with increasing normal stresses, Shear stress > A

(i.e. two separate linear relationships can be obtained for lower and higher normal stresses)

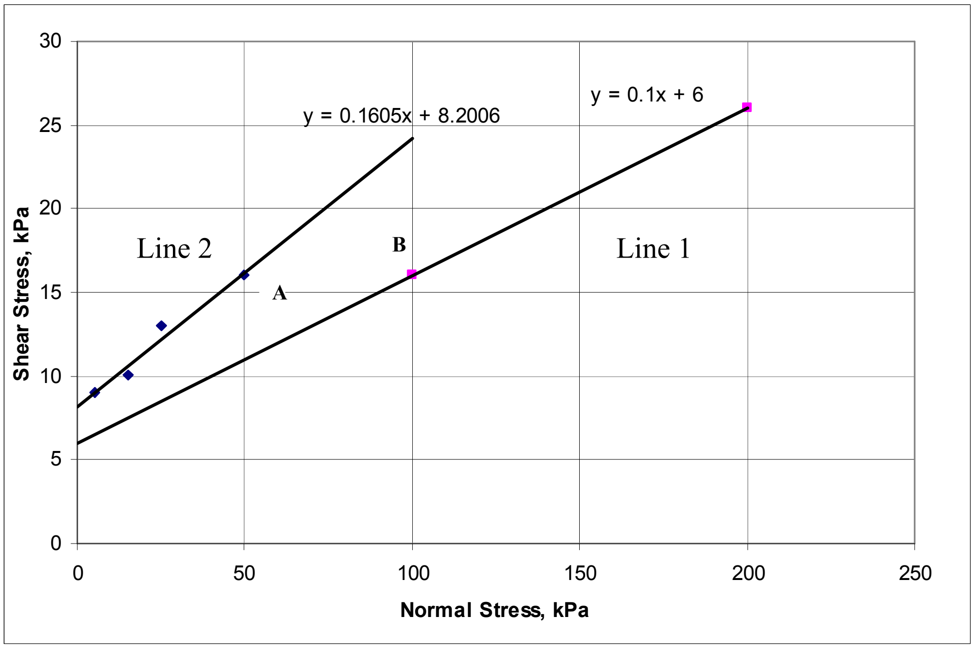


Figure 3. 20 - Shear stress, kPa against normal stress for smooth plastic/smooth plastic interface using 100mm shear box under 5, 15, 25, 50, 100 and 200 kPa
Line 1 – for higher normal stresses

Line 2 – for lower normal stresses

Fig. 3.20 shows the interface properties of the smooth plastic,

a) 15 kPa – 50 kPa shows a rapid increase in the shear stress – Line 2

b) 100 kPa -200 kPa shows lower rate of increase compared with the lower normal stress: 15-50 kPa – Line 1

c) Over the range 50 kPa - 100 kPa there is no significant variation in shear strength (as A to B in Giroud *et al* (1993))

The behaviour under the tested range of normal stresses shows the same behaviour found by Giroud *et al* (1993).

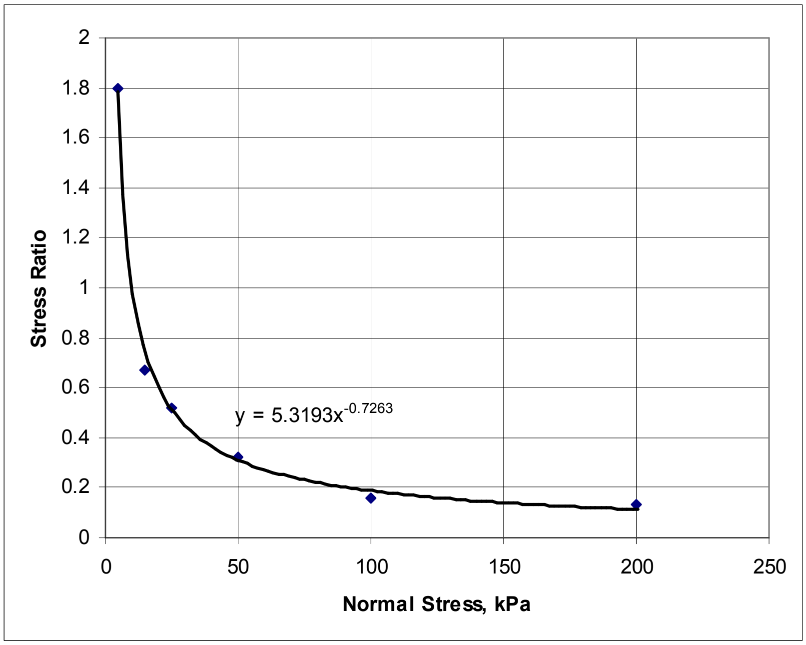


Figure 3. 21 - Stress ratio (τ/σ') against normal stress smooth plastic/smooth plastic interface using 100mm shear box at 12 mm displacement

Fig. 3.21 shows the same data plotted as stress ratio against normal stress, to give a reciprocal curve.

This shows that,

- The stress ratio changes rapidly at lower normal stresses (< 50 kPa), lower than in landfills except near the surface
- The stress ratio does not change significantly above a normal stress of about 100 kPa
- The stress ratio is related to the normal stress by

  $y = A\ x^{-b}$, where A = 5.3 and b = 0.73

c) Plastic/MBT matrix interface

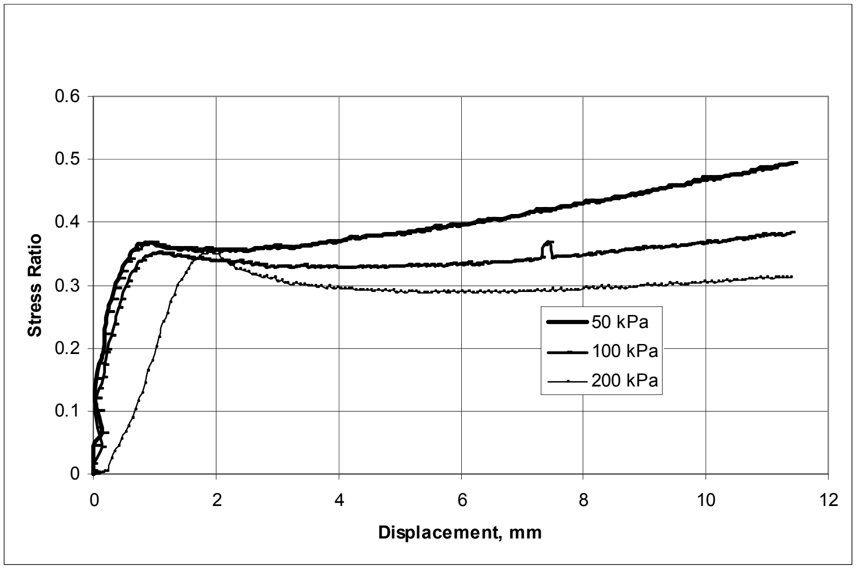


Figure 3. 22 - Stress ratio (τ/σ') against displacement for interfaces of the textured HDPE and MBT basic matrix using 100mm shear box

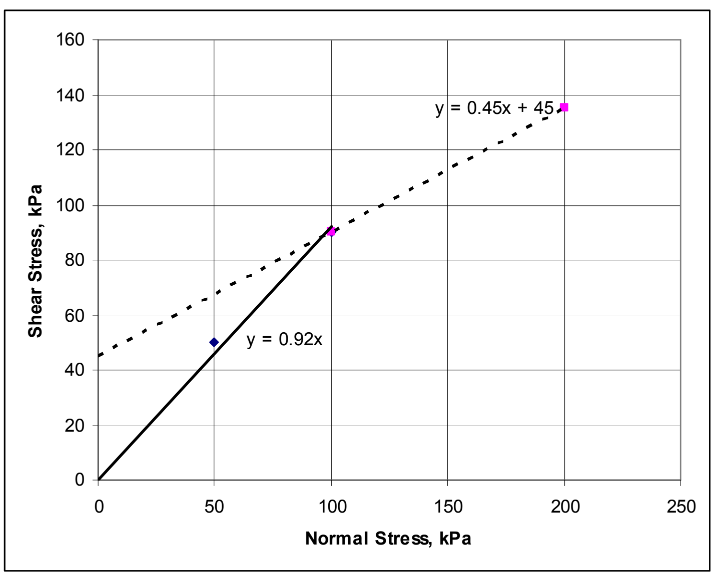


Figure 3. 23 - Shear stress, kPa against normal stress for 0-2.8 mm MBT using 100mm shear box under 50, 100 and 200 kPa

Fig. 3.23 shows the 0-2.8 mm MBT shear strength behaviour with normal stress;

- 0 kPa – 100 kPa shows a rapid increase in the shear stress (friction angle of 42°)
- 100 kPa -200 kPa shows lower rate of increase compared with the lower normal stress: (cohesion of 45 kPa and friction angle of 24°)

As shown in Fig 3.24 the strength mobilised at the MBT matrix / textured plastic interface rose rapidly during the initial 1–2 mm of displacement, but then remained approximately constant or increased only slightly – rather less than in the case of the plastic to plastic interface.

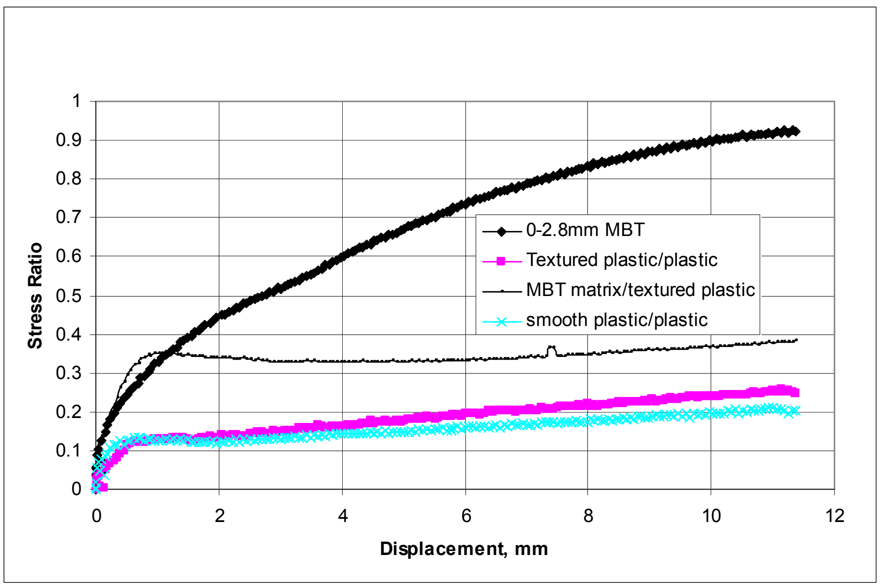


Figure 3. 24 - Stress ratio (τ/σ') against displacement for all interfaces using 100mm shear box under 100 kPa

Table 3. 6 - Interface properties at 10 mm displacement

Interface	Stress Ratio (at 10mm displacement)		
	50 kPa	**100 kPa**	**200 kPa**
Smooth plastic/ smooth plastic	0.28	0.19	0.17
Textured plastic/ textured plastic	0.40	0.25	0.18
0-2.8 mm MBT/ textured plastic	0.48	0.38	0.30
0-2.8 mm MBT / 0-2.8 mm MBT	1.00	0.90	0.68

Comparison of the interface results show,

- Slightly higher stress ratios for the textured plastics than for the smooth plastics, but not significantly at higher normal stresses (i.e. the textured plastic in waste is probably not textured enough to create a significant strength difference under landfill loads)
- Plastic/plastic interfaces are weaker than the other interfaces (MBT matrix itself and MBT matrix/plastic) – reaching about 2/3 the stress ratio of a waste/plastic interface and <1/4 that of a shear plane in the waste itself

Conclusions

- The angle of friction of both the plastics to plastics and plastics to MBT interfaces are weaker than the MBT along. This suggests that the plastics may weaken the overall material depending on the concentration
- The mechanics of reinforcement in MBT probably represent one material sliding over the other.

3.4 Particle density determination of the MBT

Particle Density is also known as Grain Density in soil mechanics. Soil particles consist of a range of mineral grains which were derived from rocks by geological processes. In a particle density test in soil mechanics the average grain density is determined. In most soils it varies over a small range of values, 2.6–2.8 Mg/m^3 (Barnes, 2000). In contrast, waste consists of different components with a much wider range of particle densities (e.g. flexible plastics less than 1 Mg/m^3 and stones more than 2 Mg/m^3). The waste particle density test covers the determination of the average particle density of a range of different materials due to the heterogeneous nature of the waste.

The aims of this testing programme are;

- to determine the average particle density of 0-10 mm and 0-20 mm MBT residues
- to identify the particle density of the each waste components and calculate the particle density of the material and evaluate the validity of this method (as a more accurate way to calculate the particle density)

The particle density also is important in (a) identifying the volume fraction and total area of reinforcements, which may have an impact on the strength characteristics of the waste and (b) determining the void ratio of the specimens

3.4.1 Modifications to the BS1377-2:1990

The particle densities of the MBT and the waste components were determined using the gas jar method (Fig. 3.25) in BS 1377-2:1990, modified in following ways;

- Many of the waste components for which the particle densities were to be determined were present in small quantities (e.g. if a component consists 1% of the whole by mass, 20 kg of MBT needs to be sorted to obtain a 200 g sample as the BS requires). Hence smaller samples were tested in a smaller gas jar than specified. Some of the materials have low densities (e.g. flexible plastics) and a 200 g sample would overfill the jar hence the sample quantity was reduced.

- BS 1377:2 requires 20-30 mins of mechanical shaking to deair the sample. In the absence of a mechanical shaker and less importance of using the shaker for the material used, the samples were hand shaken and left for at least 24 hrs for soaking.

Note: Some waste components were less dense than water, so paraffin was used instead of water as allowed by BS 1377:2.

Figure 3. 25 - Gas jar equipment for particle density testing

3.4.2 Procedure for sample preparation

To obtain the waste components;

- 7.5 kg of 0-20 mm MBT waste was oven dried at 65°C, dry sieved and the material > 5 mm was hand sorted into the components. The waste components are shown in Table 3.7.
- Particle densities of components comprising < 1.5 % of the total mass were not determined e.g. rubber, metal, bones and paper were not determined separately.
- The material that remained after sorting and that < 5 mm was considered as 'miscellaneous' and 'unidentifiable'
- Appropriate proportions of the materials consisting < 1% of the rubber, metal, bones, paper and textile/wool were added to the miscellaneous fraction
- All waste components sorted from the MBT were stored in air tight containers until their particle densities were determined

- Average particle densities for the 0-10mm and 0-20mm MBT samples were determined separately. Representative 200g samples for each were obtained by the quartering method.

Table 3. 7 - 0-20mm MBT waste analysis results

Component	**Percentage by mass (%)**
Plastic-flexible	4.6
Plastic-stiff	6.3
Textile and wool	1.3
Glass	22.8
Ceramic	2.3
Stones	1.7
Metals	0.5
Paper	0.4
Wood	1.6
Bones	0.3
Rubber	0.2
Miscellaneous and unidentified	58.1

3.4.3 Particle density results on MBT waste

Using the gas jar method the average particle densities of 0-20 mm MBT for two samples and 0-10 mm MBT were determined and the results shown in Table 3.8,

Table 3. 8 - MBT particle density results

MBT Type	Particle Density (Mg/m^3) – Sample 1	Particle Density (Mg/m^3) – Sample 2	Average (Mg/m^3)
0-10 mm MBT	1.69		1.69
0-20 mm MBT	1.911	1.948	1.929

According to BS1377-2:1990, the particle density difference of the two samples should be less than 0.03 Mg/m^3. The difference in this case (0-20 mm MBT) was 0.037 Mg/m^3 which is slightly greater than that recommended for soils. However waste is more heterogeneous than soil; thus a larger variability would be expected and the values seem acceptable.

The 0-10 mm MBT particle density results showed an average particle density of 1.69 Mg/m^3, which is a less than for the 0-20 mm MBT. This is because the high density material - glass generally can be found at higher contents in larger size range (Refer Section 3.1). This results in lower densities in the finer material.

When comparing the particle density values obtained from the waste with corresponding published values, there is a good correlation except for wood (Table 3.9) which seem to give significantly higher values than the published figures. Other materials may have been wrongly identified as wood (e.g. bones), but as a result of the relatively low content (1.6%) of wood particles, the impact on the final result is not significant.

Table 3. 9 - Particle density calculation for MBT using the particle density of the components

Component	Fractional Mass Content (m)	Fractional Volume (Vs)	Particle Density Obtained, Gs (Mg/m^3)	Published Particle Densities (Mg/m^3)[a]	Volume %
Glass	0.228	0.091	2.51	2.4 - 2.8	15.44
Wood	0.016	0.015	1.10	0.16 (balsa) 0.7 (oak)	2.47
Hard Plastic	0.063	0.059	1.06	0.97 (HDPE) 2.19 (Teflon)	10.10
Stones	0.017	0.007	2.32	2.4 – 3.0 (basalt)	1.25
Ceramic	0.023	0.010	2.36	2.5 (porcelain)	1.66
Light Plastics	0.046	0.055	0.83	0.97 (HDPE)	9.42
Unidentifiable	0.607	0.588 [b] (0.573 [c])	1.73[b] (1.81[c])		59.65
Calculated Particle Density (Gs = m / Vs)			1.70[b] (1.746[c])		

[a] from http://www.engineeringtoolbox.com/specific-gravity-solids-metals-d_293.html

[b] Particle density obtained using water

[c] Particle density obtained using paraffin

Table 3. 10 - Comparison of the particle density results

0-20 mm MBT	As received material (average)	Calculated – (unidentifiable using water)	Calculated – (unidentifiable using paraffin)
Particle Density (Mg/m^3)	1.93	1.70	1.746
Difference to the as received MBT (%)		12%	9.5%

Gas production in the MBT could have an impact on the particle density determination. Fine particles (in this case 0-5 mm) consists of organic material and may likely to start to degrade with moisture. The gas production potential of the same MBT material can be found in Siddiqui (2011). Table 3.10 shows calculated particle density value of the as received MBT in water and paraffin without gas production. Particle density using the water is low in value (2.5%) compared to the particle density with paraffin but the difference is not significant.

3.4.4 Problems Identified

The particle density test on stones showed a slurry left in the bottom of the gas jar. This shows that soil lumps may have been identified as stones. There may be other similarly wrongly identified components. The high particle density for wood is may also suggest this.

After soaking the organic material in water for a minimum of 24 hrs. organic matter may have started to biodegrade. As a result gas production from the biodegradable components may have been initiated, again creating bubbles which are a source of error, leading to underestimation of the particle density.

Unlike soil grains waste particles themselves consist with voids (waste components consist of voids with in the particles e.g. paper). Full saturation of the waste particles consist of small voids themselves are difficult to measure and confirm. With the absorption of water structure of the waste particles are likely to be changed. This may affects the particle density of the waste.

Small amounts of other particles may be attached to the components such as organic dust attached to light and hard plastics. However this error is likely to be very small.

Conclusions

By considering the heterogeneous nature of the MBT and MSW and the smaller size of the specimen needed for the test, it seems that testing the particle density of the as received material may be less accurate than the calculated density (using the sum of the different particles) using larger samples.

As MBT contains a large amount of unidentifiable and miscellaneous components (due to either be small particle size or material simply be unrecognisable), it governs the particle density. As unidentifiable and miscellaneous includes almost the all biodegradable content, it seems likely that the best results are those obtained from liquid paraffin.

Part 2

3.5 – Materials and Methods

3.5.1 Materials

In this testing programme two types of materials were used, compost and MBT. The following size fractions of the MBT from a single batch were used after screening;

- 0-10 mm
- 0-20 mm
- 0-2.8 mm (0-10 mm MBT sieved in laboratory to obtain the basic matrix of 0-2.8 mm)

0-2.8 mm was visually inspected and appeared to be free of any elements likely to act as reinforcing elements. Hence it was assumed there is no reinforcing elements in 0-2.8 mm basic matrix and as a result of that free of reinforcing effect

However it should be noted, many researchers have used different larger fractions as their basic matrices (e.g. Fucale *et al.* (2007) used 0-8 mm as the basic matrix for 0-60 mm MBT and Zekkos (2005) used 0-20 mm as the basic matrix for MSW). By considering the comparatively smaller particle sizes of the NES MBT residuals (0-10 mm and 0-20 mm), a basic matrix consists with smaller particles (such as 0-2.8 mm) seems more appropriate in this case to investigate the reinforcement impact.

The MBT process and the content of the MBT were discussed in detail in Section 3.1.

To understand the reinforcing effect, in addition to the MBT, compost was used as a basic matrix while adding reinforcing elements. Commercially available peat-free, 0-2.8 mm green waste compost was used. Compost was obtained from two batches due to the quantity required.

3.5.2 Introduction to the direct shear apparatus

The direct shear apparatus is commonly used to investigate the shear stress – displacement behaviour of soils. The direct shear test was the major laboratory shear test used in this research. The 300 mm x 300 mm direct shear apparatus and its components are shown in Fig. 3.26 & 3.27. Three shear boxes were used in this testing programme and their dimensions are shown in Table 3.11. The 60 mm shear box was used only for a limited number of tests. The fundamentals are the same for all direct shear apparatus regardless of the size of the shear box.

Table 3. 11 - Dimensions of the shear boxes

Shear box	Sample size (mm)		
	Length	Width	Height
300 mm	300	300	150
100 mm	100	100	50
60 mm	60	60	50

According to the BS 1377-7:1990 Section 4.4.1 the maximum particle size of the testing material should be 0.1 times of the height of the sample. As a result of that, the larger shear boxes are used to test the material with larger particles which also provide opportunity to investigate the behaviour under larger displacements. The validity of the results from smaller shear boxes is assessed in Chapter 4.

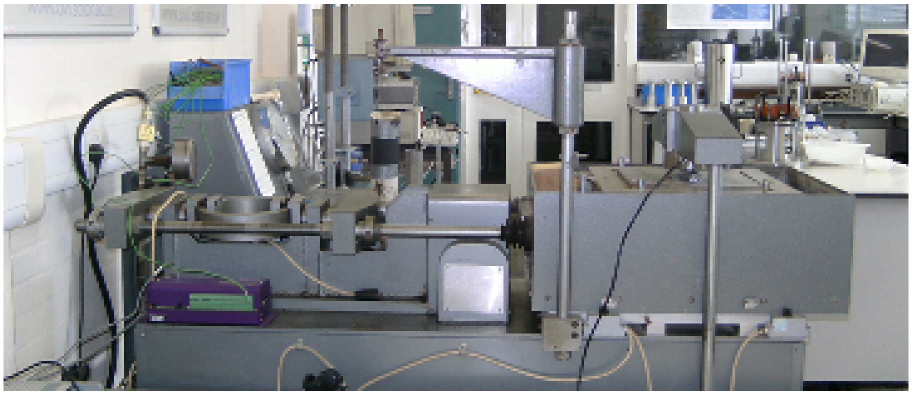


Figure 3. 26 - Direct shear apparatus (300mm x 300mm)

Direct shear equipment consists of few major components such as the shear box, loading frame, proving ring for measuring the shear force, loading system and horizontal and vertical dial gauges to measure displacements, as shown in Fig. 3.27.

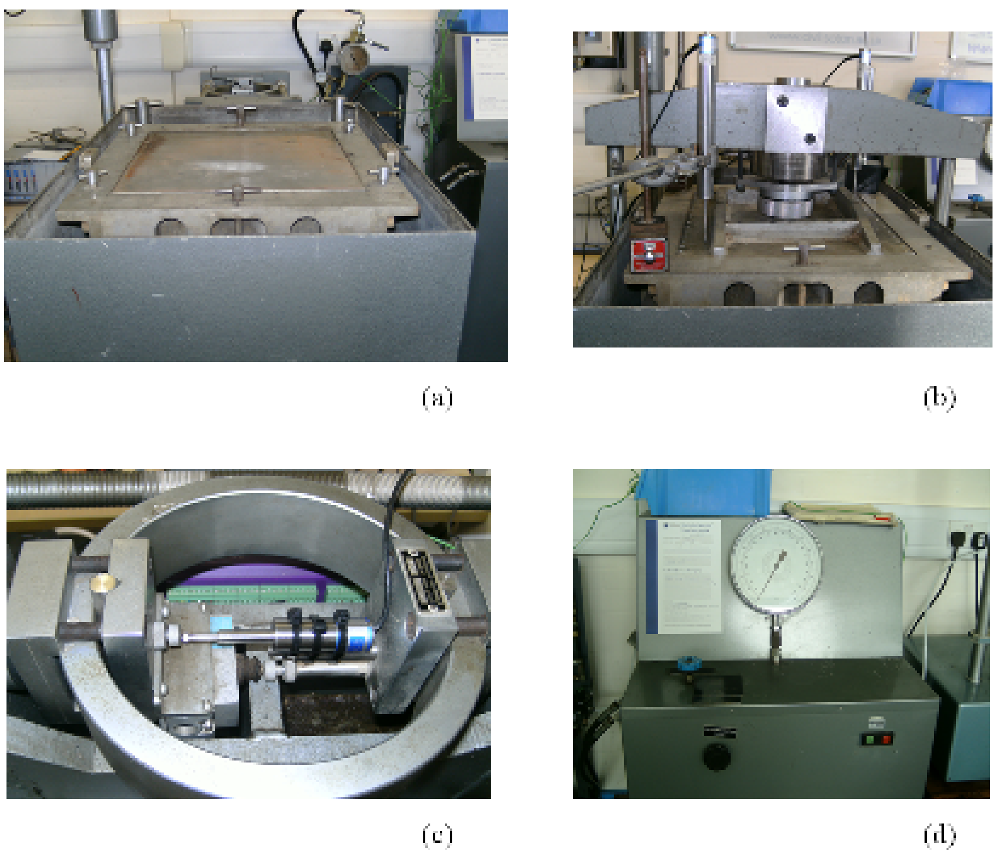


Figure 3. 27 - Main components of the shear box equipment (a) shear box (b) loading frame (c) proving ring (d) hydraulic loading system

In summary;

The shear box is a metal box which can be split horizontally into two halves as shown in Fig. 3.29. The shear box is filled with the sample and one half of the box (in this case bottom half) is moved with respect to the other half of the box (i.e. while other half is stationary). The force needed to move the shear box half gives the shear strength of the material (when divided by the shear surface area to obtain the shear stress). Before starting a shear test, the upper half of the shear box is lifted slightly by turning screws to create a small gap between two halves of the shear boxes to avoid the box halves touching (in order to minimize additional frictional forces which would increase the apparent shear strength of the material being tested).

The loading frame (Fig.3.27(b)) applies the normal load on to the sample. For the 300 mm shear box the normal load applied hydraulically (Fig. 3.27(d)) and for 100 mm and 60 mm shear box load was applied using dead loads. In general, the normal load is decided by considering the overburden likely to be experienced in field conditions (or that to which the sample has previously been subjected).

The proving ring (as shown in 3.27(c)) or a load cell is used to measure the shear force from which shear stress can be calculated.

A detailed description of the direct shear equipment can be found in Head (2006) and the concept is described in Powrie (2004).

3.5.3 Arrangements to the direct shear 300mm x 300mm apparatus

The Datataker DT515 Series 3 data logger (as shown in Fig. 3.28) was used to log all the data at 15 second intervals.

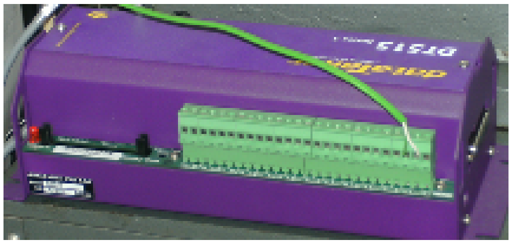


Figure 3. 28 - Datalogger

A Linear Variable Differential Transformer (LVDT) was clamped to the proving ring in order to measure the deflection of the proving ring on the 300 mm equipment as shown in the Fig. 3.27(c). The deflection of the ring was measured and the data were logged.

An LVDT was used to measure the horizontal displacement of the shear box as shown in Fig. 3.29.

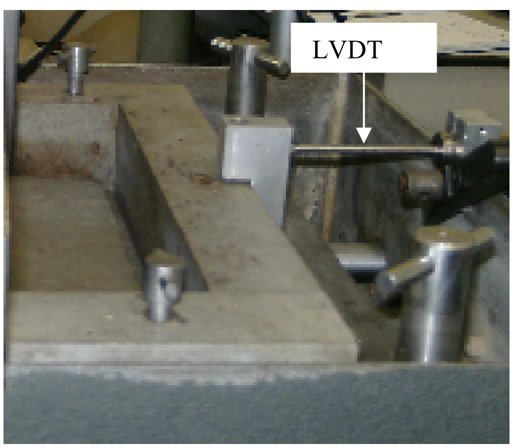


Figure 3. 29 - Arrangement for horizontal displacement measurement

Four LVDTs were used to measure the vertical displacement with shear in the 300 mm direct shear tests. Normal practice is to use a single measurements point for the vertical movement of the upper plate. In early tests, it was observed that the movements of the upper plate was non uniform and multiple measuring points were required in order to measure the average vertical displacement (to determine the volume change). As a result of the differential movements of the lid, single point measurement would have been insufficient. These LVDTs measured the vertical displacement (vertical settlement) of points on the cover plate. Using these settlement measurements the movement of the waste surface can be obtained, and hence the volume change of the sample during shear identified (Chapter 4).

The equipment setup for the 100 mm x 100 mm test is almost identical to that of the 300 mm x 300 mm setup. Shear force was measured using a load cell rather than a proving ring. The vertical displacement was measured using a single LVDT instead of four in the 300mm shear box due to a lack of space to install more LVDTs. The normal load was applied using dead loads with a lever arm. The setup of the 60 mm shear box was identical to that of the 100 mm box.

3.5.4 Sample preparation

A representative MBT sample large enough for a series of tests was obtained. Sample selection methods, such as quartering, were not used to select the material due to the more homogeneous nature of the material and the large amount of waste required. Particles larger than the nominal upper sieve size limit (e.g. ball point pens, lollypop sticks) were hand sorted and removed before sample preparation. The 100 mm shear box has a volume only 1/27 that of the 300mm shear box so requires a much smaller volume of waste, which was obtained using the quartering method.

As received waste was found to be fairly dry and cohesionless and hence the loose sample method could be use to prepare samples, as recommended by the BS 1377-7:1990 clause 5.4.7 for dry gravelly cohesionless soils. The specimens were prepared as follows;

- MBT was placed in a number of suitable containers (for the 300 mm shear box, 10 litre buckets filled up to 6 litre level)
- The contents of each bucket were steadily poured into the shear box from a height of about 0.5 m as quickly as possible
- When pouring the material, an effort was made to spread the material as evenly as possible to avoid heaping
- After emptying each container the sample surface was leveled using a spirit level without causing disturbance to the main body of the waste
- A cardboard cover was used over the shear box to collect any unused or spilled MBT as shown in Fig.3.30(a)
- The procedure was continued until the shear box was full
- The top porous plate and the cover plate was placed on the waste sample and the normal stress (same normal stress that the direct shear test propose to be conducted) was applied
- If the sample was compressed below an acceptable level (lower than expected shear zone), the plates were removed and the sample was topped up using the same procedure
- All mass measurements were taken to the nearest 1g

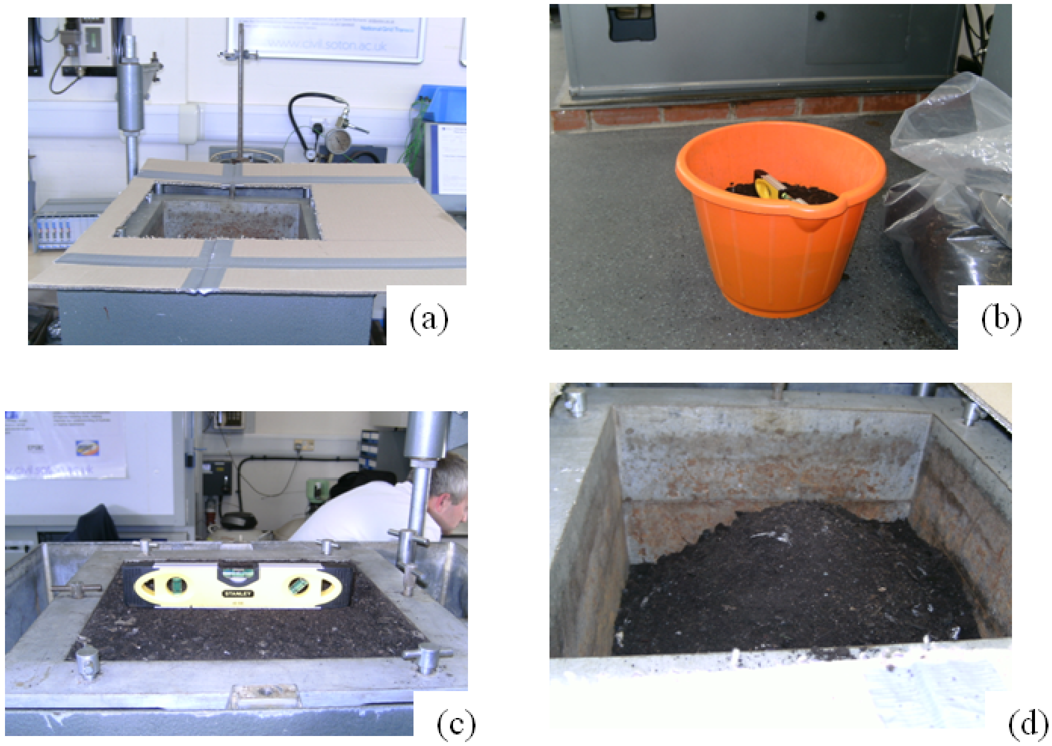


Figure 3. 30 - Sample preparation in 300 mm x 300 mm shear box (a) covered shear box to collect any MBT spilled during sample preparation (b) one of the levelled containers (c) Levelling of the MBT surface (d) after pouring the sample in to the shear box

3.5.5 Direct shear procedure

The direct shear test was carried out according to BS1377-7:1990 as follows;

- The top porous plate was placed on the waste sample manually and the top cover plate was placed (using a small crane in the case of the 300mm shear box). When placing the cover and the porous plates it was ensured that there was uniform clearance all around the edges of the plate and the walls of the shear box.
- The loading yoke was placed and the normal stress was applied, using the hydraulic pump for the 300 mm shear box and using dead loads with a lever arm for the 100 mm shear box.

- The specified normal load of 50, 100 or 200 kPa (BS1377-7:1990 recommends doubling the previous normal stress) was applied and allowed to compress the sample.
- If the sample was compressed to a lower sample height due to the high compressibility of the MBT as has been previously stated, the sample was topped up with MBT and the procedure repeated until a satisfactory sample height obtained to conduct the direct shear test.
- Sample was compressed for at least 24 hours under the particular normal stress which the shear test was to be conducted (Refer to Note 1 at the end of the section).
- After the sample was consolidated, the top of the shear box was lifted from the bottom by rotating the separating screws on the shear box by one turn. All the screws were removed before commencing the direct shear test. By lifting the top of the box relative to the bottom (creating a gap) and therefore, there was no friction between two box halves.
- A shear rate of 0.45 mm/min. was used for almost all of the tests (Refer Appendices)

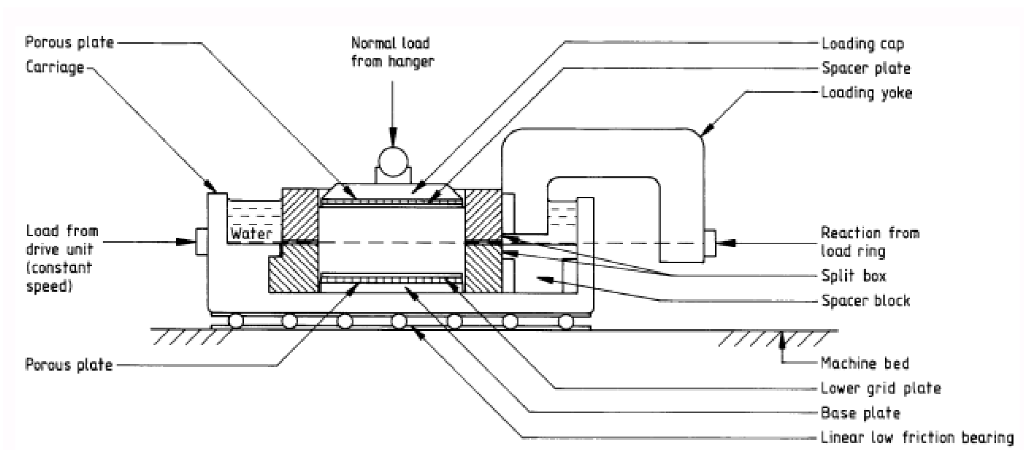


Figure 3. 31 - Direct shear apparatus (BS 1377-7:1990)

3.5.6 Repeatability

The repeatability of the shear tests was assessed by conducting repeat tests on the same material from the same batch under same conditions as shown in Fig. 3.32. The particle size and related size restrictions of the shear box (BS1377-7:1990) suggest that repeatability is likely to be a bigger issue in the smaller shear boxes, so 100 mm shear box tests were conducted. It was assumed that, if the tests were repeatable for the 100 mm shear box, then they would be repeatable for the larger (300 mm) shear box.

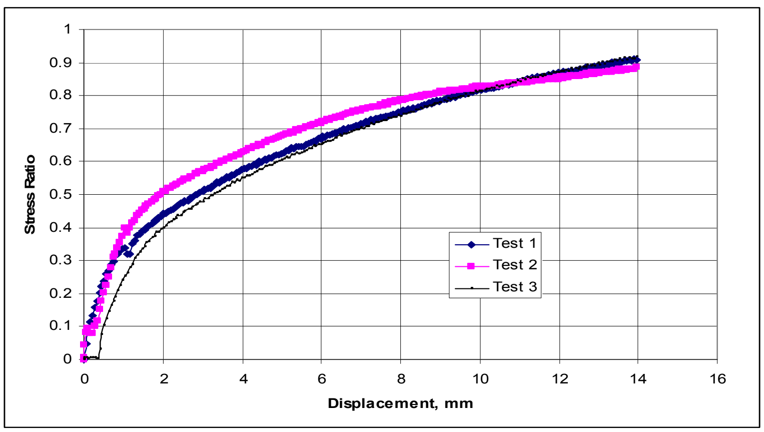


Figure 3. 32 - 10 mm x 20 mm 2% stiff plastic by mass in 0-2.8 mm MBT tested under a normal stress of 100 kPa in the 100 mm shear box

The results show;

- Test two shows a higher initial stiffness and slightly reduced final strength characteristics relative to the other two tests but the differences are not significant

- All three tests show the same behaviour and similar strength characteristics

3.5.7 Orientation

Orientation of the reinforcements may have an impact on the strength of the material as discussed in Chapter 2. Understanding how the reinforcements are orientated in the specimen is important to understand the impact of the reinforcing elements. For example if the reinforcement is all arranged horizontally there is no mechanism to create a reinforcing effect in a direct shear test. The reinforcement arrangement of the sample was assessed using systematic deconstruction of the sample.

Systematic deconstruction of the sample

The sample was prepared with the 0-2.8 mm MBT basic matrix and using 22 pieces of 10 mm x 20 mm stiff plastic reinforcements. The sample was prepared using the same sample preparation method as used through out this research and the 100 mm shear box was used to mould the sample.

Table 3. 12 - Orientation of the reinforcements by sample destruction method

Particle no.	Closest distance from the surface (mm)	Greatest distance from the surface (mm)	Angle to vertical (°)
1 [a,b]	0	0	90
2	0	8	41
3	0	7	46
4	0	10	25
5	0	15	41
6	0	12	57
7	0	10	68
8	11	13	78
9	14	25	74
10	12	18	74
11 [a]	5	5	90
12	14	20	78
13	0	17	48
14 [a]	15	16	89
15	12	15	78
16	12	21	71
17 [a]	26	26	90
18 [a,b]	34	36	87
19 [a,b]	32	32	90
20 [a,b]	21	25	78
21 [a,b]	37	37	90
22 [a,b]	34	37	73

[a] Horizontal or almost horizontal [b] Particles laying on upper or lower surface

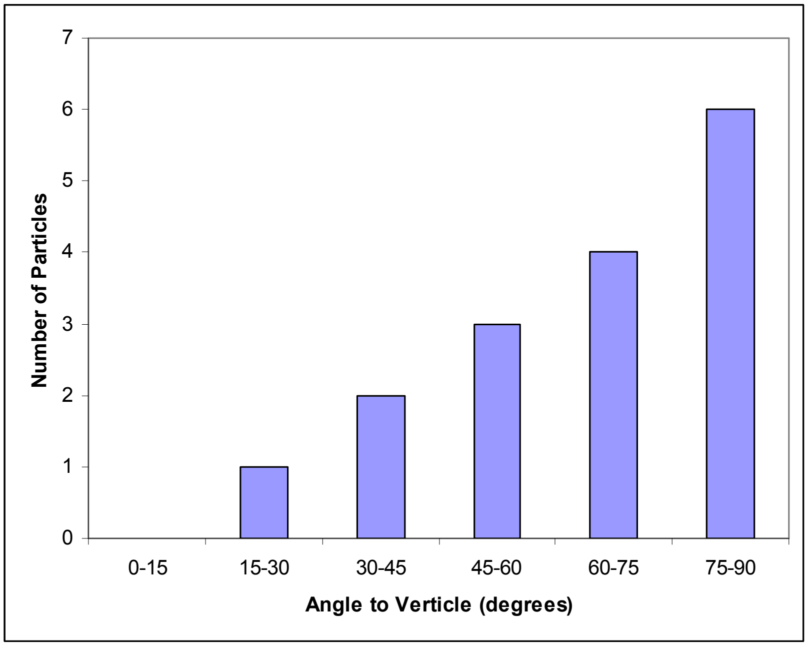


Figure 3. 33 - Distribution of the particles with angle to vertical
Disregarding the particles laying on upper and lower surfaces

Table 3.12 shows that;

- Most of the horizontal reinforcements (78%) can be found on either the upper or lower surface of the sample
- Only three reinforcements within the sample were horizontal, which may have an impact on the strength (marked as [a])
- Only three reinforcements are oriented closer to the vertical
- Most of the particles (56%) more or equal to 60°, proving the orientation is more to horizontal (excluding the horizontal particles near surface from the calculations)
- The orientation of the axis of the 2D reinforcement is considered as the orientation of the particle

Another sample prepared with the same procedure and same materials was CT scanned (Fig. 3.34). The details of the scanning can be found in Caicedo *et al.* (2011).

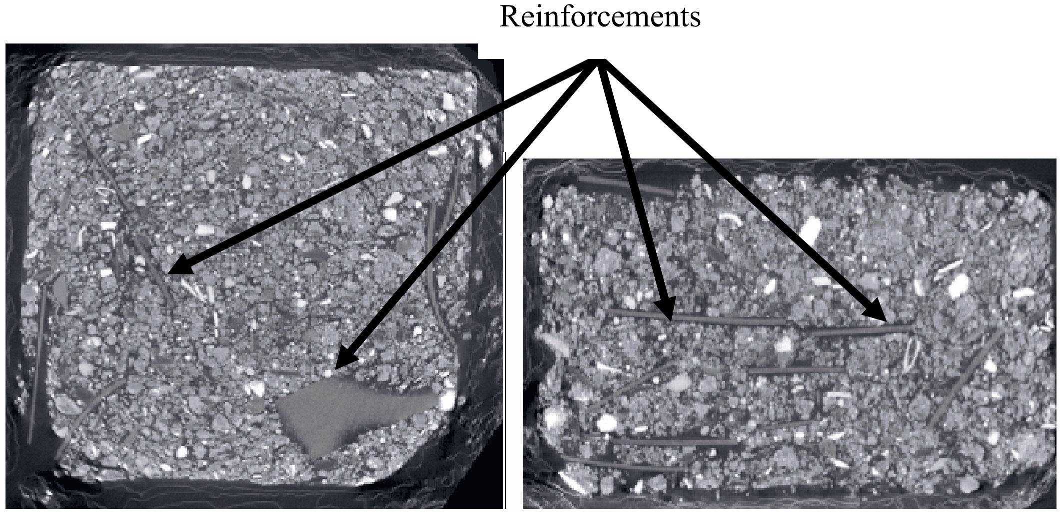


Figure 3. 34 - CT scan picture on the sample showing reinforcements (a) horizontal view at 10.04 mm (b) Verticle view at 9.67 mm (Caicedo *et al.* 2011)

Both the above methods used to identify the reinforcing element distribution show that

(a) reinforcements appeared uniformly distributed throughout the sample and

(b) reinforcements appeared to be distributed close to the horizontal than to the vertical (Fig.3.33 shows 10/17 > 60°, i.e. horizontal or sub horizontal)

It is well known waste particles are arranged more horizontally in landfill environment. It was assumed that the sample preparation method used in this research is satisfied the arrangement which occurs in landfill environment.

3.5.8 Particle densities of the materials

Particle density of the material is important in identifying the void ratio of the specimens. Particle densities of the materials used are shown in Table 3.13.

Table 3. 13 - Measured mean particle densities of the material

Material	Particle Density (Mg/m^3)
0-10 mm MBT	1.69
0-20 mm MBT	1.93
0-2.8 mm MBT	1.70

3.5.9 Problems identified

(a) Rotation of the cover plate

It was found that the lid of the shear box tilted to the opposite direction of the displacement as shown in Fig. 3.35.

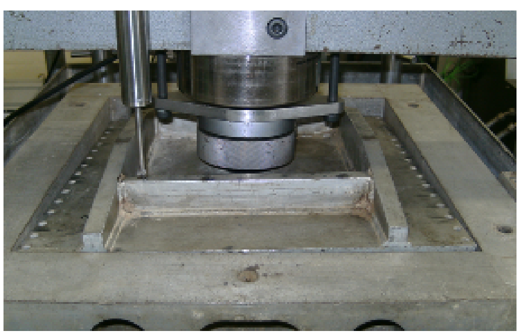
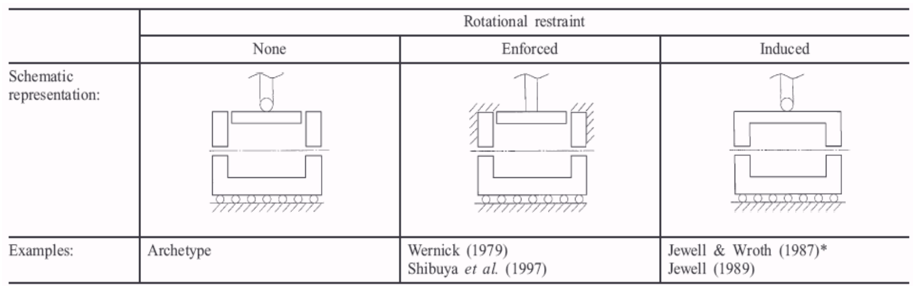


Figure 3. 35 - Tilting of the shear box lid

The direct shear equipment used has no rotational restraint and as a result, the cover plate was free to tilt. Lings & Dietz (2004) discussed this issue and suggested modifications to the apparatus shown in Fig. 3.36. The characteristic most commonly addressed is the tendency for the load pad and upper frame to rotate during testing, often in the opposite direction to the shear displacement.

Shibuya *et al.* (1997) identified two generic modifications as shown in Fig. 3.36. One of them physically prevents the upper frame from rotating; and the other also aims to stop rotation but without restricting free displacements. However Lings & Dietz (2004) conducted shear tests on sand and compared the results from tests in which rotation of the top plate was permitted and those in which it was restricted and showed that the rotation of the cover plate did not have a significant impact on the shear stress results as shown in Table 3.14.



(1) (2) (3)

Figure 3. 36 - Modifications to the Shear box to avoid the rotation of the upper frame (after Shibuya et al, 1997 & Lings & Dietz, 2004)

Table 3. 14 - Direst shear tests conducted under different shear box conditions using sand under 25 kPa (after Lings & Dietz, 2004)

Shear box type*	**Angle of friction (φ_p°)**
Type 1	50.7
Type 2	50.4
Type 3	50.4

*Type according to Fig. 3.36

(b) Gap between the two halves of the shear box

The gap between two halves of the shear box appears to have an impact on the shear stress characteristics as shown in Table 3.15.

The gap between the shear box halves can be controlled easily during the first test. However when the same sample is used under different normal stresses (which is the general practice in waste testing) the gap between the two halves of the box is difficult to control. The upper half of the box is lifted during shear and this will increase the gap in subsequent tests. Higher gaps greater than a particular range probably affect the results.

Table 3. 15 - Gap between two shear boxes and impact on strength (Lings & Dietz, 2004)

Gap (mm)	Angle of friction (φ_p°)
0.5	50.1
2	48.5
4	48.6
6	46.5
8	45.1

(c) Frictional internal walls of the shear box (Edging)

Table 3.16 shows that the frictional properties of the sidewalls have an impact on the measured shear strength characteristics. The sidewalls of the 300 mm shear box are made of steel, which has weathered so that the finish of the metal is slightly textured suggesting a rough and hence high friction interface. The 100 mm shear box walls have a smooth finish and probably provide lower friction conditions. Lings & Dietz, (2004) showed that the edging has an impact on the final shear results as shown in Table 3.16. Lings & Dietz, (2004) used a 100 mm x 100 mm shear box for these tests.

Table 3. 16 - Edging of the shear box and its impact on shear strength (Lings & Dietz, 2004)

Edging	**Angle of friction (φ_p°)**
Continuous rubber	49.7
Split rubber	48.2
Continuous latex	48.3
Split latex	47.8
No edging	46.0

Beaven & Powrie (1995) using a 2 m diameter metal cell found a significant reduction in normal stress due to sidewall friction, however 90% of the load was transmitted to 2 m depth. By considering the larger size of the shear box used for this research (300 mm x 300 mm) it can be assumed that edging conditions probably had reduced impact compared to Lings & Dietz, (2004). Higher frictional edgings may have provided slightly lower strength characteristics.

Chapter 4
Shear strength characteristics of MBT waste

The shear strength characteristics of MSW have been studied by many researchers including; Kölsch (1996), Pelkey *et al*. (2001), Gisolia *et al*. (1995), Kavasanjian *et al*. (1999) and Dixon & Langer (2008). Knowledge of the shear strength of the waste is an important factor for landfill design. Dixon & Jones (2005) showed that 9 out of 10 landfill infrastructure failure modes (identified by the authors) are influenced by waste shear strength.

It is likely that MBT will be one of the major residual waste streams and will probably be landfilled in the future instead of MSW (Environment Agency, 2005). The shear strength characteristics of MBT are unlikely to be the same as those of MSW, as a result of the pretreatments (Chapter 3). The shear strength of MBT residues has been studied by many authors including; Bauer *et al*.(2009), Kölsch (2009) and Mahler & de Lamare Netto (2003). However the strength characteristics of MBT landfilled in the UK could be different from other European countries as the UK only regulates the biodegradable content, whereas Germany controls the calorific value of the residue (Environment Agency, 2005). This has been discussed in detail in Chapter 2.

4.1 Direct shear results on MBT residues

Aims of the testing,

- To identify the shear strength characteristics of MBT (from UK) and compare the strength characteristics with European (e.g. German) MBT residuals
- To compare the strength values of MBT with MSW to understand the impact on future landfill infrastructure

All direct shear tests on both residues (Aerobically treated MBT obtained from NES MBT plant, UK) were conducted using the same procedures and conditions as discussed in Chapter 3.

- Tests were conducted under normal loads of 50 kPa, 100 kPa and 200 kPa (i.e. doubling the previous load following BS1377-7:1990). The 0-10 mm MBT under 50 kPa normal stress test was terminated due to a failure in the 300 mm direct shear equipment and the test was not repeated.
- Specimens were allowed to compress under the same normal stress that the direct shear test would be conducted
- Particles much larger than the nominal maximum particle size were removed (e.g. long wires)
- As a result of the large amount of material needed for the specimen and the relative by homogeneous nature of the MBT no specific sample selection method was used for the 300 mm shear box specimens
- The tests were conducted according to BS1377-7:1990

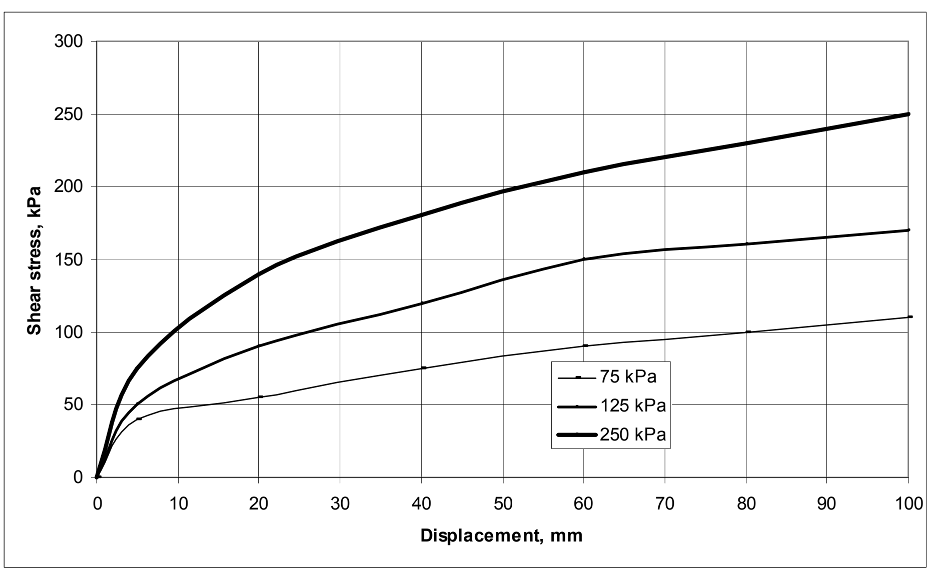


Figure 4. 1 - Direct shear results on 0-60 mm MBT waste (after Scheelhaase et al. 2001)

Scheelhaase *et al*. (2001) conducted direct shear tests on 0-60 mm MBT. The results in Fig. 4.1 show;

- A smooth curve with increasing mobilised strength until the test was terminated
- No clear peak despite a very large displacement
- That the higher the normal stress, the lower the stress ratio at a given strain(e.g. at 50mm displacement approximately 1.07, 1.04, 0.8 stress ratios for 75, 125, 250 kPa normal stresses)

The results from both residues, 0-10 mm and 0-20 mm tested under this programme are shown in Fig. 4.2 and 4.4 respectively, and the strength characteristics at 50 mm displacement are shown in Fig. 4.3 and 4.5.

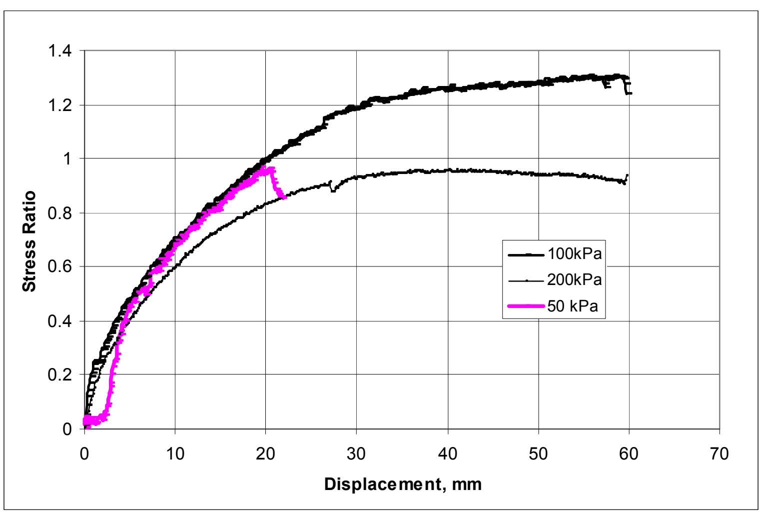


Figure 4. 2 - Direct shear test on 0-10 mm as received MBT using 300 mm shear box

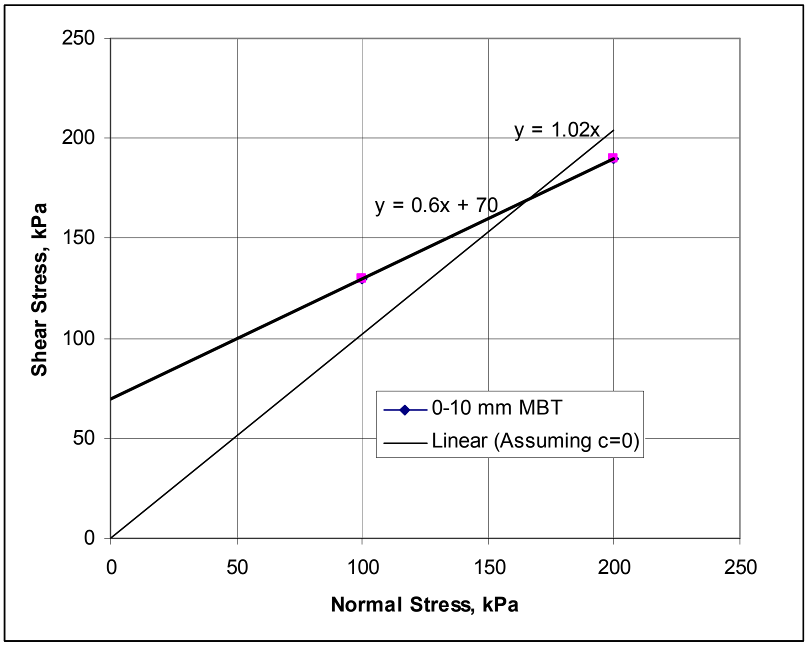


Figure 4. 3 - Modified strength envelop for the 0-10 mm MBT at 50 mm displacement

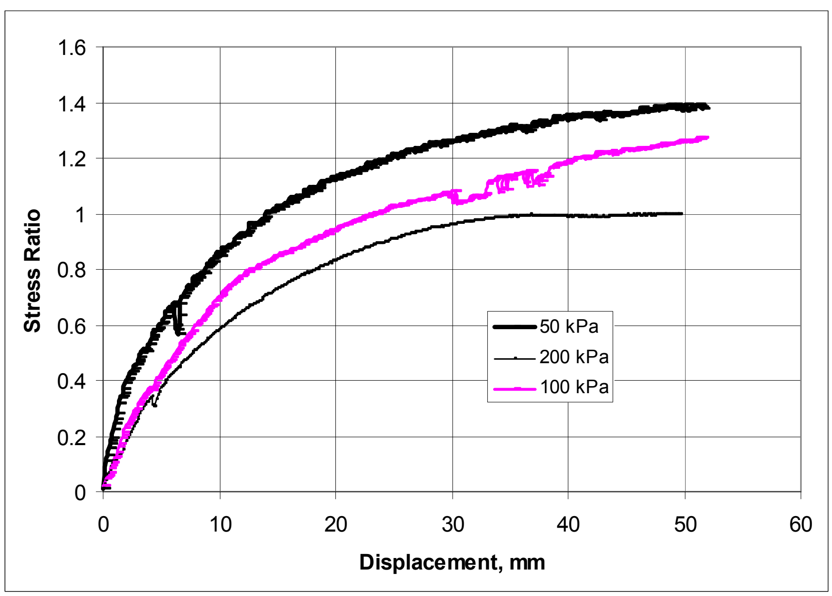


Figure 4. 4 - Direct shear tests on as received 0-20 mm MBT using 300 mm shear box

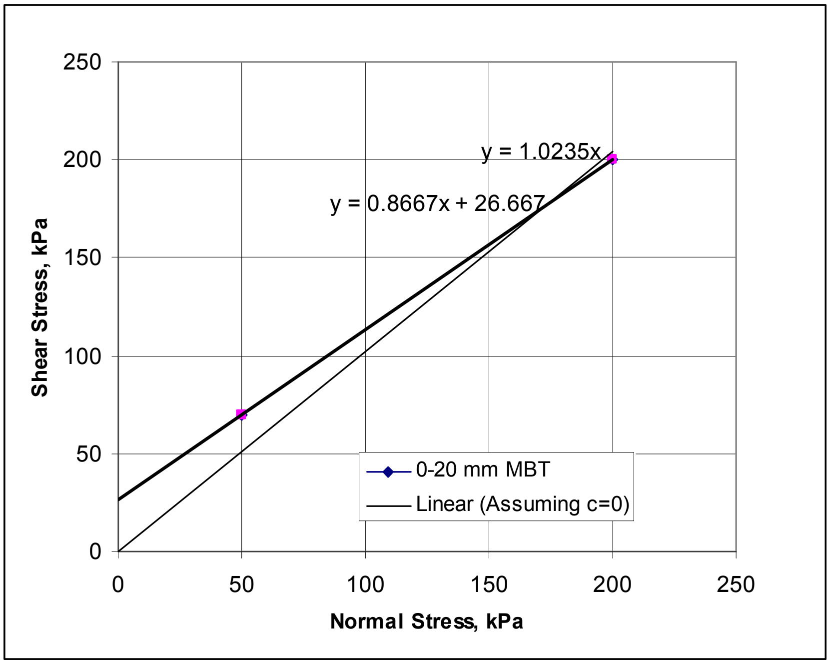


Figure 4. 5 - Modified strength envelop for the 0-20 mm MBT at 50 mm displacement

The results show identical behaviour to Scheelhaase *et al*. (2001), which can be summarised as,

- Smooth stress-strain curves throughout the displacement
- Higher stress ratios at lower normal stresses (compared with the higher normal stresses)
- Slightly increasing stress ratios at larger displacements for lower normal stresses (50 kPa and 100 kPa)
- No clear peak was found in any of the tests. In this case constant or slightly decreased stress ratios were observed under large displacements with higher normal stresses - 200 kPa, in contrast to Scheelhaase *et al*.,(2001).
- Continued displacement under a constant stress may indicates a failure. The lack of peak is less significant in loose samples.

Table 4. 1 - Stress ratios and test conditions of the MBT residues

Material	Normal Stress	Bulk Unit Weight (Mg/m^3)	Stress Ratio (at 50 mm displacement)	φ assuming c=0	c and φ
0-10 mm MBT	100 kPa	1.03	1.3	45.6°	70 kPa
	200 kPa	1.15	0.95		31°
0-20 mm MBT	50 kPa	1.3	1.4	45.7°	27 kPa
	200 kPa	2.06	1.0		41°

The shear strength of the soil is conventionally described by Mohr-Coulomb failure envelope as stated below,

$\tau = c' + \sigma \tan \varphi'$ ……………………. eqn. 4.1

Powrie *et al*. (1999) argued the cohesion at zero effective stress is valid for geotechnical material with particle bonding and not applicable to unbonded soils unless demonstrated (i.e. unless cohesion is proven at lower normal stresses). In this case the Mohr-Coulomb envelopes for the test results show huge variation in the cohesion values from 27 to 70 kPa (by extrapolating) for the two residues as Kuehle-Weidemeier (2004) observed. Kuehle-Weidemeier (2004) studied the shear strength characteristics of the German MBT and found cohesion varied in a wide range from 10 – 62 kPa and concluded that the investigation of cohesion in waste is difficult and with limited in reliability.

In this study,

- 0-10 mm MBT under 100 & 200 kPa (by extrapolating) shows a high cohesion value of 70 kPa
- 0-20 mm MBT under 50 & 200 kPa (by extrapolating) shows a lower cohesion value of 27 kPa
- When the test was conducted in lower normal stresses (0-20 mm MBT) cohesion has been reduced substantially compare to 0-10 mm MBT (i.e from 70 to 27 kPa) as shown in Table 4.1
- As Powrie *et al*. (1999) suggested it may be that the angle of shearing resistance is a more appropriate measure of MBT strength than the Mohr-Coulomb model in eqn. 4.1. Powrie's concept of the shear strength of MSW is discussed more detail in Chapter 2.

The angle of shearing resistance (φ', assuming the cohesion is zero in eqn. 4.1, after Powrie *et al*., 1999) for both residues show almost the same values (approximately 46°). 0-20 mm MBT contains both greater amounts and larger sizes of reinforcing (detailed in Chapter 3) than the 0-10 mm MBT and would be expected to show greater strength. However both materials show similar stress ratios in tests with a 200 kPa normal stress (Fig. 4.6). In this case it can be seen that the greater reinforcing element (refer Chapter 2 for details) content and size in the 0-20 mm waste does not result in an enhanced strength. The reasons for this behaviour may be; (a) the particle size may be too small to act as reinforcements or/and (b) the reinforcement content may be higher than the optimum range to enhance the strength. This will be further discussed in Chapter 5, in which the impact of the both the content and size of reinforcing element are considered.

0-20 mm MBT has higher unit weights than the 0-10 mm material. This is due to the greater quantity of glass in the 0-20 mm MBT. The glass content and its impact on the density of the two residues were discussed in Chapter 3.

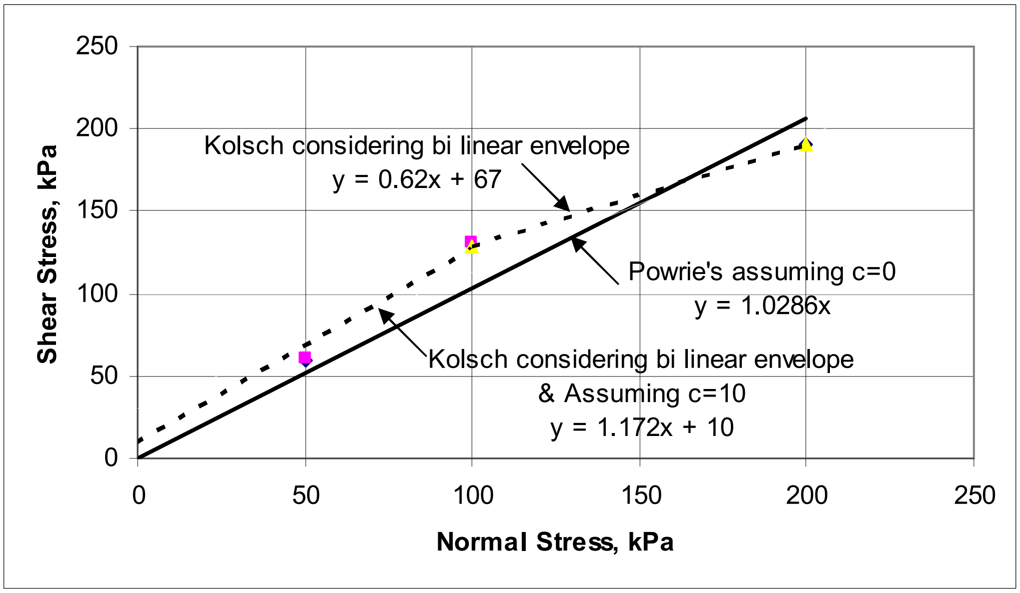


Figure 4. 6 - Modified strength envelops for the 0-10 mm MBT at 50 mm displacement using Powrie et al. (1999) and Kölsch (1995) concepts

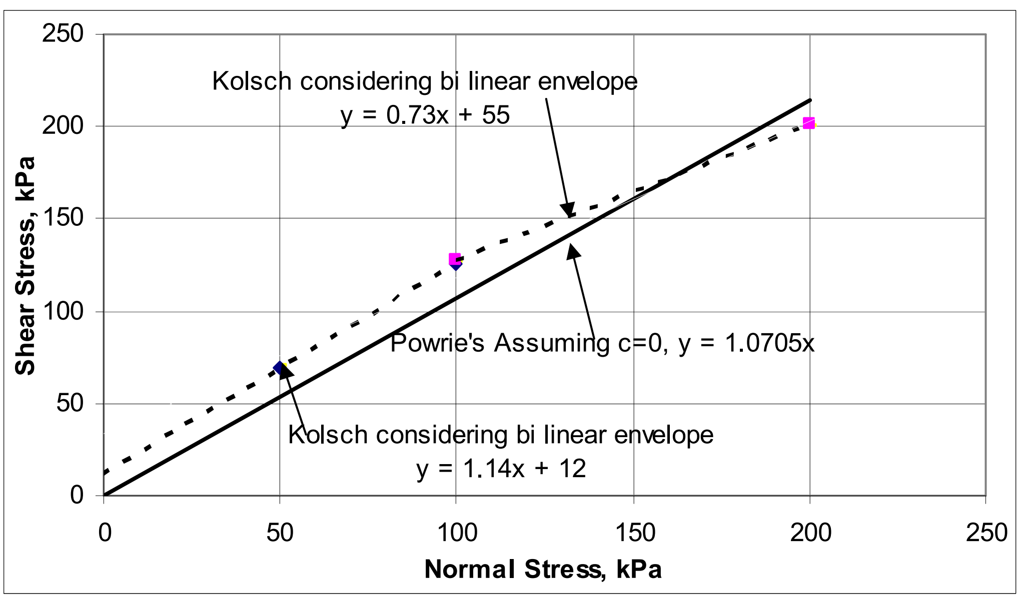


Figure 4. 7 - Modified strength envelop for the 0-20 mm MBT at 50 mm displacement using Powrie et al. (1999) and Kölsch (1995) concepts

Table 4. 2 – Shear strength parameters for the 0-20 mm and 0-10 mm MBT at 50 mm displacement using Powrie et al. (1999) and Kölsch (1995) concepts

MBT Fraction	Normal Stress, kPa	Following Powrie et al.	Following Kölsch	
		Friction angle assuming c=0	0 – 100 kPa c and friction angle	100 – 200 kPa, c and friction angle
0-10 mm	50	45.8°	10 kPa[1] 49.5°	67 kPa 31.8°
	100			
	200			
10-20 mm	50	47°	12 kPa 48.7°	55 kPa 36.1°
	100			
	200			

[1]Due to unavailability of the data it was assumed c=10 kPa

Figure 4.6 and 4.7 were plotted using the direct shear results at 50 mm displacement to obtain the strength parameters (cohesion and friction angle) based on Kölsch's work and Powrie's c=0 assumption.

Due to the test failure, the shear strength at 50 mm displacement for the 0-10 mm material under 50 kPa was obtained by extrapolation from the existing results. When the Kölsch concept (bi linear envelope) was applied to the 0-100 kPa range, a cohesion value of less than 0 kPa was obtained. Hence for the Kölsch 0-100 kPa range parameter determination purposes, it was assumed that c=10 kPa.

Table 4.2 shows compatible results for the 0-10 mm MBT and 0-20 mm MBT using Powrie's assumption friction angle values are 45.8° and 47° respectively. Kölsch's bi-linear concept shows highly increased cohesion values (55 kPa and 67 kPa) which seem in high for 100 – 200 kPa normal stress range. The highest normal stress used in this testing was 200 kPa which is adequate to represent the UK landfill, which are not highly raised landfills compared to other European landfill sites (e.g. 60-70 m high). Powrie's concept seems adequate and well represent the low rise landfills in the UK. Kölsch's concept probably will be useful for the highly raised landfills commonly seen in other European countries (the normal stress range used in this research does not cover the highly raised landfills). However it should be noted that φ is not a constant according to the Powrie's concept.

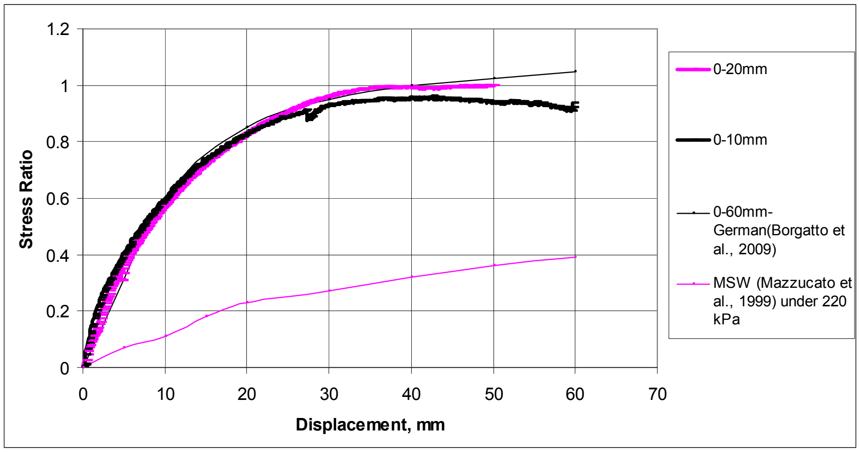


Figure 4. 8 - 0-10 mm, 0-20 mm UK and 0-60 mm German MBT under 200 kPa and MSW under 220 kPa

The European MBT (on German residues) , 0-60 mm shows similar strength characteristics (Fig. 4.6) and behaviour (except for the still increasing stress ratio at 60 mm displacement) to the UK MBT residues, which consist of smaller particles. The reason for this similar behaviour is probably due to the post optimal (higher) content of reinforcing elements. This will further discuss in Chapter 5.

0-10 mm MBT probably has been peaked and 0-20 mm MBT very much sheared compare to the 0-60 mm MBT and MSW.

All of the MBT results in Fig. 4.8 were obtained under a normal stress of 200 kPa. However the direct shear test on the MSW was conducted at 220 kPa. However, because these normal stresses are within 10%, it is reasonable to compare the MSW results with those from the MBT tests. As

MSW contains more and larger reinforcing elements a higher strength would be expected. However the results show that MSW has a substantially lower strength than the MBT residues.

Conclusions

- Due to particle size reduction and the reduction of the recyclable content (i.e. reinforcements such as plastics, paper) it was thought that MBT would be a weak material. However shear tests have shown that MBT is the stronger material

- MBT residues with particle sizes of 0-10 mm, 0-20 mm, 0-60 mm do not show significant strength differences. Particle size variation seems to have limited impact on the strength of the MBT.

- 0-20 mm MBT has a higher unit weight than the 0-10 mm residue (for the same compactive effort), but the strength characteristics are similar. As the unit weight of the residues very much depend on the high density particle content and due to the heterogeneous nature of the waste, however comparing the unit weight of the two different waste materials may not be informative.

- The cohesion values (obtained from extrapolating to c') from the shear test prove to be very variable as has been reported by Kuehle-Weidemeier (2004) and this has raised concerns about the reliability of the cohesion value. The interpretation of the c value seems unsound for the waste. Powrie *et al*. (1999) suggested obtaining the angle of shearing resistance of waste (while assuming zero cohesion and using Mohr-Coulomb failure) and this seems to be more appropriate.

4.2 Strength of the MBT with changing moisture content and unit weight

The strength of the MBT was tested bearing in mind some of the conditions commonly found in a landfill site. In these tests, the following two conditions were investigated.

- Changing moisture content under the same normal stress
- Changing unit weight under the same normal stress

4.2.1 Changing moisture content under the same normal stress

In this test programme, the stress ratios with different moisture contents of the 0-10 mm MBT residue were investigated using 100 mm direct shear.

Samples of three different moist MBT were used in this study;

- 0% - by oven drying the sample at 65°C
- 26% - the as received moisture content of the sample (without moisture content alterations)
- 65% - the sample was wetted to approximately the field capacity moisture content

Beaven & Powrie (1995) explained field capacity as ‘when the total absorptive capacity has been fully utilised with free draining conditions’. In Beaven and Powrie, field capacity was determined by flooding the specimen from the bottom and then allowing it to drain. However field capacity was recognised as being a qualitative term.

In this experiment the field capacity sample was prepared using a funnel, spacious enough to accommodate sufficient material for a direct shear test. The funnel was lined with a filter paper and placed on a bottle to allow the water to drain from the sample. The MBT sample was placed inside the funnel and sprayed with water until excess water was observed and water began to drain. In order to allow the sample to reach field capacity, the sample needs to be prevented from drying locally, the contact between the funnel and the bottle was greased and funnel opening was covered by a plastic film to make the system air tight (Fig. 4.9). The sample was allowed to drain until draining stopped, when it was assumed the sample had achieved field capacity. The moisture content of the sample at this stage was measured as 65%.

Possible errors of the system can be identified as,

- There may present an easy pathway for water as the specimen was not under stress, which could lead to dry areas within the sample, so that the total absorptive capacity of the MBT was not fully met. However the sample was thoroughly mixed before conducting the direct shear test. The aim of the testing programme was to understand the strength as a function of moisture content and this aim was unaffected.

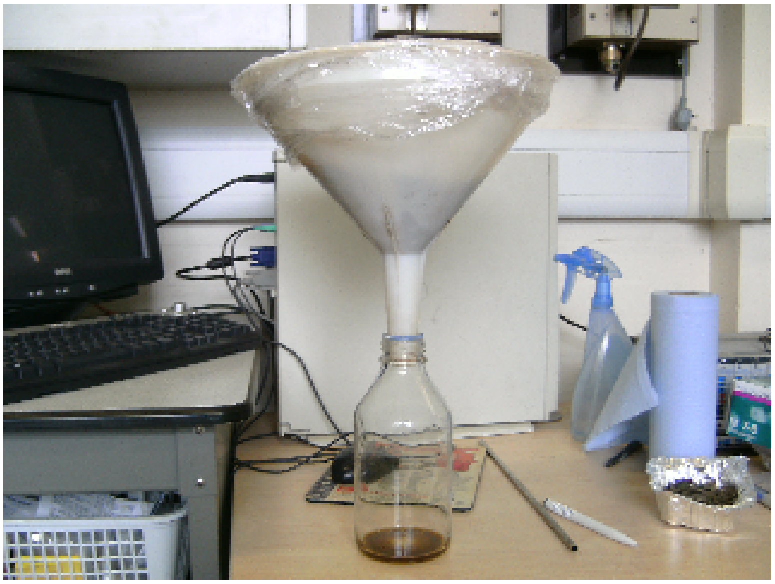


Figure 4. 9 - Apparatus used to obtain a field capacity sample

Attempts were made to perform a direct shear test under saturated conditions. However, difficulties in sample preparation for direct shear and moisture content determination, made this impossible.

Bauer *et al.* (2007) investigated the impact of the moisture content on the shear strength. The moisture content was varied from 28% to 44%, probably targeting the emplacement moisture contents. Fig. 4.10 shows that specimens with moisture contents of 28%, 34% and 38% have similar strength characteristics. However sample with a moisture content of 44% shows a lower strength than the other samples.

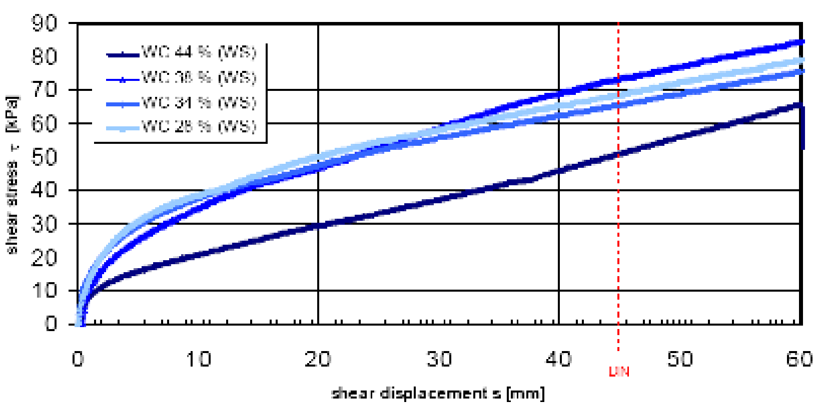


Figure 4. 10 = Shear stress changes with the moisture content under 50 kPa (Bauer et al. 2007)

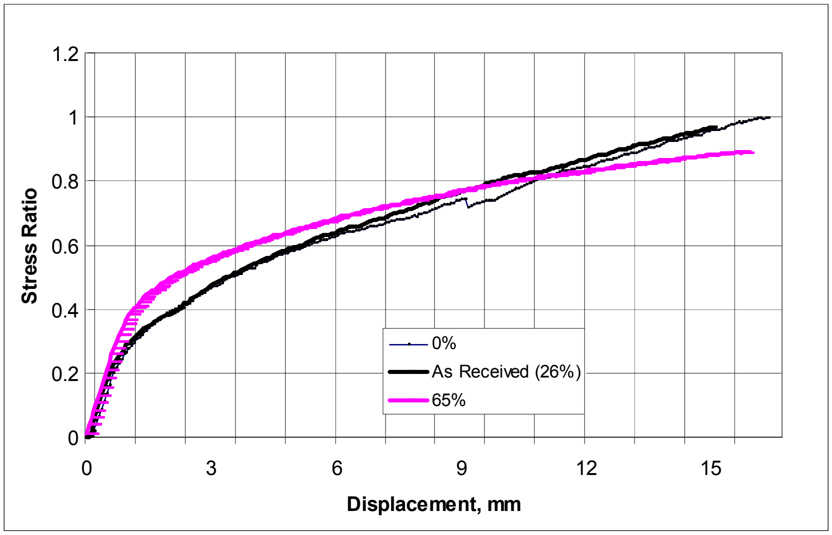


Figure 4. 11 - Shear strength with changing moisture content 0-10 mm MBT using 100 mm shear box under 200 kPa, moisture content in wet basis

Under this testing programme moisture content was varied over a wider range than Bauer *et al.*, (2007), from 0% to 65%. It was assumed (a) the waste moisture content was changed uniformly in all over the material when varying the moisture content and (b)drying the sample at 65°C did not have an impact on the strength of the reinforcements due to heating.

The results show (Fig. 4.11),

- The dry and as-received MBT samples both show almost identical behaviour despite the difference in moisture content
- The sample at high moisture content (65%) shows a high stiffness initially (in contrast to Bauer *et al.* 2007) and lower ultimate shear strength characteristics compared to the other two drier samples (but not significant).

It is clear that a higher moisture content has an impact on the MBT strength. Excess moisture may have reduced the bond between waste particles such as plastics and the matrix. Also, reinforcement stiffness (in particles such as paper and wool) probably have reduced due to moisture absorption.

Conclusions

- Reduction the moisture content from the as-received has no significant impact on the strength of MBT. Higher moisture contents leads to a higher initial stiffness and slightly lower strength with increased displacement

4.2.2 Changing unit weight under the same normal stress

The sample status (loose or dense) is known to have an impact on the strength of the soil (e.g. Barnes, 2000). Due to the high compressibility of the waste, the unit weight of the waste is likely to increase much more under increasing stress than for soils. As with soils: layer thickness, compaction energy and moisture content all have an impact on the unit weight of the MBT (see Chapter 3). Unlike soils, the wider particle size range to soils, composition, and age/decomposition affect the unit weight of the waste.

The unit weight of waste is most strongly influenced by emplacement practises and the depth of the burial. The landfill waste density and strength is important in the point of view of the landfill engineering, which are vital factors in infrastructure designs and stability assessments. Highlighting the importance of the unit weight, Dixon & Jones (2005) considered the unit weight of the waste as a governing factor in all the landfill infrastructure failure modes (in all 10 failure modes identified).

The aim of this testing programme is to identify the impact of the unit weight on the shear strength of MBT waste at the same normal stress.

Methodology

The methodology used in this test is same as the methodology described in Chapter 3 with following modification to the sample preparation method.

- The MBT sample was allowed to settle under different normal stresses to obtain different unit weights
- The direct shear test was carried out under 50 kPa normal stress regardless of the stress used during the settling stage. As the reinforcing effect is high with lower/moderate normal stresses (Kölsch, 1995) a 50 kPa normal stress was used.

Results

Powrie & Beaven (1999) studied the density variation of MSW with changing average vertical stress. Three equations were derived for MSW that was saturated, at field capacity and dry as shown in equations 4.2 to 4.4 respectively,

Density of saturated waste = $0.6691\ (\sigma)^{0.0899}$……………. Eqn. 4.2

Density of field capacity waste = $0.448\ (\sigma)^{0.1563}$……………. Eqn. 4.3

Density of dry waste = 0.1554 $(\sigma)^{0.248}$……………. Eqn. 4.4

In this research, the waste samples were all tested at the as-received moisture content. The moisture content of the material can be considered as in between dry and field capacity to Powrie and Beaven's as shown in Table 4.3.

Table 4. 3 - Unit weight of the 0-10 mm MBT and MSW

Normal stress (kPa)	**Unit Weight (Mg/m^3)**			
	MBT		**MSW from Powrie & Beaven**	
	Unit weight (as received)	**Dry[1]**	**Dry**	**Field Capacity**
50	0.99	0.79	0.41	0.83
100	1.12	0.89	0.49	0.92
200	1.37	1.09	0.58	1.02

[1] Dry unit weight = Unit weight / (1 + Moisture content)

Fig. 4.12 shows the unit weight of the MBT and MSW with normal stress;

- MBT behaves similarly to MSW with increasing vertical stress
- MBT behaves according to;

  Unit weight(Mg/m^3) = 0.3905 $(\sigma)^{0.1833}$ relationship with good correlation (R^2=0.97) - the equation is derived in accordance with Powrie & Beaven (1999)
- MBT at the as-received moisture content has a higher unit weight at a given normal stress than dry MSW or MSW at field capacity . This is consistent with the Proctor compaction results in Chapter 3. The explanations by Powrie (2004) covers Proctor compaction behaviour with moisture content.

(However it should be keep in mind that MSW and MBT are two different materials)

- In Powrie & Beaven (1999) compression tests were conducted at vertical stresses up to 500 kPa but it seems the equations are valid as high as 800 kPa, where this test was conducted

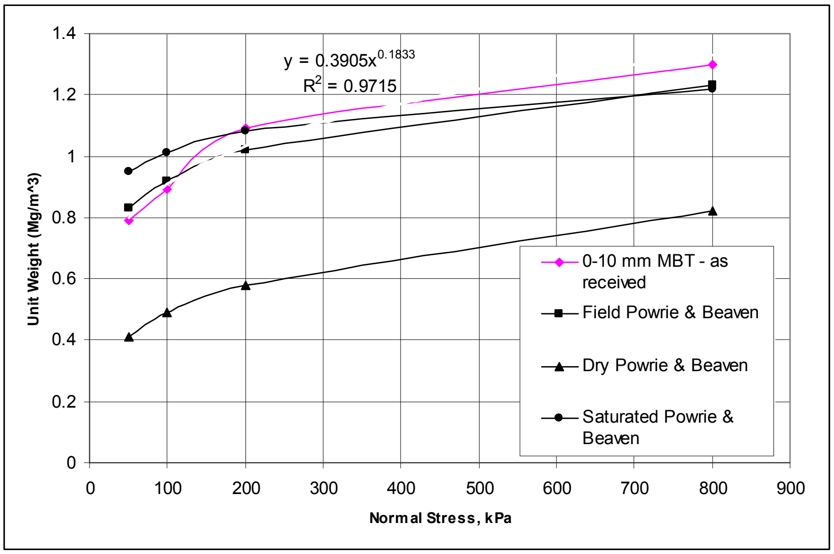


Figure 4. 12 - Behaviour of the unit weight of the MSW and MBT under normal stress

To understand the strength variation, direct shear tests were conducted on MBT samples of different unit weights under the same normal stress. Results for the 0-10 mm MBT under the same normal stress (50 kPa) are shown in Fig. 4.13. The results show that:

- The stiffness of the material changes rapidly with the unit weight of the specimen, the higher the unit weight, the higher the stiffness:
- The loose MBT sample (0.99 Mg/m^3) shows increasing stress ratio with displacement identical to loose soils
- High density samples show a high stiffness over the first 2 mm displacement. Strength then plateaus before rising again after about 6mm displacement

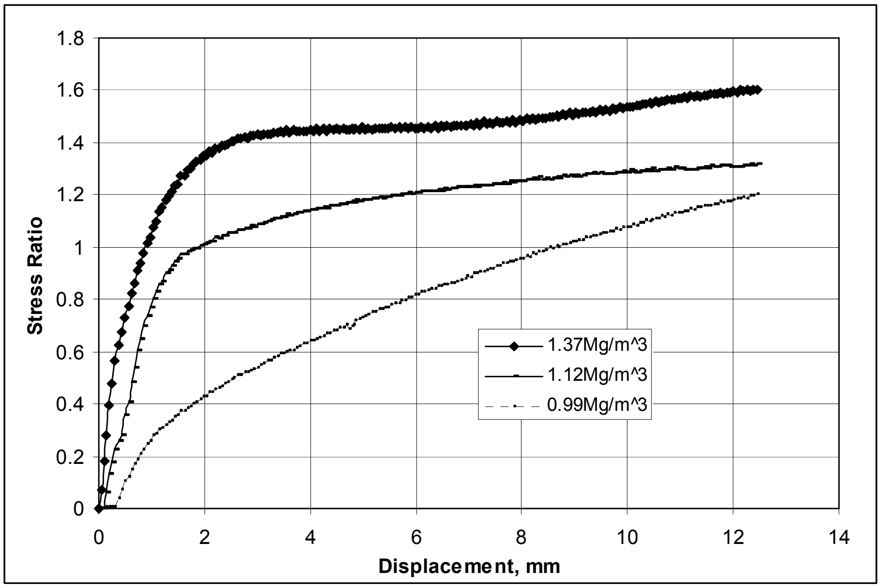


Figure 4. 13 - Shear strength with changing unit weight 0-10 mm MBT using 100 mm shear box under 50 kPa

Table 4. 4 - Direct shear results under 50 kPa on 0-10 mm MBT with varying unit weight

Unit weight (Mg/m^3)	Stress sample consolidated (kPa)	Stress ratio at 12 mm displacement	φ assuming c=0 (°)
0.99	50	1.2	50
1.12	100	1.3	52
1.37	200	1.6	58

Table 4.4 shows a clear trend in increasing strength of the MBT with increasing unit weight which can be observed with soil. Fig, 4.14 shows a linear relationship between unit weight and stress ratio with a high correlation of 0.99 within the tested unit weight range.

Stress Ratio = A* Unit Weight + B

Where in this case A = 1.0724

B = 0.1227

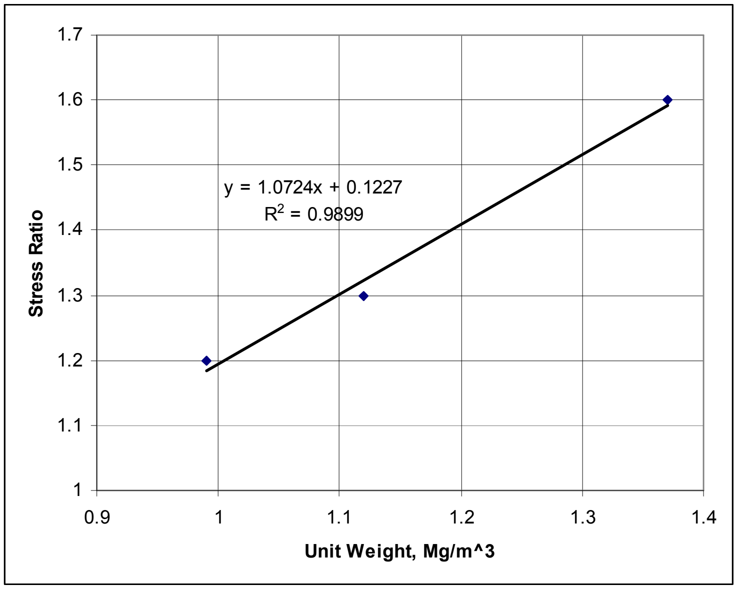


Figure 4. 14 - Unit weight and stress ratio relationship using 0-10 mm MBT using 100 mm shear box under 50 kPa

Conclusions

- Unit weight of the MBT waste behaves similarly to the concept by Powrie & Beaven (1999) on MSW
- The as-received moisture content MBT seems related to;

  Unit weight (Mg/m^3) = 0.3905 $(\sigma)^{0.1833}$
- For higher unit weight, increased strength characteristics of the MBT was observed but without a clear peak
- 0-10 mm MBT under 50 kPa at 12 mm displacement shows a relationship of ;

  Stress Ratio = 1.0724 * Unit Weight + 0.1227

4.3 Direct shear test on MBT using different shear boxes

MBT was tested using three direct shear apparatus (shear boxes) - 60 mm, 100 mm and 300 mm in this testing programme. The 60 mm shear box results have been produced as an Appendix.

Aims

- To understand the MBT particle size restriction in relation to the apparatus size.
- To understand the shear stress and strain relationship of the MBT in direct shear.

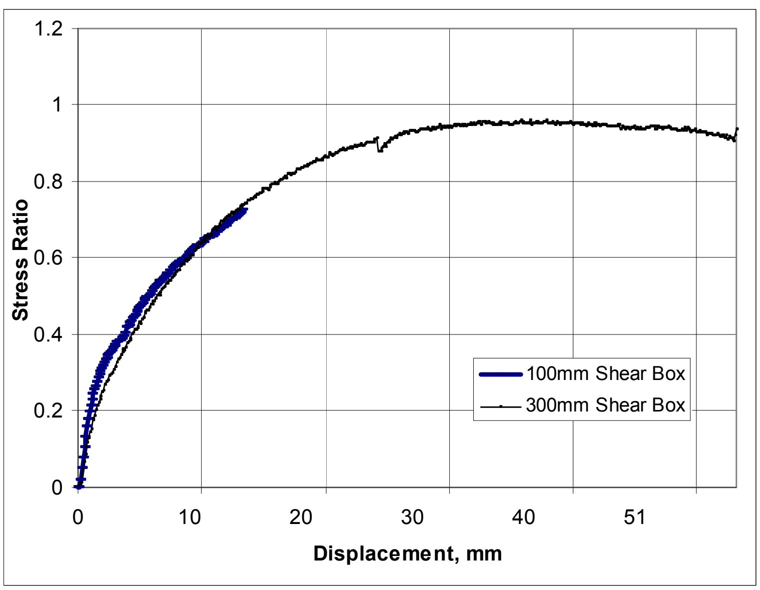


Figure 4. 15 - Stress ratio, displacement relationship 0-10 mm MBT using 100 mm and 300 mm shear boxes under 200 kPa

To understand the impact of the shear box size, the smaller MBT fraction (0-10 mm MBT) was tested under 200 kPa (high normal stress used in this testing programme) using both 100 mm and 300 mm shear boxes. The results are presented in Fig. 4.15 and show that,

- the 100 mm shear box provides similar results to the 300 mm shear box up to the displacement limit of the smaller apparatus. This is somewhat unexpected as the particle size recommendation in BS1377:2 state that the maximum particle size should be 1/10 of the sample height.
- in order to fully understand the shear behaviour (in larger displacements) the larger apparatus is needed

To understand the behaviour of the larger MBT fraction (0-20 mm MBT) under lower normal stresses, 0-20 mm MBT was tested under 50 kPa normal stress.

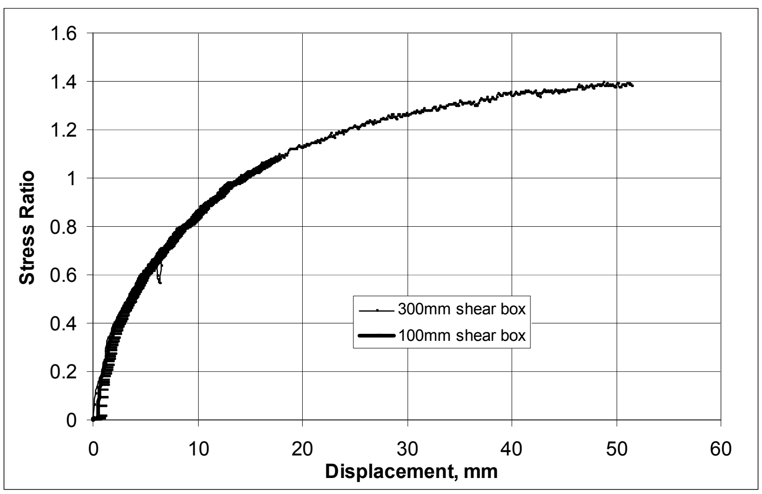


Figure 4. 16 - Stress ratio, displacement relationship 0-20 mm MBT using 100 mm and 300 mm shear boxes under 50 kPa

The results show that:

- Despite the larger particle size (0-20 mm), the 100 mm shear box results are still very similar to those from the 300 mm shear box, up to the displacement limit of the smaller shear box.

- 0-10 mm and 0-20 mm MBT can be tested 100 mm shear box in the normal stress range of 50 - 200 kPa, although tests in the smaller apparatus will not show the full stress strain behavior.

Conclusions

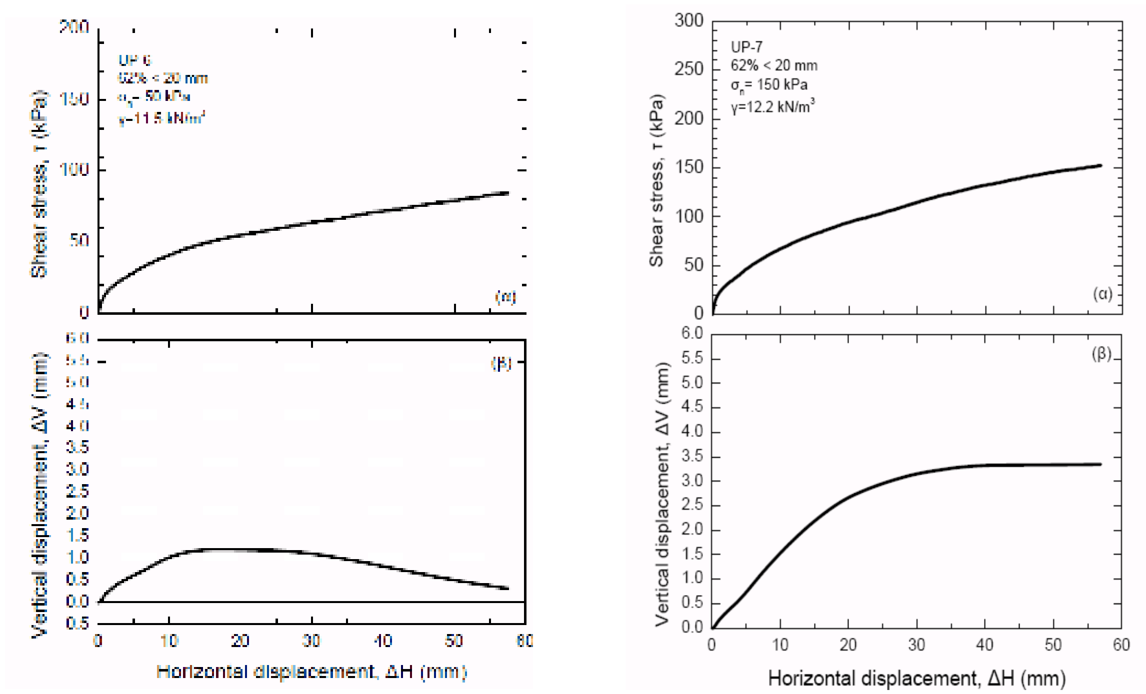
The experiments described above have shown that:

- the 100 mm shear box is able to provide accurate results (results are the same as 300 mm box) on both MBT fractions (0-10 mm and 0-20 mm), despite having a maximum particle size larger than that permitted for soil testing in the same apparatus.
- The mobilised shear stress in an MBT is related to displacement across a potential shear plane rather than strain as is more usually stated.

4.4 Volume change during shear

Volume change of the sample during shear and its relationship to the strength is well understood in soil mechanics (e.g. Powrie, 2004). The volume change during the shearing of waste is less well understood. The aim of this testing programme is to investigate the volume change and shear stress relationship of the MBT waste.

Zekkos (2005) studied the vertical displacement of MSW in direct shear and the results are shown in Fig. 4.17 (a) and (b).



(a) **(b)**

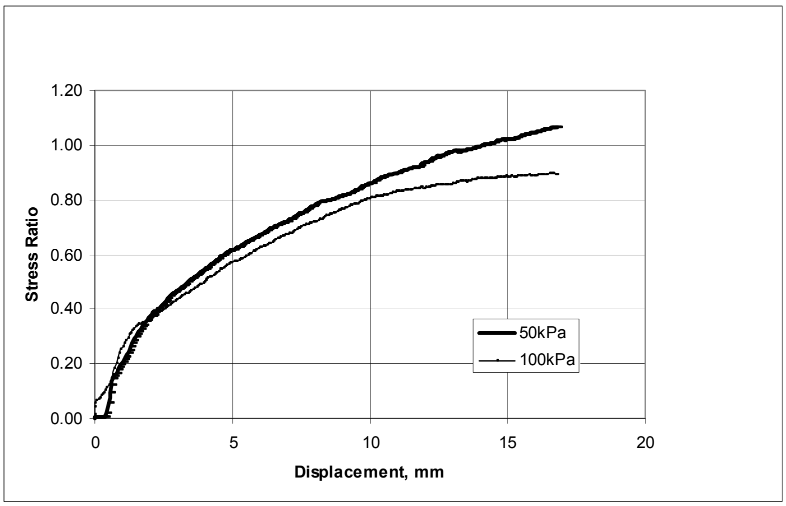
Figure 4. 17 - Direct shear results on MSW using 300 mm shear box (a) under 50 kPa (b) under 150 kPa initial stress (Zekkos, 2005)

In both cases (Fig. 4.17 (a) & (b)) show that:

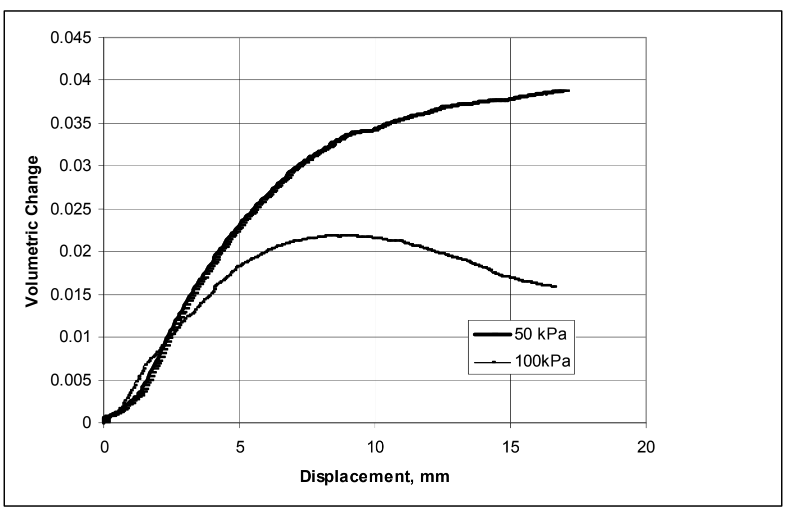
- Both samples show the same behaviour, with shear stress increasing throughout the displacement
- Vertical displacement of the samples show two different behaviours which are not compatible with each other. In the tests with 50 kPa normal stress, there is an initial volume increase (dilatancy) of the sample followed by volume reduction (compression). The test under 150 kPa normal stress shows dilatancy of the sample up to the end of the test at 40 mm displacement.

One vertical probe (LVDT) was used to measure the volume change in these tests and have had the same problem with rotation of the cover plate.

Using one probe, vertical displacement of the MBT samples were tested in 100 mm shear box as shown in Fig. 4.18.



(a)



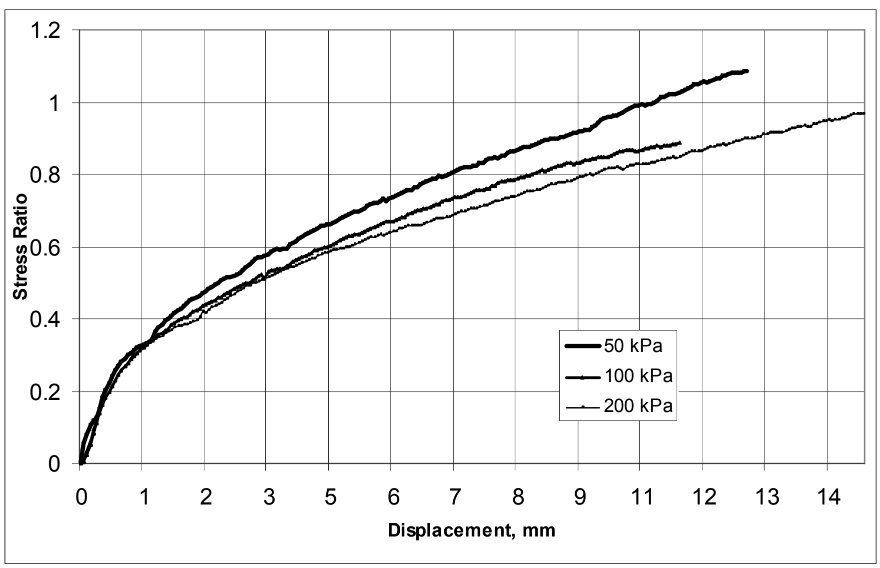
(b)

Figure 4. 18 - Direct shear results on 0-20 mm MBT waste using 100 mm shear box (a) stress ratio (b) volume change

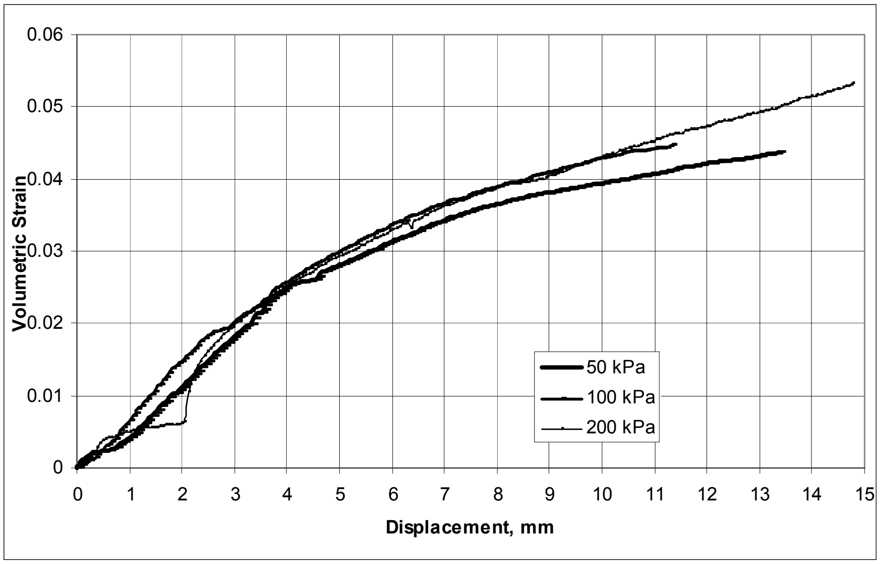
As shown in Fig. 4.18;

- Shear stress shows a continuous increase with the displacement
- As with Zekkos (2005), the volume change behaviour of the samples was inconsistent. In this case the sample under higher normal stress (100 kPa) showed an initial increase in volume (dilatancy) and an apparent reduction (compression) afterwards (contrast to the Fig. 4.17(a))
- No critical state was observed in either case

Volume change of the 0-10 mm MBT was measured using the same strain measurement technique as Zekkos' (using one LVDT centre of the cover plate) and the results are presented in Fig. 4.19.



(a)



(b)

Figure 4. 19 - Direct shear results on 0-10 mm MBT waste using 100 mm shear box (a) stress ratio (b) volume change

Fig. 4.19 shows that:

- shear stress and volume increases with displacement under all three normal stresses
- tests at 100 kPa and 200 kPa show almost the same volume strain, while the test at 50 kPa shows a lower displacement for a given shear stress than the tests at the higher normal stresses
- A critical state has not been observed in any of the tests

All these tests only used one LVDT to measure the vertical displacement. The shear box type used in all these tests (including Zekkos, 2005) is likely to suffer tilting of its cover plate (discussed in Chapter 3) with shear displacement. By assessing the results obtained and reported (specifically the apparent inconsistency of the behaviour according to the results obtained) the accuracy of the volume change measurement using one probe raised doubts.

Methodology

To identify the volume change more accurately, four LVDTs were used to measure the movements of the cover plate at the four corners as shown in Fig. 4.20.

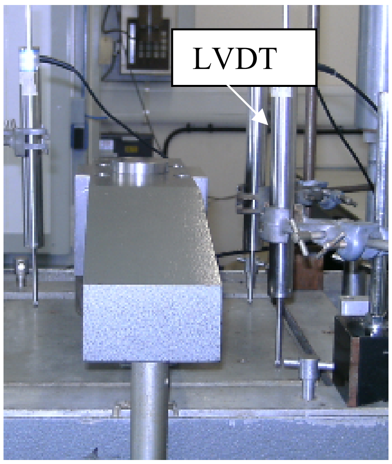
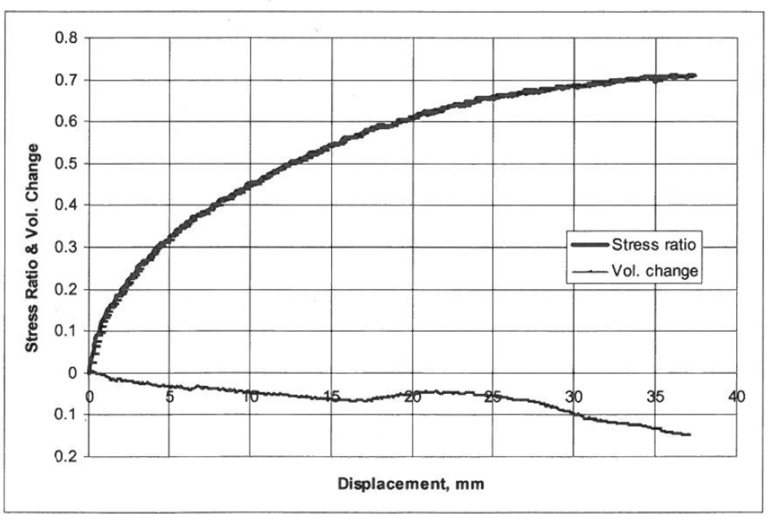
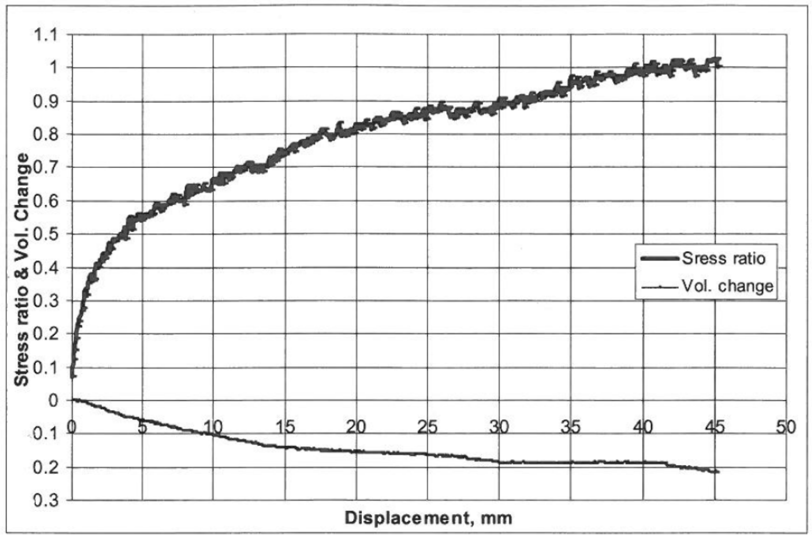


Figure 4. 20 - LVDT arrangement to measure the sample volume change

Results



(a)



(b)

Figure 4. 21 - Direct shear test on 0-10 mm MBT using 300 mm shear box under a normal stress of (a) 200 kPa (b) 50 kPa

Fig. 4.21 shows the volume change of the samples. 0-10 mm MBT samples were created using the same methodology and similar unit weights (for both 100 mm and 300 mm shear boxes), of 11.6 kN/m^3 and 9.8 kN/m^3 respectively for the 200 kPa and 50 kPa tests.

Fig 4.21 shows,

- Both samples are subject to compression throughout the test
- Critical states seems not have been achieved even after a large displacement in both cases (30 mm), but it is not far off.

Fig. 4.19 shows dilatancy of the sample instead of compression proving the low accuracy of the volume change measuring strategy using just a single vertical movement measuring point on the cover plate (as shown in Fig.4.17, 4.18, 4.19). The reason for this occurring may be the cover plate tilt during the shear.

Conclusions

- The use of one LVDT on the centre of the cover plate (general practice) does not give an accurate picture of sample volume change
- The loose MBT samples used in this testing programme show similar volume change behaviour to loose soils with compression continuing to occur throughout
- Despite large displacements, the critical state was not reached in each, the high (200 kPa) or low normal stress (50 kPa) tests on 0-10 mm MBT
- Higher compression occurred at the lower normal stress (50 kPa) than at the higher normal stress (200 kPa). For example at 30 mm displacement under 50 kPa the compression of the sample is twice that of the sample tested at 200 kPa

Chapter 5

Reinforcing Elements and Their Effect on Shear Strength

Studies to determine the strength of MSW have been reported by Kölsch (1995), Zekkos (2005), Kavazanjian (2001), etc. The properties of the MBT residues are not the same as MSW.

In the MBT process much of the material is broken down into finer particles. Non degradable materials such as plastics remain the same through the biological treatment process (but might be affected by heat during the aerobic treatments), but the particle size reduction that occurs during the mechanical process e.g. shredding, affects the non biodegradable fraction as well. The impact on the shear strength of the changes to the material that occur during the MBT process has not been fully investigated.

It is believed that the reinforcing elements in raw MSW enhance the strength of the material (Zekkos *et al*. (2007), Fucale *et al*. (2007)). The MBT reinforcements have different properties from those in MSW and the impact is likely to be different. In geotechnics, more extensive studies have been conducted on fibre reinforced sand to explore the impact of fibres as reinforcements than in waste. As stated in Chapter 2, reinforced sand has a similar structure in principal to MBT waste, consisting of a basic matrix and reinforcing elements. Thus assumed the properties of the fibres and grains that affect the strength of reinforced sand have a qualitatively similar impact on the MBT waste strength in developing the structure of this test programme.

The laboratory experiments described here were focused on identifying the impact of reinforcements on shear strength. The reinforcing effect was investigated by introducing controlled quantities and types of reinforcing material (called inclusions) into a basic matrix. The compound material (basic matrix + inclusions) creates a structure (reinforcements + matrix) as proposed by Jessberger *et al*. (1995), discussed in Chapter 2.

The properties of the reinforcing elements have an impact on the reinforcing effect. The main reinforcing element properties likely to influence strength can be identified as their stiffness, content, area, length, aspect ratio, interface friction (Gary *et al.* (1985), Shewbridge *et al.* (1988) & Tang *et al* (2007)). In addition, the soil like particles (called the basic matrix), reinforcing element orientation, dimension and shape have an impact on the reinforcing elements performance (Zekkos (2005), Kaniraj & Gayathri (2003), Santoni & Tingle (2001)). These factors have been discussed in detail in Chapter 2.

In this study,

- Stiffness, content, length, area, aspect ratio of the reinforcements and the properties of the basic matrix and their impact were investigated
- Orientation, skin frictional properties of the reinforcements, shape, dimension (1D and 3D), relative particle size (basic matrix particle size to the reinforcement particle size) of the reinforcements were not investigated
- The inclusions/reinforcements (as Langer, 2005) used were 2D particles, which have one dimension significantly smaller than the other two dimensions as defined by Kölsch (1995)
- Two basic matrices (0-2.8 mm) were used (a) commercially available green waste compost and (b) MBT residues
- Stiff plastics (obtained from the same type of waste bottles) and flexible plastics (obtained from the same type of carrier bags) were used as inclusions
- Volume change (dilation & compression) during shear is not discussed due to the low accuracy of the measuring arrangement (due to tilting of the cover plate as explained in

Chapter 3) in this chapter, but the volume change of the 0-10 mm MBT sample was discussed in detail in Chapter 4

- Direct shear tests were conducted according to BS 1377-7:1990, with some modifications as discussed in Chapter 3

5.1 Strength characteristics of the basic matrix

The shear strength characteristics of the basic matrix (0-2.8 mm material) were investigated using the direct shear apparatus, to understand its strength characteristics (without any reinforcing effect) and establish benchmark values against which to quantify the effect of the reinforcing elements.

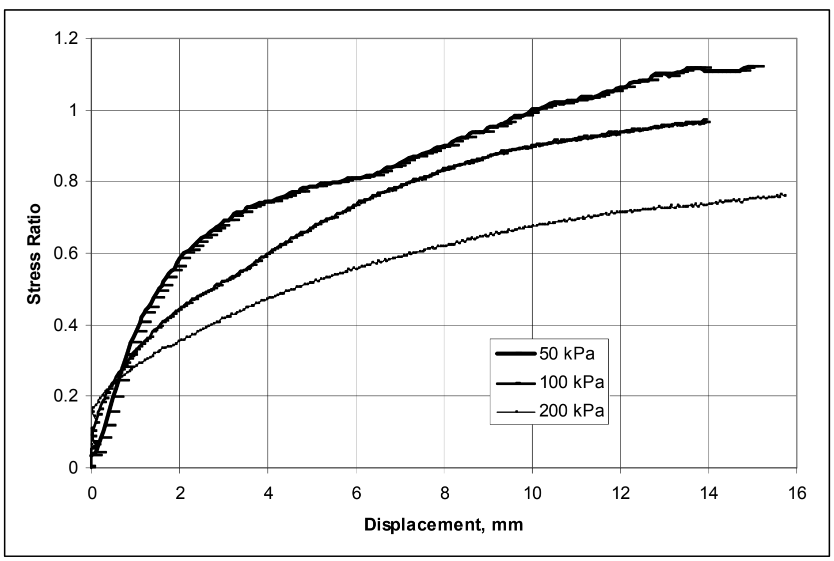


Figure 5. 1 - Stress ratio (τ/σ') against displacement for 0-2.8 mm MBT using 100 mm shear box
50 kPa using 300 mm shear box

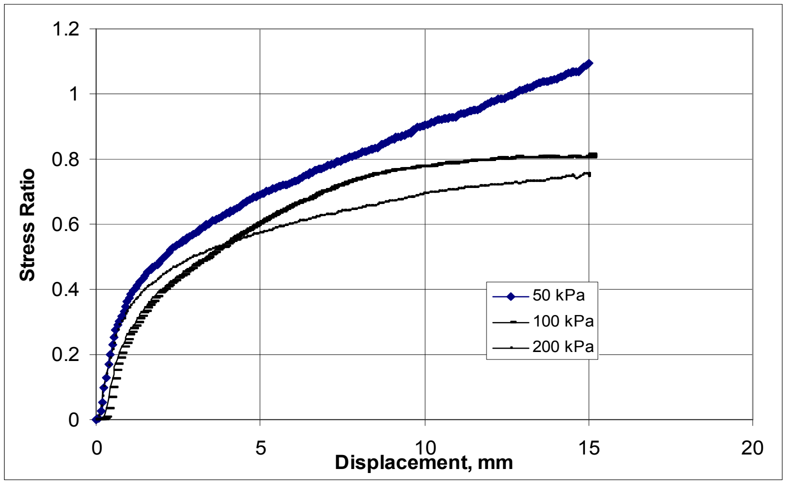


Figure 5. 2 - Stress ratio (τ/σ') against displacement for 0-2.8 mm compost using 100 mm shear box

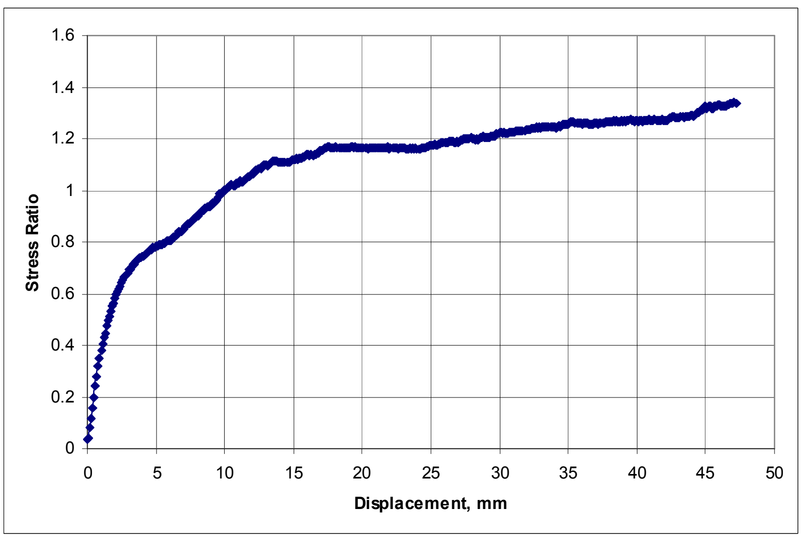


Figure 5. 3 - Stress ratio (τ/σ') against displacement for 0-2.8 mm MBT sheared at a normal stress of 50 kPa using 300 mm shear box

The direct shear tests were conducted under the same conditions for both materials and the results for the 0-2.8 mm MBT & compost are presented in Figs 5.1 & 5.2. All graphs show a rapid initial increase in the mobilised strength and a gradual increase thereafter. Fig. 5.3 was produced using the 300 mm shear box and thus continues to larger displacements than the 100 mm shear box. A slightly increasing stress ratio was observed after a significant displacement, until the test was terminated in the 300 mm shear box. The stress ratio did not reach either a peak or a steady value in any of the tests.

Stress ratios for the MBT in general seem to be much higher than the compost as shown in Table 5.1. The MBT matrix gave higher stress ratios for lower normal stresses (up to 100 kPa) as shown in Table 5.1 and Fig. 5.4. At higher normal stresses (200 kPa), both materials gave the same stress ratios (at a displacement of 14mm).

Table 5. 1 - Comparison of 0-2.8mm MBT and Compost results

	Compost			MBT		
Normal stress, kPa	Stress ratio at 14mm displacement	φ (assuming c=0)	Initial unit weight, Mg/m^3	Stress ratio at 14mm displacement	φ (assuming c=0)	Initial unit weight, Mg/m^3
50	0.9	42°	0.57	1.15*	49°	
100	0.8	39°	0.67	1	45°	0.96
200	0.75	37°	0.82	0.75	37°	1.08

* conducted in 300 mm shear box

The reason for the greater differences in stress ratio between MBT and compost at lower normal stresses and smaller differences at higher normal stresses may be explained by the particle stiffness. The particle stiffness of the MBT is greater than for compost due to presence of stiffer particles such as glass, metal, sand, etc. The green compost comprises decomposed organic matter with low stiffness, which may be the reason for the low strength of the compost matrix at low stresses. Tests at 200 kPa (higher normal stress) on both materials show the same end results, although the bulk stiffnesses of the two materials are different (probably shear resistance is reduced with increasing stress).

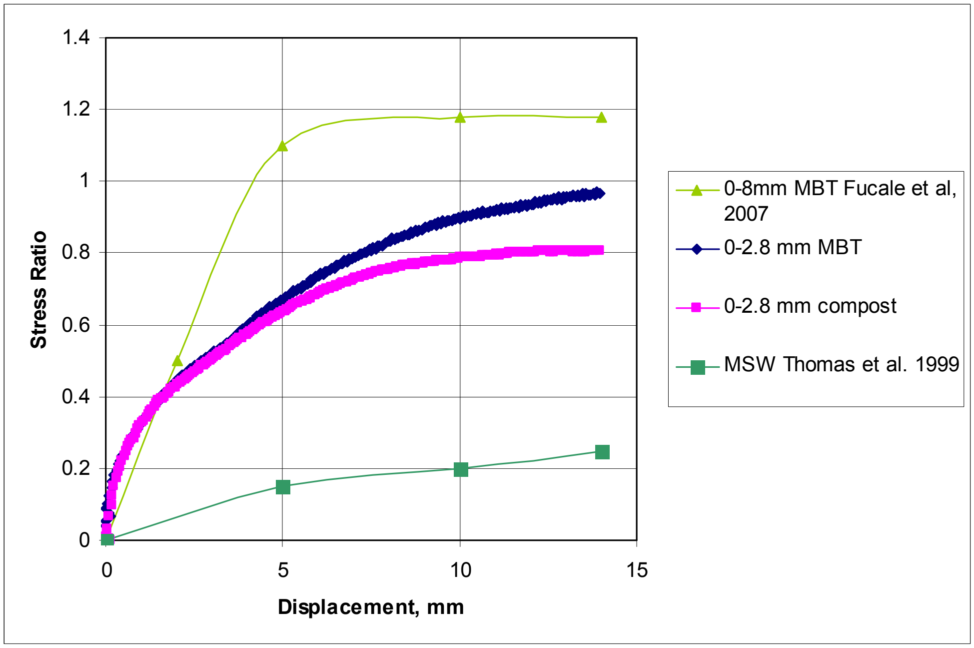


Figure 5. 4 - Stress ratio (τ/σ') against displacement at a normal stress of 100 kPa

The plots for the MBT and the compost basic matrices at 100 kPa shown in Fig. 5.4 confirm that the behaviour of the two materials is initially identical; however the curves begin to diverge at 4mm displacement. Higher stress ratios are achieved by the MBT than by the compost as the displacement exceeds 4 mm.

In general the particle sizes of the basic matrices used by the other researches are larger than the particle size used in this research. In this study, basic matrices (0-2.8 mm MBT and compost) attained stress ratios of approximately 1 and 0.8 respectively at 14 mm displacement using the direct shear apparatus under a normal stress of 100 kPa. In Fucale *et al*., (2007) 0-8 mm MBT attained a stress ratio of 1.17 at the same displacement. Fucale's basic matrix (0-8 mm matrix) shows a high stiffness initially and greater strength than the compost and MBT matrices. The unit weights of the two samples are 9.2 kN/m^3 (Fucale's dry) and 7.5 kN/m^3 (dry MBT) as shown in

Table 5.1. Reasons for this difference in stress ratio could include the substantial amount of high stiffness particles, differences in the materials and the higher dry unit weight in Fucale's sample.

The MSW with a large amount of reinforcing elements shows lower strength characteristics (using Thomas et al., 1999) than the all compost and MBT matrices (Fig. 5.4). The high reinforcement content has not provided a beneficial effect on strength. The reinforcing element content and its impact of strength will be discussed later in this chapter.

Conclusions

- MBT Matrix is a stronger material MSW (compare to the Thomas *et al*. 1999 results on MSW). It mobilises strength rapidly with strain.

5.2 Basic matrix and its impact on the shear strength of the compound material

The soil like material properties in the MBT residues are likely to have an impact on the mobilization of the reinforcing effect in reinforcing elements by interface frictional properties. Michalowski & Cermák, (2003) concluded that sand/fibre interaction was predominately frictional (i.e. due to friction between the matrix and the reinforcement interface some of the tensile strength of the reinforcement elements will be mobilized and this enhances the shear strength of the material).

The basic matrix seems to be one of the major factors that influences the reinforcing effect by means of the interface frictional properties between it and the reinforcing element (Michalowski & Cermák (2003)). The particle size of the basic matrix and its importance has been discussed by Tang *et al*. (2010).

Kaniraj *et al*. (2003) used 6 mm long fibres of the same type to reinforce two different types of fly ash specimens (DA and RA) as shown in Fig. 5.5. The PSDs of the two materials are shown in Fig. 5.6.

The aim of these tests was to identify the impact of the basic matrix on the shear strength.

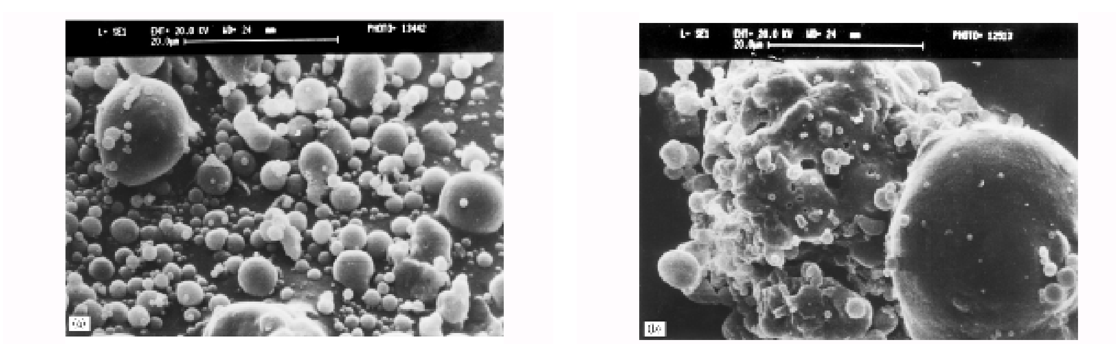


Figure 5. 5 - SEM (Scanning Electron Micrograph) pictures of fly ash (a) DA (b) RA (Kaniraj et al. (2003))

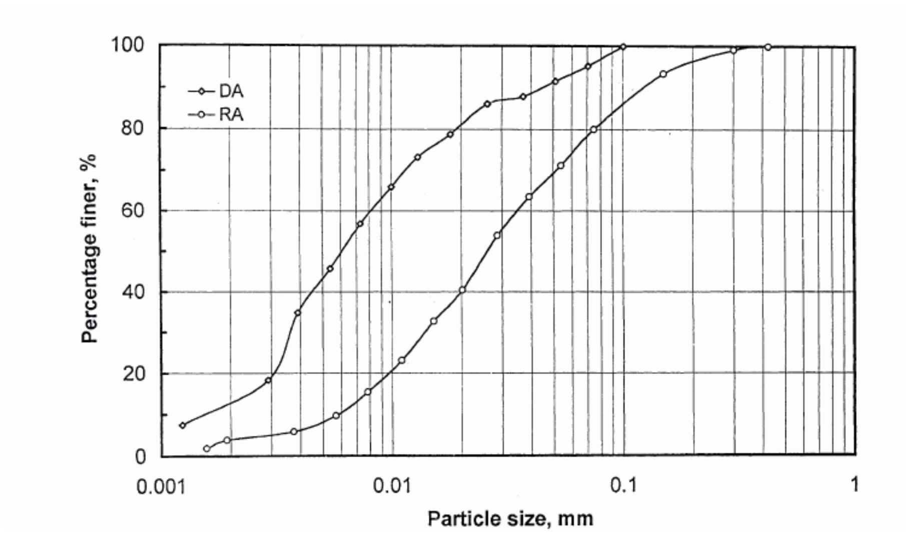


Figure 5. 6 - Particle Size Distribution (PSD) of two fly ashes (Kaniraj et al. (2003))

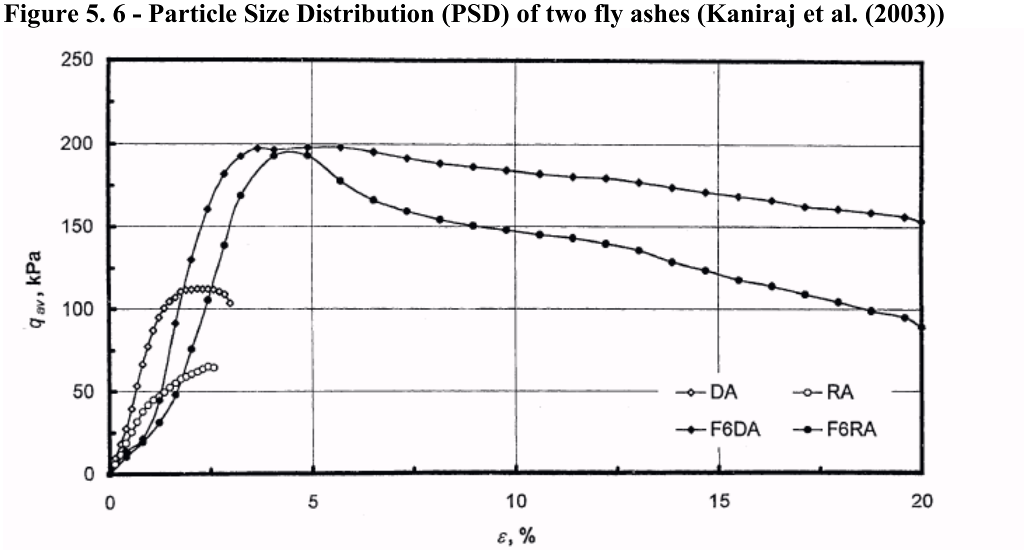


Figure 5. 7 - Stress strain curves of unreinforced and reinforced damp fly ash in unconfined compression test (Kaniraj et al. (2003))

Fig. 5.7 shows that;

- the unreinforced DA has a higher peak strength in unconfined compression test than the unreinforced RA
- the reinforced DA shows higher initial stiffness than the reinforced RA and both samples have similar peak values
- reinforced DA had significantly greater post peak strength than the reinforced RA

- finer ash DA has 0.4% and RA has 1.4% loss in ignition highlighting the level of oxidisation probably leading to different properties
- the basic matrix has a significant influence on the strength characteristics of the reinforced matrix. In this case the finer particles have a significantly greater influence on the reinforcing effect than the coarse matrix probably due to the different basic material properties

Dixon *et al*. (2008) determined the strength of synthetic wastes using sand and clay as the basic matrices. The results cannot be compared due to the differences in composition between in two compound materials, but they do show that the basic matrix has a huge influence on the strength.

In the present study, two basic matrices (0-2.8 mm) were used; (a) MBT residues (b) Compost. Differences between the two materials are that

- The MBT matrix consists of various types of particles compared with mainly biodegraded organic matter in compost
- The compost matrix is more homogeneous
- The MBT matrix includes of stiff particles made of glass, stones, metal, etc.
- The two matrices may have different skin friction characteristics (i.e. interface frictional properties against the reinforcing elements)

This study aimed to identify the impact of changes to the basic matrix (0-2.8 mm) on the reinforcing effect of the reinforcing elements. In this section unreinforced and reinforced MBT and compost matrices were used to assess the impact of the 10 mm x 20 mm hard plastic inclusions (2% by dry mass) in the basic matrices. Fig 5.8 compares the behaviour of the reinforced material with that of the basic, unreinforced material. As shown in Table 5.1, the stress ratios are almost the same in the two materials at 15 mm displacement. The compost has an initial high stiffness and the stiffness of the MBT residue increases with the displacement compare to the compost.

- The compost and the reinforced compost material plots seem very similar (almost overlapped each other) and do not show any significant increase in the shear strength as a result of the inclusions
- However the reinforced MBT matrix shows a slightly greater stress ratio than the unreinforced matrix
- Fig 5.8 shows that the basic material influences the strength of the compound material (according to the results at 200 kPa normal stress), by comparing the compost and the MBT basic matrices.

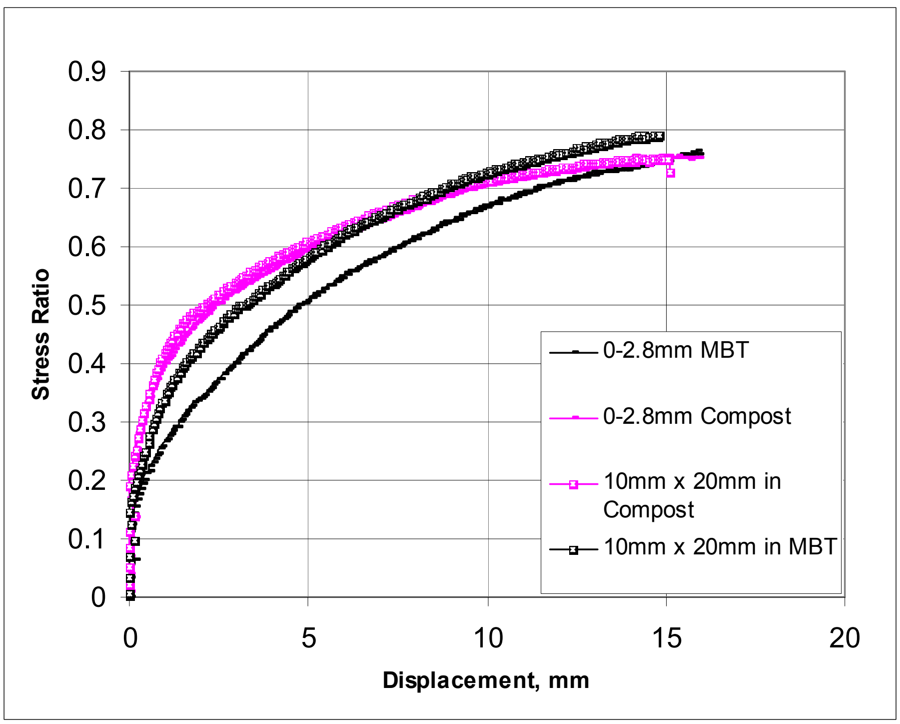


Figure 5. 8 - Stress ratio (τ/σ') against displacement for 0-2.8 mm compost and MBT and 2% 10 mm x 20 mm stiff plastic by weight compound matrices sheared in 100 mm shear box at 200 kPa

Conclusions

- Basic matrix has an influence on the reinforcing effect, although the influence is not significantly difference for the two basic matrices used.

5.3 Stiffness of reinforcing elements (flexible and stiff plastic) and impact on shear strength

There is some evidence that the stiffness of reinforcements has a strong influence on the strength from reinforced sand studies (Gray & Ohashi (1983), Shewbridge *et al.,* (1988)).

The aim of the tests reported in this section was;

- To identify the impact of the reinforcement stiffness on the strength enhancement of the MBT

Shewbridge *et al.* (1988) conducted a study using sand reinforced with different stiffness reinforcing elements namely wooden rods, parachute cord, bungy cord and steel wires (Fig. 5.9). The number of reinforcing elements used in this study was 14 (very low content of reinforcements compare to waste). The important facts that emerged from this research were;

- Regardless of the small content, the reinforcements showed the ability to enhance strength
- In all cases the reinforced compounds had higher strength than the unreinforced material

- The higher the stiffness of the reinforcement, the higher the strength of the compound

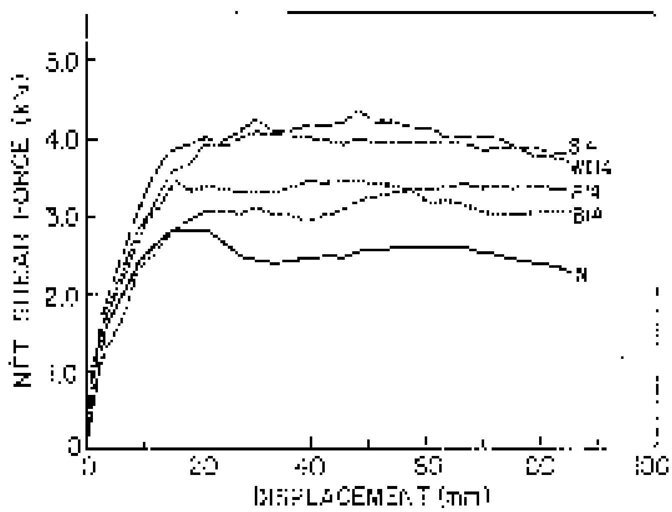


Figure 5. 9 - Direct shear test on reinforced sand N-no reinforcement, S-steel, W-wood, B-bungy cord, P- parachute cord – number of reinforcements 14 (after Shewbridge et al. 1988)

To identify the impact of the reinforcement stiffness on MBT 2% by mass of 10 mm x 10 mm flexible plastics and stiff plastics were added to a compost matrix and the results are shown in Figs 5.10 and 5.11.

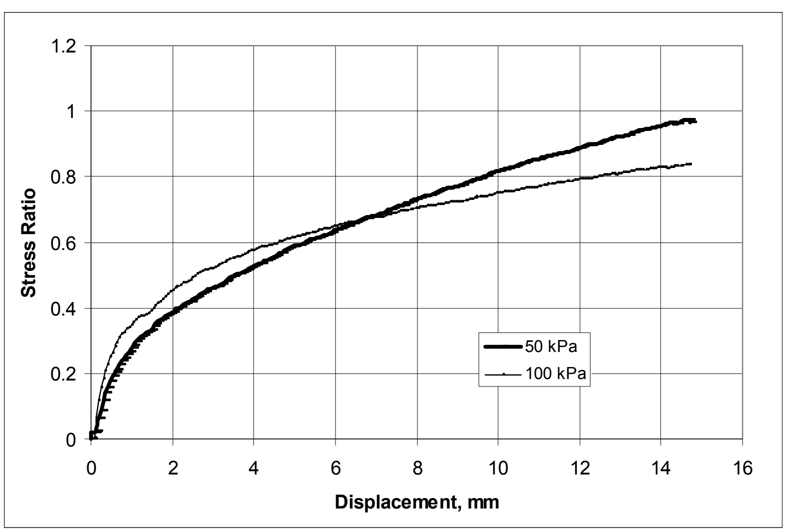


Figure 5. 10 - Results for 0-2.8 mm compost reinforced with 2% by dry mass of 10 mm x 10 mm flexible plastic in a 100 mm shear box

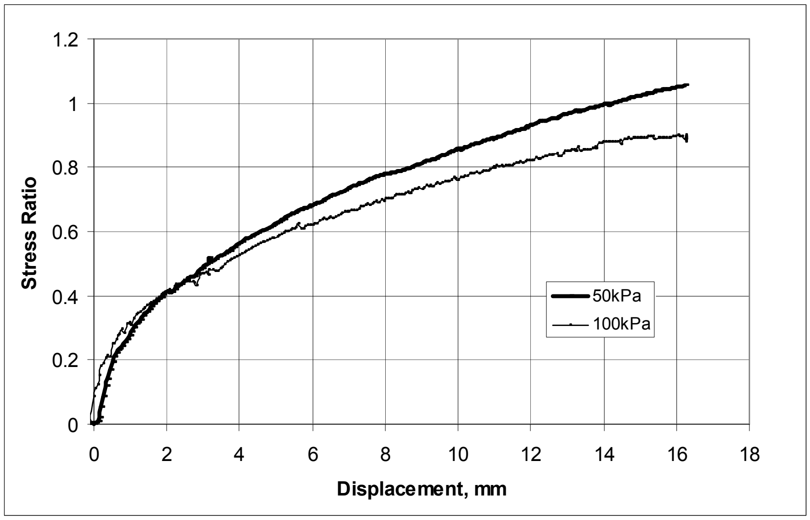


Figure 5. 11 - Results for 0-2.8 mm compost reinforced using 2% by dry mass 10 mm x 10 mm stiff plastic in a 100 mm shear box

Both materials show that the initial stiffness is slightly higher for the higher normal stress and reduces with displacement.

The two compound materials showed very similar results for the both load cases, although the stiff plastic compound material showed slightly higher stress ratios at the end of the test than the flexible plastics (Fig. 5.10 & 5.11).

Fig. 5.12 shows the shear behaviour measured in a 100 mm shear box at a normal stress of 50 kPa for the unreinforced compost and the compost reinforced with flexible and stiff plastics.

- The basic matrix (compost) shows the highest stress ratio
- The material reinforced with flexible plastics shows lowest stress ratio
- The reinforcements reduce the strength in both cases

- Lower stress ratios in the compound materials may be result of the plastics acting as slip planes due to their small size and high content. (If the particles act as slip planes, a lower strength can expected from the light plastic compound material as a result of the greater number of particles).

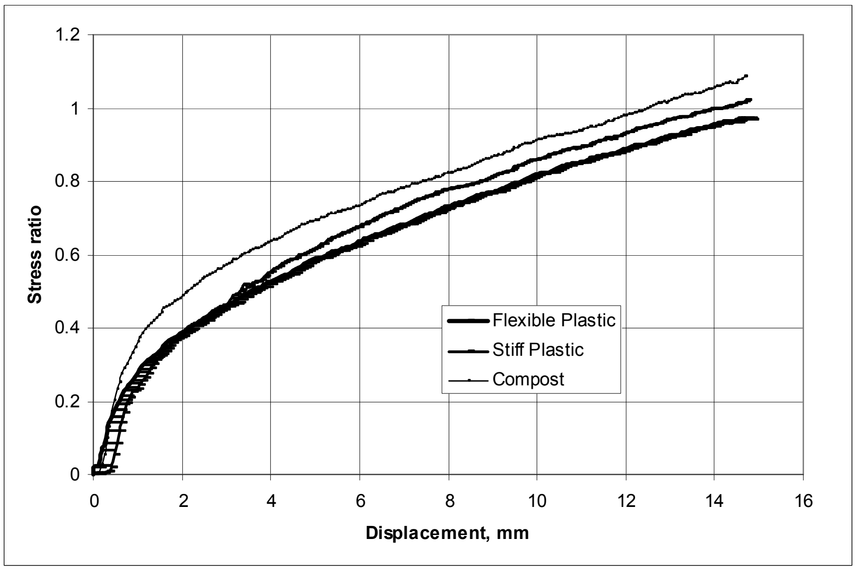


Figure 5. 12 - Results for stiff plastic, flexible plastic matrices and compost without intrusions under 50 kPa normal load

Figure 5. 13 - Picture inclusions in basic matrix

Santoni *et al*. (2001) stated that a high amount of reinforcements do not provide a beneficial impact on the strength and may instead reduce the strength. However, a smaller amount of reinforcing elements may increase the strength (Shewbridge *et al*. 1988). The high content of reinforcement present in MBT is unlikely to provide a beneficial impact regardless of the stiffness (flexible and stiff plastics) and further discussed in Section 5.5.

Conclusion

- Reinforced sand studies show that the reinforcing element stiffness has an impact on the strength when the reinforcement content is low. However both the high content and particle size of the reinforcements in MBT suggest reinforcement stiffness will have no significant impact on the strength (by considering 2D particles)
- Compound materials containing inclusions of stiff and flexible plastics both showed a strength loss compared with the unreinforced matrix
- Results indicate that the number of reinforcement particles(i.e. area) probably plays an important role, rather than the content in mass

5.4 Length of the reinforcing elements and impact on shear strength

Aims

- Identify the impact of the reinforcing length in increasing strength
- Identify the minimum length of the inclusion to act as a reinforcement

The impact of the length of fibres/reinforcements on reinforced sand has been extensively studied, (Consoli *et al.* (2007), Santoni *et al.* (2001)) and it has been suggested that;

- there may be a minimum length to act as a reinforcement Consoli *et al.* (2007) - as discussed in Chapter 2
- reinforcement longer than an optimum length gives lower performance (Santoni *et al.* (2001))

In this testing programme 10 mm x 10 mm, 10 mm x 20 mm, 10 mm x 30 mm and 10 mm x 60 mm particles were tested in basic matrices to identify the impact of the reinforcement length on the shear strength.

Fig 5.12 shows that the 10 mm x 10 mm inclusions do not increase the strength of the compound matrix, but instead reduces the strength slightly. It may be that the inclusions are not big enough to act as reinforcements.

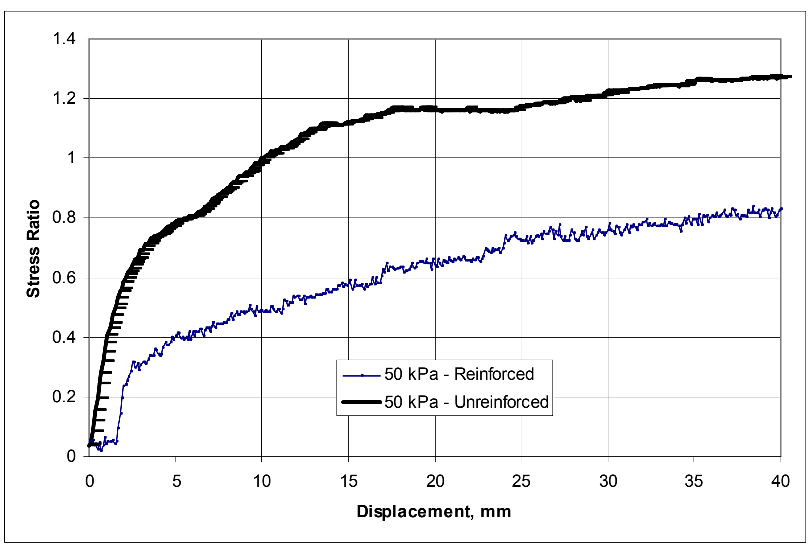


Figure 5. 14 - Stress ratio (τ/σ') against displacement for unreinforced and flexible plastic 10mm x 60mm (280cm2/kg) reinforced 0-2.8mm MBT in 300mm shear box under 50 kPa and 100 kPa

Fig. 5.14 shows that the basic matrix gives higher stress ratios than the reinforced matrix with 10 mm x 60 mm inclusions. The results from the compound matrix show a very jagged curve compared to the results obtained from almost all the other tests. The 10 mm x 60 mm compound material may have provided lower than expected results due to;

(a) the large particle size relative to the equipment (In BS1377:1990 there is a requirement that the maximum particle diameter is 1/10 of the sample height, in this case maximum particle size with the 300 mm shear box should be 15 mm. However due to the differences of the properties in waste compared with soil, it was understood higher waste particle sizes (than BS recommendations) can be tested probably result of the different particle properties.)

b) the much bigger particle size relative to the basic matrix (Santoni *et al.* (2001) suggests the strength reduction may be due to the relative particle sizes (particle size of the basic matrix to reinforcement) as discussed in Chapter 2)

(c) Particles may fold due to this increased length

Table 5. 2 - Summarised results on the impact on strength of the reinforcement length

	10 x 10 mm[1]	**10 x 20 mm**[2]	**10 x 30 mm**[3]	**10 x 60 mm**[3]
Flexible	Reduced (Fig. 5.15)		No change (Fig. 5.21)	Reduced[4] (Fig. 5.17)
Stiff	Reduced (Fig. 5.15)	Improved (Fig. 5.19)		

[1] 2% by mass

[2] 1% by mass

[3] same area as [2]

[4] reduced or out perform values

Conclusions

- 10 mm x 10 mm 2D particles reduce strength (Fig. 5.12)
- smaller 2D particles likely to act as slip planes
- 10 mm x 20 mm stiff plastic has beneficial impact on strength
- 10 mm x 30 mm flexible plastic has no impact on strength as shown in Fig. 5.18
- particles within the optimum length range can provide an beneficial impact on the shear strength
- particles longer than the optimum length likely to provide adverse effects on the strength

5.5 Reinforcing content and its impact on shear strength

Aims

- To identify the optimum reinforcement content for the MBT waste
- To identify the impact of the actual reinforcement content in MBT on strength

Reinforced sand studies (Foose *et al*. (1996), Tang *et al*. (2007)) showed that reinforcing elements can provide a beneficial impact on shear strength by increasing the strength of the unreinforced material.

- When the reinforcement content is lower than optimum, there is little or no impact on strength (Webster & Santoni, 1997)

- When the reinforcement content is in the optimum range, strength increases. The optimum fibre content for reinforced sand with 1D inclusions is about < 1%, a somewhat smaller content of reinforcement than is present in the waste (Webster & Santoni, 1997). The optimum range depends on many factors such as material stiffness, particle shape, interface properties and particle size.
- When the reinforcement content is higher than the optimum range, strain softening behaviour or strength reductions occur (Santoni *et al.* 2001, Webster & Santoni, 1997)

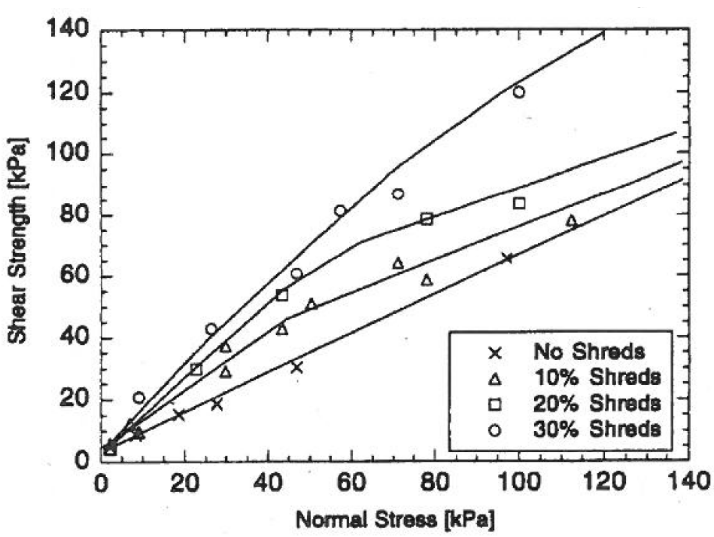
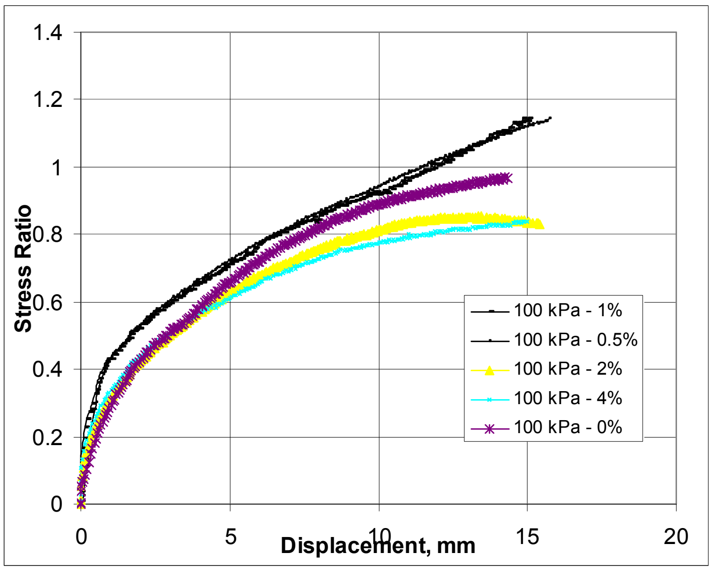


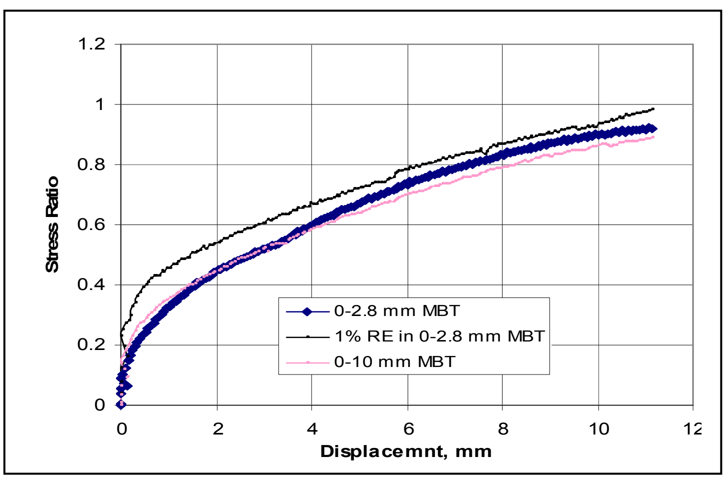
Figure 5. 15 - Strength of the reinforced sand with the increasing content of reinforcing tyre elements (Foose et al. 1996)

Foose *et al.* (1996) conducted a study of tyre reinforced sands with varying content (10%, 20%, 30%), tested using direct shear. Fig. 5.15 shows the strength of the reinforced sand with increasing reinfocement content. The strength increases with increasing fibre content, proving that the reinforcement content has an influence on the strength.

Unsurprisingly almost all the reinforced sand studies have focussed on maximising the strength of the reinforced sand. Because of this, few studies have looked at the effects of quantities of reinforcing above the optimal level. However, waste typically has much greater quantities of reinforcement than the typical optimum level for sands.



(a)



(b)

Figure 5. 16 - (a) Stress ratio (τ/σ') against displacement for 0-2.8 mm MBT and different contents of 10mm x 20mm stiff plastic by mass sheared in 100mm shear box under 100 kPa
(b) Strength characteristics of the 0-28 mm MBT, reinforced (1% hard plastic) 0-2.8 mm MBT and 0-10 mm MBT under 100 kPa

Fig 5.16(a) shows the results obtained using the 10 mm x 20 mm stiff plastics as inclusions in the 0-2.8 mm MBT under 100 kPa. The compound material was tested with an inclusion content of 0.5%, 1%, 2% and 4% by mass.

- The samples with 0.5% and 1% inclusions by mass show higher strength than the unreinforced sample
- At 14 mm displacement (i.e. termination of the test) the 0.5% and 1% specimens show still rapidly increasing stress ratios
- The samples with 2% and 4% inclusions by mass show lower strength characteristics than the unreinforced sample
- Results show a slower rate of increasing stress ratio for higher content (2% and 4%) specimens compared to the lower content (0.5%, 1%) compound materials at the termination of the test

Santoni *et al*. (2001) & Fucale *et al*. (2009) found that once the optimum reinforcement content has been exceeded, the shear strength tends to reduce in reinforced sand and waste respectively. These tests showed that the samples with greater reinforcing contents have lower strengths than the basic matrix. The reason for this behavior was discussed in detail in connection with the interface friction results in Chapter 3.

Fig. 5.16(b) shows very comparable results to the Webster & Santoni, 1997,

- The optimum content (in this case 0.5%, 1% by mass) has provided a beneficial impact on shear strength compared with the strength of the basic matrix

- Higher reinforcement content than the optimum reduce the strength – comparing 0-10 mm MBT with the basic matrix and the reinforced compound matrix

Conclusions

- 0.5% - 1% inclusions by mass under 100 kPa normal stress showed a beneficial impact on the shear strength
- Over 2% of inclusions by mass showed no beneficial impact on shear strength, instead reducing the strength
- From Fig. 5.16 it is clear that the optimum amount of reinforcements to increase the shear strength (in this case) is about 0.5% to 1% (but not higher than 2%)
- Given the high reinforcement content present in MBT waste, it is unlikely to provide a beneficial impact on strength (i.e. Considering the substantially higher than optimum content of the reinforcements in MBT waste as described in the waste analysis (Chapter 3), it is clear the reinforcement content present in MBT is too high to provide additional strength and instead weakens the material as can be seen in Fig. 5.16(b).)

5.6 The impact of reinforcing area on shear strength

Aims

- To identify the impact of the reinforcement area on strength
- To identify meaningful measure of the reinforcement content from the perspective of strength (i.e. percentage by mass or area to a unit mass)

It is clear that the interface friction plays a major role in influencing reinforcing effect. In reinforced sand studies reinforcement content is generally measured by mass. However the interface frictional force for a given reinforcement depends also on the reinforcement surface area as shown on Fig. 5.17.

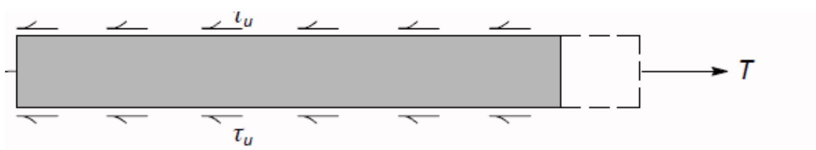


Figure 5. 17 - Pull out test on extensible reinforcement (from Sobhi and Wu, 1996)

In this experiment,

- Areas equivalent to the 1% stiff plastic content (the content which showed an increase in strength characteristics in Fig. 5.16) of the same type (HDPE) reinforcing elements were used
- Instead of stiff plastic, 10 mm x 30 mm flexible plastic of the same area density (i.e. 280 cm^2 per kg of dry mass) were used as the inclusions. Even if the flexible plastic is extensible a strength enhancement would still be expected (In Fig. 5.9 (Shewbridge & Sitar, 1988) showed that the higher the stiffness of the reinforcement, the higher the strength of the reinforced material throughout the displacement. However Jewell & Wroth (1987) showed that extensible reinforcing elements may provide lower peak strength than the inextensible elements, but both provide close post peak strength.)
- An equal area of the flexible plastic did not provide any enhancement of the strength with the same basic matrix (as shown in Fig. 5.18). Instead, the strength was less than that of the basic matrix (with the same area stiff plastic showing a higher strength than the basic matrix throughout the displacement as shown in Fig. 5.16)

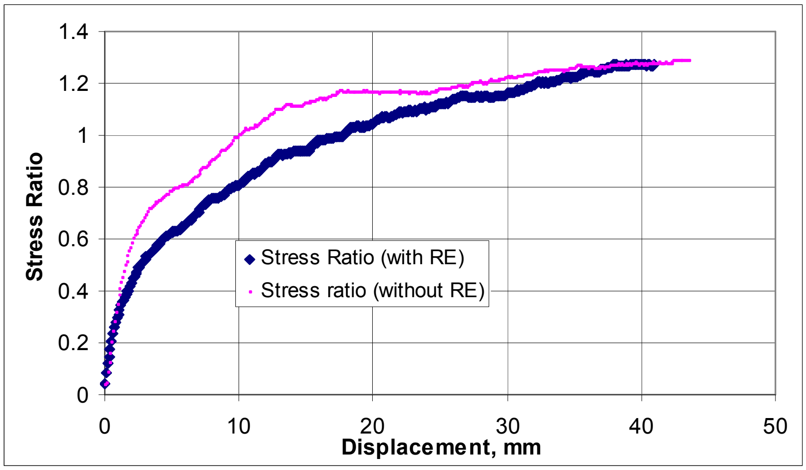


Figure 5. 18 - Stress ratio (τ/σ') against displacement for 0-2.8 mm MBT and light plastic (280 cm2 per/kg dry mass) 10mm x 30mm in 300mm shear box under 50 kPa

- Fig. 5.12 shows the strength characteristics of the stiff and flexible plastic reinforced results at 2% by mass. No increase in strength was observed with either reinforcement type, stiff or flexible.
- When the same area of stiff and flexible plastics were used, the higher stiffness inclusions showed higher strength characteristics (compairing Fig. 5.16(a) & 5.18)
- Fig. 5.20 shows that equal areas of the same stiffness reinforcement (high stiff) provides the same effect on strength regardless of reinforcement size/aspect ratio.

Problems identified

Despite being made of the same material, the interface properties of the two inclusions (stiff and flexible) may be different and this may have influenced the shear strength results.

Conclusions

- Fig. 5.12 shows same two type of (stiff and flexible) inclusions with same content by mass has not significant impact on the strength
- The same areas of the two type inclusion show different outcomes (Fig. 5.18 and 5.16)
- The same area of the same inclusions (stiff plastics different particle sizes) shows same strength characteristics (Fig. 5.20)
- The results show that the area of the reinforcement has an impact on strength more meaningful than the content by mass

5.7 Aspect ratio and its impact on the shear strength

The aspect ratio of the reinforcing elements is one of the factors that could affect the shear strength. This test was conducted using the same reinforcement material and the same area with two different aspect ratios.

However, with the reinforced sand studies, it was found that the interfacial frictional force on the reinforcement is a critical factor in the strength of the reinforced material (e.g. Sirinivasan Murthy *et al.*, 1993). It can be seen that the same friction will be acting, as long as the unit area remains the same (as the basic matrix and the inclusions are in the same propotions in by mass).

In this study, 2% by mass of stiff plastic elements with an aspect ratio of 1:2 (10 mm x 20 mm) and 1:4 (5 mm x 20 mm) were used to identify the impact of the aspect ratio in the MBT matrix. It was assumed the two chosen aspect ratios would represent the majority of particle sizes and aspect ratios of the 2D reinforcements in the MBT tested (considering that the nominal particle sizes are 0-10 mm and 0-20 mm). The results for the stiff plastics 10 mm x 20 mm and 5 mm x 20 mm inclusions can be found in Fig 5.16 and 5.19 respectively.

Note: In Fig 5.19, both plots show some abnormality approximately at the same displacement, due to possible LVDT errors.

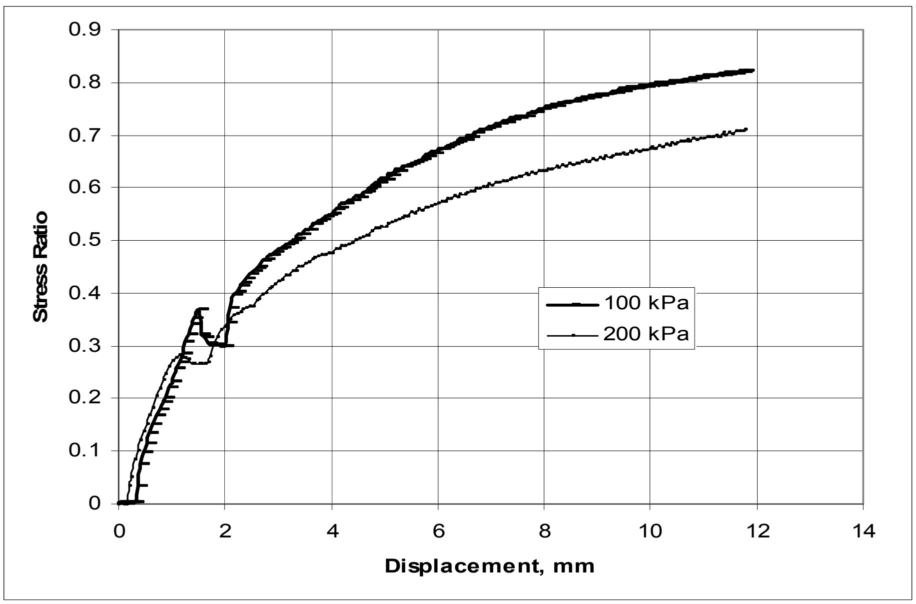


Figure 5. 19 - Stress ratio (τ/σ') against displacement for 0-2.8 mm MBT and hard plastic 5 mm x 20 mm 2% by mass in 100 mm shear box under 100 kPa and 200 kPa

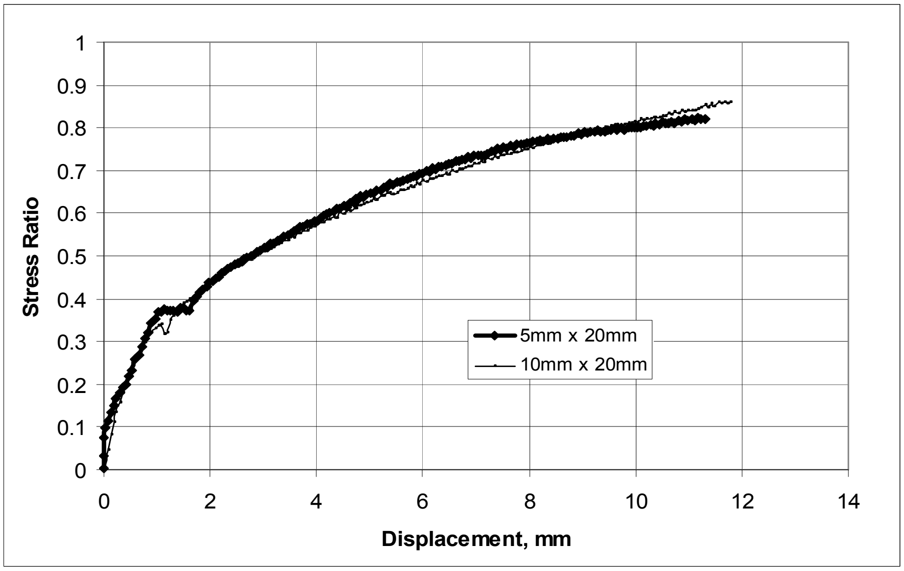


Figure 5. 20 - Stress ratio (τ/σ') against displacement for hard plastic 10 mm x 20 mm and 5 mm x 20 mm 2% in 0-2.8 mm MBT in 100 mm shear box under 100 kPa

As shown in Fig. 5.20,

- The compound material with 1:4 and 1:2 aspect ratios showed the same behaviour
- As discussed earlier the same total frictional forces act on the inclusions in both compound materials as a result of the total reinforcing area being the same (regardless of the relative particle size difference in basic matrix to inclusions). However it should be noted the ratio, basic matrix particle size to reinforcement size seems have an impact on the influence of the reinforcement (refer Fig. 5.6 and 5.7 from Kaniraj *et al.*, 2003).

Conclusions

- Changes to the aspect ratio (within a range likely to be found in UK MBT) of the reinforcements does not seem to have an impact on the shear strength as long as the area remains unchanged

Chapter 6

Conclusion and future work

Conclusions

The main conclusions drawn from this research are that:

- MBT processes lead to a significant decrease in particle size, a change in component contents (e.g. paper content reduced to less than 1 %), significant reduction in reinforcement content (6% & 11% plastics in 0-10 mm & 0-20 mm MBT respectively), increased 0D content (59% and 73% in 0-10 mm and 0-20 mm MBT respectively) and increased homogeneity compared to the parent MSW.

- The angle of friction of both the plastics to plastics (10° - 12°) and plastics to MBT interfaces (20°) are weaker than the MBT (46°) alone. This suggests that the plastics may weaken the overall material depending on the concentration.

- During the MBT process, (reinforcement content and particle size are reduced substantially as a result of screening and shredding) due to these changes in the material it was believed MBT would have weak shear strength characteristics. However MBT proves it is a strong material. Assuming cohesion is zero, 0-10 mm MBT and 0-20 mm MBT friction angles are 45.6° and 45.7° respectively.

- Reduction of the moisture content from the as-received (26%) down to 0% has no significant impact on the strength of MBT. Higher moisture (65%) contents leads to a higher initial stiffness and slightly lower strength with increased displacement.

- By considering the heterogeneous nature of the MBT and MSW and the smaller size of the specimen needed for the test, it seems that testing the particle density of the as received material may be less accurate than the calculated density (using the sum of the particle densities of different particles) using larger samples. As MBT contains a large amount of unidentifiable (often agglomerations of particles) and miscellaneous components (<5mm), these dominates the particle density.

- MBT basic matrix with controlled amounts of reinforcing particles (2D hard plastics) shows that the benefits of the reinforcements on shear strength start to decrease once the proportion by mass exceeds about 1%. The high content of reinforcing particles (typically 6% and 11% plastics by mass in 0-10 mm and 0-20 mm MBT respectively) present in the MBT waste, probably leads to a reduction in the strength of the MBT. When the reinforcement content was increased to 2% or more, the shear strength was lower than the basic matrix proving high reinforcement contents in MBT probably reduce shear strength rather than increase the strength.

- In contrast to reinforced sand studies, compound materials reinforced with 2% by mass of 2D flexible or stiff plastics typical of those found in MBT, show the same strength characteristics regardless of the stiffness difference of the 2D reinforcements. This shows there is no significant impact on the shear strength as a result of the stiffness changes of the 2D reinforcements found in MBT.

- It seems that the failure of MBT waste in direct shear is dependent on the displacement (in mm) along a potential shear plane, rather than on the shear strain in tests using 300 mm and 100 mm shear boxes.

- Basic matrices reinforced with 2D particles (10 mm x 20 mm) show increase in shear strength. Reinforcing particles smaller (10 mm x 10 mm) or larger than the optimum (10 mm x 60 mm) do not increase the shear strength, instead reduced proving there is an optimum length to act as a reinforcement.

- Conventionally reinforcing content is measured as the content by mass, but reinforcement area per unit weight of the matrix would seem more meaningful.

Future work

- This study mainly concentrated on the 2D reinforcements and their impact on the shear strength. Smaller amount of 1D reinforcements are present in waste. The role of the 1D particles and their impact on shear strength of waste have been not investigated. The contribution of the 3D particles for the shear strength is another area still to be investigated.

- In this research using 2D particles with two different aspects ratios it was found that aspect ratio can be changed without affecting shear strength probably within a limited particle size range. Real reinforcement particle shapes are more complex due to irregular shapes. How the reinforcement particle shape affects the shear strength has not been studied and remains unclear.

- The impact of fibre orientation has been studied in reinforced sand using 1D particles. However there is a recent attempt by Athanasopoulos *et al*.(2008) on MSW reinforcement orientation and its impact. How this is applicable to reinforcements in MBT has to be investigated.

- In this study, shear stress in direct shear was observed to be related to shear displacement. In order to better understand this phenomenon, the development of shear zones within MBT during direct shear should be investigated.

- It is argued decomposition level does not have significant impact on the shear strength (e.g. Kavazanjian, 2001). Using MBT and compost matrices it was found that changes to the basic matrix have an effect on the shear strength. However this is an unclear area that needs further investigation.

- In this research it has been shown the moisture content variations have an impact on the strength of the material. It is clear that some reinforcing particles (e.g. paper and card) probably have reduced stiffness and strength at higher water contents. How the moisture content changes the basic matrix and reinforcement stiffness and the interfacial properties has not been investigated.

- A mathematical model to understand the strength of the waste as a function of the reinforcement properties, basic matrix properties and field situations is necessary.

Appendix 1 - Proctor test (mould selection)

Referring to the Fig A-1 from BS 1377-4:1990 part 4, it was expected that both MBT materials 0-10mm and the 0-20mm MBT, should fall into the material category 1 (as 100% particles passed through the 20mm sieve at plant). Referring to the Fig. A-2 it was found that the both MBT fractions fell into category A, as both material has been sieved under 20mm or 10mm. Hence it was assumed that the 1 liter mould could be used for Proctor compaction with a single sample (in accordance with Bauer *et al*. (2006)).

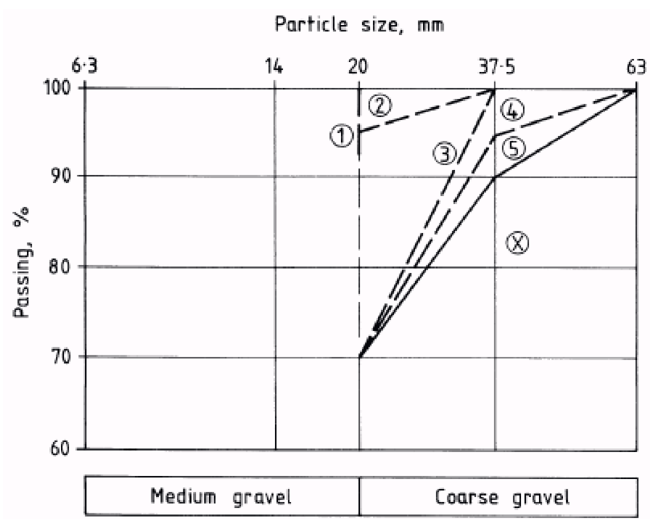


Figure A-1 - Grading limits relating to sample preparation procedures for compaction tests (BS standard 1377-4:1990 part 4)

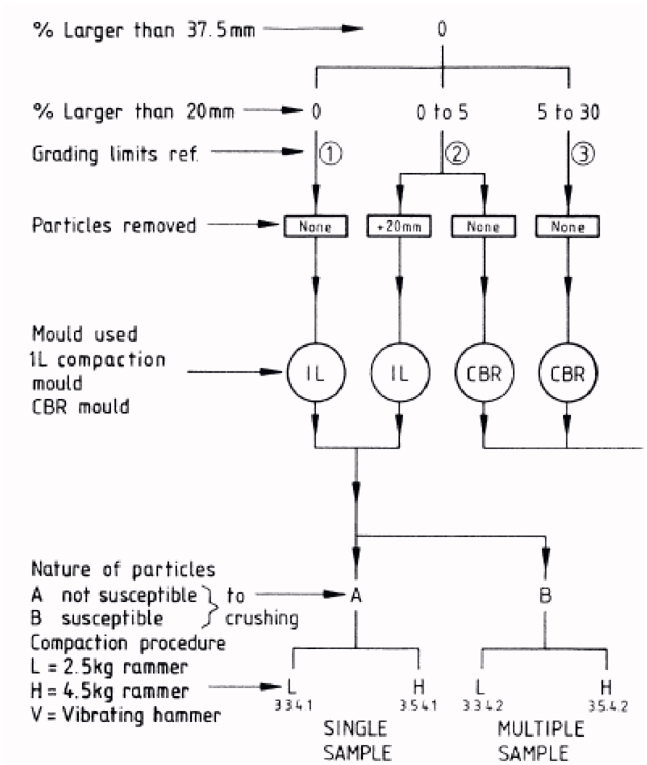


Figure A-2 - Flow chart representing sample preparation methods for compaction tests (BS standard 1377-4:1990 part 4)

Appendix 2 – Quartering Method

Quartering method – When a representative sample needed from a large sample the quartering method is used to reduce the sample while maintaining the composition of the large sample. Initially mixed the sample thoroughly and then divided in to four equal parts (quarters) as shown in Fig. A-3. Two opposition of the quarters are saved while other two are discarded. If sample is needed to reduce further this method can be used again and again until reduce the sample to the exact amount.

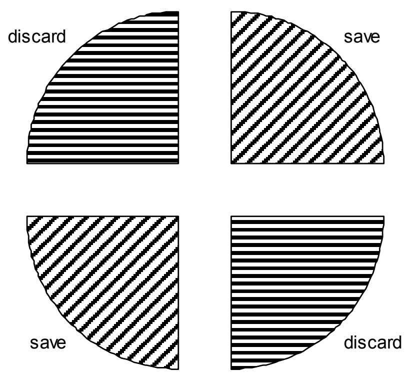


Figure A-3 - Quartering a sample

Appendix 3 – Particle Density

Selection of the particle density measuring method

BS 1377-2:1990 recommends three different methods for determining the particle density.

(a) Small pyknometer method - for soils consisting of particles finer than 2 mm (BS1377-2:1990), not selected by considering the larger particles in the MBT

(b) Pyknometer - according to the BS1377-2:1990, the least accurate method, not selected due to low accuracy

(c) Gas jar method - suitable for soils with up to 10% retained on a 37.5mm sieve and due to acceptable accuracy, selected by considering the accuracy and suitability for larger particles

Particle density determination

Particle density of the material can be determined using the following equation from BS1377-1:1990 section 8.2.5

Particle density (Mg/m^3) = $(M_2 - M_1) / ((M_4 - M_1) – (M_3 – M_2))$ ………….. eqn. A1

= Mass of the material / Volume of the material

M_1 – mass of the empty gas jar

M_2 – mass of the jar with sample

M_3 – mass of the jar with sample and water

M_4 – mass of the jar filled with water

To test the low density particles, paraffin oil was used as allowed in BS1377-2:1990 and the eqn. 3.4.2 was modified as eqn. 3.4.3

Particle density = (density of paraffin) * $(M_2 - M_1) / ((M_4 - M_1) - (M_3 - M_2))$……eqn. A2 (Mg/m^3)

Paraffin density was calculated as 0.87 Mg/m^3

Appendix 4 – Sample settlement and shear rate determination

Compression

The compression curve for the MBT waste under a normal load of 100 kPa is shown in Fig. 3.38. This result shows that the MBT waste went through a quick initial compression during a period of few minutes. After that period (primary compression) only a small amount of settlement occurs. This is probably due to the fairly dry nature of the material, hence there was probably no liquid to remove during consolidation. Fig. A-4 shows the settlement curve covering a period of 1 hour. The sample was topped up at point 'A' by adding more material as outlined. The samples used were allowed to go through the compression stage for 24 hrs.

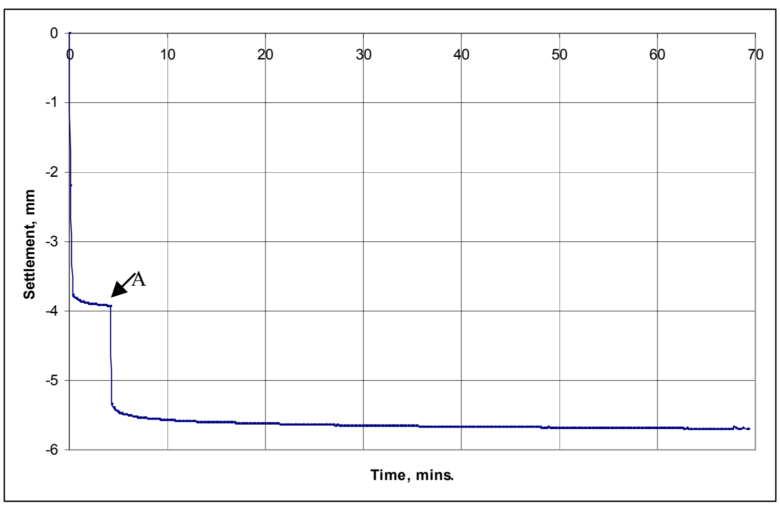


Figure A-4 - 0-10 mm as received moisture content MBT settlement under 100 kPa

Shear rate

Dixon *et al.* (2008) stated that the shear rate had no significant impact on the direct shear results after conducting test in a range of shear rates. The shear rate used by Dixon *et al.* (2008) was 6 mm/min. in a 1 m x 1 m x 0.8 mm shear box and showed no difference in the results when tested at lower rates.

By considering the height of the sample (150 mm) for this study, it was decided to use 0.45 mm/min. (Before deciding the shear rate direct shear tests were conducted on the waste changing the shear rate and found the same finding to the Dixon's that the shear rate change higher or lower does not provide significant impact on the final results as shown in Fig. A-5. Shear rate range of 0.4 – 2 mm/min was used for this study.)

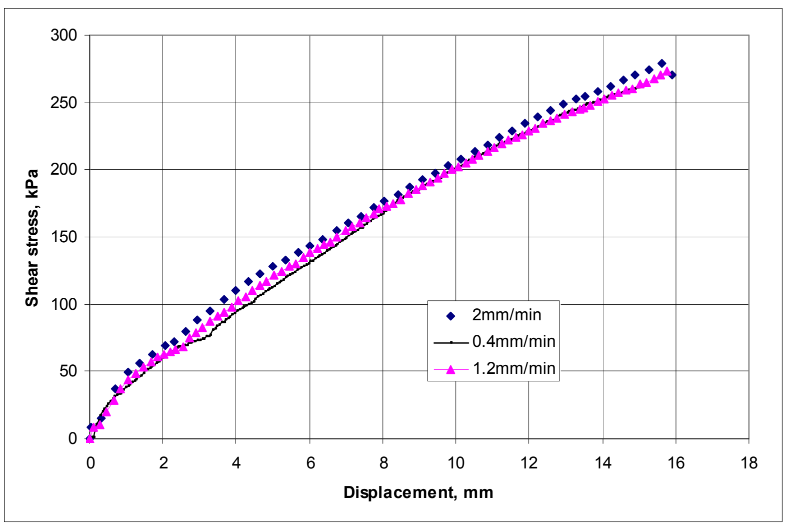


Figure A-5 - Direst shear test on MBT changing the shear rate

Appendix 5 – 60 mm x 60 mm Shear box testing results

Both 0-10 mm and 0-20 mm MBT fractions were tested using the 60 mm shear box. The results on 0-20 mm MBT are presented in Fig. A-6.

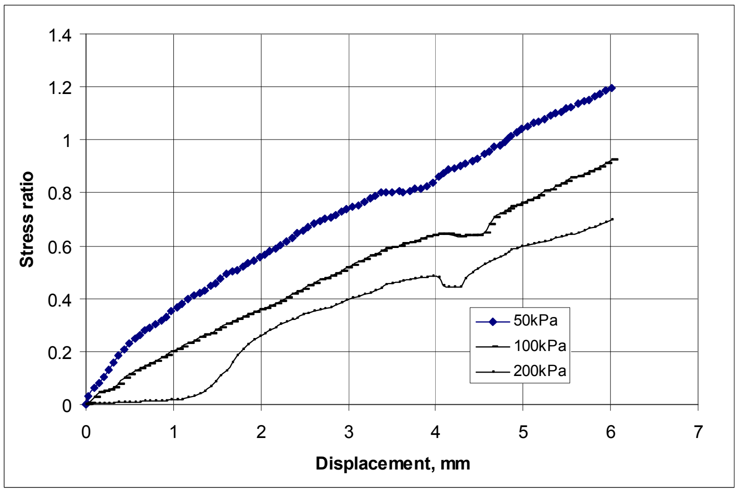


Figure A-6 - Stress ratio, displacement relationship 0-20 mm MBT using 60 mm shear box

The results show less smooth curves compared to the results obtained from the 100 mm and 300 mm shear boxes.

A comparison of the 60 mm and 100 mm shear box tests on 0-10 mm MBT is shown in Fig. A-7.

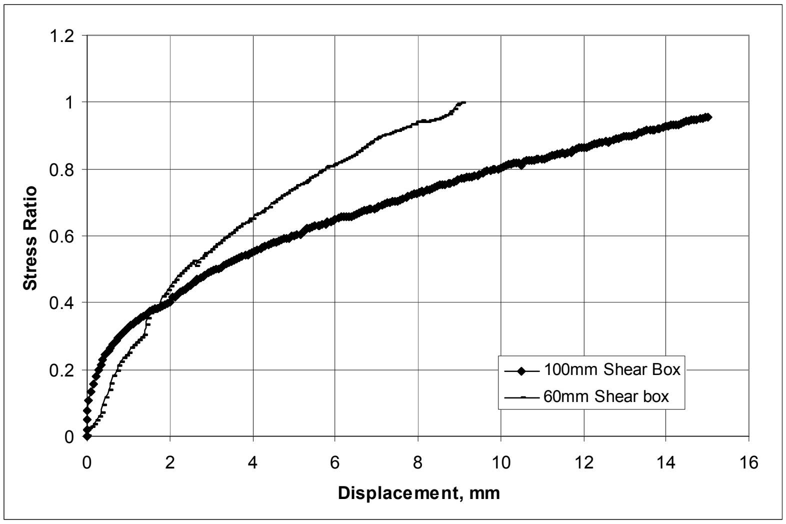


Figure A-7 - Stress ratio, displacement relationship for 0-10 mm MBT in 60 mm and 100 mm shear box tests under 200 kPa

Fig. A-7 shows that the 60 mm shear box does not provide results which are compatible with those from the 100 mm shear box. This would suggest that the 0-10 mm fraction is probably too large to test in a 60 mm shear box and hence the apparatus is not suitable for MBT testing.

References

Archer, E., Baddeley, A., Klein, A., Schwage, J. & Whiting, K. (2005) *Mechanical-biological-treatment: A guide for decision makers – processes, policies and markets.* Report for Juniper Consultancy Services Ltd (Glucestershire, UK).

Athanasopoulos, G., Grizi, A., Zekkos, D., Founta, P. & Zisimatou, E. (2008) Municipal solid waste as a reinforced soil: Investigation using synthetic waste. *GeoCongress 2008.*

Barnes, G. E. (2000) *Soil mechanics - principles and practice,* (second edn) (Palgrave macmillan).

Bauer, J., Munnich, K. & Fricke, K. (2006) Investigation of mechanical properties of mbt waste. *4th Asian-Pacific Landfill Symposium* Shanghai, China

Bauer, J., Munnich, K. & Fricke, K. (2007) Influence of hydraulic properties on the stability of landfills *Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium*S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Bauer, J., Munnich, K. & Fricke, K. (2009) Response of mbt residues in large scale triaxial compression tests. *Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Beaven, R. P. & Powrie, W. (1995) Hydrological and geotechnical properties of refuse using a large scale compression cell. *Proceedings Sardinia 1999, Seventh International Waste Management and Landfill Symposium.* S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, Italy.

Benson, C. H. & Khire, M. V. (1994) Reinforcing sand with strips or reclaimed high density polyethylene. *Journal of Geotechnical Engineering,* 120(5)**,** 838-855.

Borgatto, A. V. A., C.F., M., Izzo, R. L. S. & Bauer, J. (2009) Influence of soft plastics on msw geomechanical behaviour. *Third international workshop Hydro-Physica-Mechanics of Landfills.* Braunschweig, Germany, Technical University of Braunschweig.

Bsi (1990) Methods of test for soils for civil engineering purposes — part 2: Classification tests. BSI.

Bsi (1990) Methods of test for soils for civil engineering purposes — part 4: Compaction-related tests

Bsi (1990) Methods of test for soils for civil engineering purposes — part 7: Shear strength tests (total stress). BSI.

Bsi (2011) Specification for composted materials.

Caicedo, D., M., Watson, G. V. R., Richards, D. J. & Powrie, W. (2011) Exploring the use of micro-focus computed tomography for a better conceptual understanding of structure in landfilled waste in the context of post-closure management for landfills. *Sustainable Environmental Research in process for publication.*

Casagrande, M. D. T., Coop, M. R. & Consoli, N. C. (2006) Behavior of a fiber reinforced bentonite at large shear displacements. *Journal of geotechnical and geoenvironmental engineering,* 132(11)**,** 1505-1508.

Consoli, N. C., Casagrande, M. D. T. & Coop, M. R. (2005) The effect of fibre-reinforcement on the isotropic compression behaviour of a sand. *Journal of geotechnical and geoenvironmental engineering,* 131(11).

Consoli, N. C., Casagrande, M. D. T. & Coop, M. R. (2007) Performance of a fibre-reinforced sand at large shear strains. *Ge´otechnique,* 57(9)**,** 751-756.

Consoli, N. C., Montardo, J. P., Prietto, P. D. M. & Pasa, G. S. (2002) Engineering behavioor os a sand reinforced with plastic waste. *Journal of geotechnical and geoenvironmental engineering,* 128(6)**,** 462-472.

Cresswell, A. W. & Barton, M. E. (2003) Direct shear tests on an uncemented, and a very slightly cemented, locked sand. *Journal of Engineering Geology and Hydrogeology,* 36(119-131.

Cresswell, A. W. & Powrie, W. (2004) Triaxial tests on an unbonded locked sand. *Geotechnique,* 54(2)**,** 107-115.

Dessena, L. & Favaretti (1999) Behaviour of mixtures of mbp waste and inert wastes when used for land reclamation. *Proceedings Sardinia 1999, Seventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Dixon, N. & Jones, D. R. V. (2005) Engineering properties of municipal solid waste. *Geotextiles and Geomembranes,* 23(205-233.

Dixon, N. & Langer, U. (2006) Development of a msw classification system of mechanical properties *Waste Management,* 26(220-232.

Dixon, N., Langer, U. & Gotteland, P. (2008) Classification and mechanical behavior relationships for municipal solid waste: Study using synthetic wastes. *Journal of geotechnical and geoenvironmental engineering,* 134(1)**,** 79-90.

Dixon, N., Langer, U., Gotteland, P. & Gourc, J. P. (2004) Factors influencing shear behaviour of msw. *WASTECON 2004.* Phoenix, Arizona, USA, SWANA.

Eid, H. T. (2011) Shear strength of geosynthetic composite systems for design of landfill liner and cover slopes. *Geotextiles and Geomembranes,* 29(335-344.

Eid, H. T., Timothy, D. S., Douglas, E. & Paul, E. S. (2000) Municipal solid waste slope failure 1: Waste and foundation soil properties. *Journal of geotechnical and geoenvironmental engineering* 123(5)**,** 397-407.

Environment-Agency (2005) Guidance on monitoring mbt and other pretreatment processes for the landfill allowances schemes (england and wales). IN E. Agency (Ed.).

Eu, E. P. A. C. O. T. (1999) Directive 2000/76/ec on the landfill of waste. *Journal of the European Communities***,** 1-19.

Foose, G. J., Benson, C. H. & Bosscher, P. J. (1996) Sand reinforced with shredded waste types. *Journal of Geothechnical Engineering,* 122(9)**,** 760-767.
Fucale, S. P., Juca, J. F. T., Munnich, K. & Bauer, J. (2007) Study of the mechanical behaviour of mbt-waste

IN R. Cossu, L. F. Diaz & R. Stegmann (Eds.) *Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium*
S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Gary, D. H. & Al-Refeai, T. (1985) Behavior of fabric versus fiber reinforced sand. *Journal of Geotechnical Engineering,* 112(8)**,** 804-820.

Gary, D. H. & Ohashi, H. (1983) Mechanics of fiber reinforcement in sand. *Journal of geotechnical engineering,* 109(3)**,** 335-353.

Giroud, J. P., Darrasse, J. & Bachus, R. C. (1993) Hyperbolic expression for soil-geosynthetic or geosynthetic-geosynthetic interface shear strength. *Geotextiles and Geomembranes,* 12(275-286.
Gourc, J. P. Grisolia, M., Napoleoni, Q. & Tancredi, G. (1995) Contribution to a techncal classification of msw. *Proceedings Sardinia 1995, Fifth International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Grisolia, M., Napoleoni, Q. & Tancredi, G. (1995) The use of triaxial tests for the mechanical characterization of msw *Proceedings Sardinia 1995, Fifth International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Head, K. H. (1996) *Manual of soil laboratory testing*.

Heiss-Ziegler, C. & Fehrer, K. (2003) Geotechnical behaviour of mechanically – biologically pre-treated municipal solid waste (msw). *Sardinia 2003, Ninth International Waste Management and Landfill Symposium.* S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, Italy.

Http://Www.Engineeringtoolbox.Com/Specific-Gravity-Solids-Metals-D_293.Html Available online).

Http://Www.Newearthsolutions.Co.Uk/Residual-Waste-Treatment/Process-Description/ Available online).

Http://Www.Wardlab.Com/Samplinginfo/Propersampling.Aspx Available online).

Ivanova, L. K. (2006) *Quantification of factors affecting rate and magnitude of secondary settlement of landfills.* University of Southampton.

Jessberger, H. L., Syllwasschy, O. & Kockel, R. (1995) Investigation of waste body behaviour and waste structure interaction. *Proceedings Sardinia 1995, Fifth International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy

CISA, Environmental Sanitary Engineering Centre, Italy.

Jewell, R. A. & Wroth, C. P. (1987) Direct shear test on reinforced sand. *Ge´otechnique,* 37(1)**,** 53-68.

Jones, D. R. V. & Dixon, N. (1998) *The stability of geosynthetic landfill lining systems,* (Thomas Telford Books).

Kaniraj, S. R. & Gayathri, V. (2003) Geotechnical behavior of fly ash mixed with randomly oriented fiber inclusions *Geotextiles and Geomembranes,* 21(123–149.

Kaniraj, S. R. & Havanagi, V. G. (2001) Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures. *Journal of geotechnical and geoenvironmental engineering,* 127(7)**,** 574-584.

Kavazanjian, E. (2001) Mechanical properties of municipal solid waste. *Proceedings Sardinia 2007, Eighth International Waste Management and Landfill Symposium.* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Kavazanjian Jr., E., Matasovic, N. & Bachus, C. (1999) Large diameter static and cyclic laboratory testing of municipal solid waste. *Sardinia 1999, Seventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Kavazanjian Jr., E., Matasovic, N., Bonaparte, R. & Schmertmann, G. R. (1995) Evaluation of msw properties for seismic analysis. *Geoenvironment 2000.* New Orleans, Louisiana, American society of civil engineers.

Koerner, R. M. & Soong, T. Y. (2005) Analysis and design of veneer cover soils. *Geosynthetics International,* 12(1)**,** 28-49.

Koerner, R. M., Wilson-Fahmy, R. F. & Narejo, D. (1996) Puncture protection of geomembranes part 111:Examples *Geosynthetics International,* 3(5)**,** 655-675.

Kölsch, F. (1995) Material values for some mechanical properties of domestic waste. IN T. H. Christensen, R. Cossu & R. Stegmann (Eds.) *Proceedings Sardinia 1995, Fifth International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, Italy.

Kölsch, F. (2009) Shear strength of waste. *Third international workshop Hydro-Physica-Mechanics of Landfills* Braunschweig, Germany, Technical University of Braunschweig

Kuehle-Weidemeier, H. & Doedens. H (2003) Landfilling and properties of mbp waste. *Ninth international waste management and landfill symposium.* Cagliari, Italy, CIAS, Environmental sanitry centre, Italy.

Kuehle-Weidemeier, M. (2006) *Geomechanical properties and emission behaviour of mechanically and biologically treated municipal solid wastelandfill properties of mbt waste.* Report for Wasteconsult International (Langenhagen, Germany).

Landva, A. & Clark, J. (1990) *Geotechnics of waste fills: Theory and practice* (American society for testing and materials).

Langer, U. (2005) *Shear and compression behaviour of undegraded municipal solid waste.* Loughborough University.

Lings, M. L. & Dietz, M. S. (2004) An improved direct shear apparatus for sand. *Ge´otechnique,* 54(4)**,** 245-256.

Madhavi Latha, G. & Murthy, V. S. (2007) Effect of reinforcement form on the behavior of geosynthetic reinforced sand. *Geotextiles and Geomembranes,* 25(23-32.

Mahler, C. F. & Carvalho, A. R. (2007) Development of equipment to determine geotechnical parameters of solid waste. *Sardinia 2007, Eleventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Mahler, C. F. & De Lamare Netto, A. (2003) Shear resistance of mechanical biological pre-treated domestic urban waste, paper presented at the *Sardinia 2003, Ninth International Waste Management and Landfill Symposium* City, 6-10 October 2003.

Mazzucato, N., Simonini, P. & Colombo, S. (1999) Analysis of block slide in a msw landfill. *Seventh International Waste Management and Landfill symposium.* S. Margherita di Pula, Cagliari, Italy

CISA, Environmental Sanitary Engineering Centre, Italy.

Michalowski, R. L. & Cermak, J. (2003) Triaxial compression of sand reinforced with fibers *Journal of geotechnical and geoenvironmental engineering,* 129(2)**,** 125-136.

Munnich, K., Bauer, J., Bahr, T. & Fricke, K. (2005) Landfilling of pre-treated waste – consequences for the construction and operation of landfills paper presented at the *The future of residual waste management in Europe* City.

Narejo, D., Koerner, R. M. & Wilson-Fahmy, R. F. (1996) Puncture protection of geomembranes part 11:Experimental *Geosynthetics International,* 3(5)**,** 629-653.

Parfitt, J. (2002) *Analysis of household waste composition and factors driving waste increases.* Report for WRAP (Banbury).

Pelkey, S. A., Valsangkar, A. J. & Landva, A. (2001) Shear displacement dependent strength of municipal solid waste and its major constituent. *American society for testing and materials***,** 381-390.

Powrie, W. (2004) *Soli mechanics - concepts and applications,* (Second edn) (A & FN Spon).

Powrie, W. & Beaven, R. P. (1999) Hydraulic properties of household waste and implications for landfills. *Civil engineers and geotechnical engineering,* 137(235-247.

Powrie, W., Beaven, R. P. & Harkness, R. M. (1999) Applicability of soil mechanics principles to household waste. *Sardinia 1999, Seventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Rajan, G., Vasan, R. M. & Charan, H. D. (1996) Probabilistic analysis of randomly distributed fiber reinforced soil. *Journal of Geotechnical Engineering,* 122(6)**,** 419-426.

Sadek, S., Najjar, S. S. & Freiha, F. (2010) Shear strength of fiber-reinforced sands. *Journal of geotechnical and geoenvironmental engineering,* 136(3)**,** 490-495.

Santoni, R. L., Tingle, J. S. & Webster, S. L. (2001) Engineering properties of sand-fiber mixtures for road construction. *Journal of geotechnical and geoenvironmental engineering,* 127(3)**,** 258-268.

Scheelhaase, T., Bidlingmaier, W., Klumper, A., Maile, A. & Rechberger, M. (2001) Geotechnical behaviour of mechanically biologically treated residual waste. *Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, Italy

Shewbridge, S. E. & Sitar, N. (1989) Deformation characteristics of reinforced sand in direct shear. *Journal of Geotechnical Engineering,* 115(8)**,** 1134-1147.

Shewbridge, S. E. & Sitar, N. (1996) Formation of shear zones in reinforced sand. *Journal of Geotechnical Engineering,* 122(11)**,** 873-885.

Shibuya, S., Mitachi, T. & Tamate, S. (1997) Interpretation of direct shear box testing of sand a quasi-simple shear. *Ge´otechnique,* 47(4)**,** 769-790.

Siddiqui, A. A. (2011) *Biodegradation and settlement behaviour of mechanically biologically treated (mbt) waste.* University of Southampton.

Siddiqui, A. A., Richards, D. J. & Powrie, W. (2009) A preliminary analysis of mechanically biologically treated waste: Biodegradation and settlement behaviour. IN P. Sardinia (Ed.) *Twelfth International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy.

Sirinivasa Murthy, B. R., Siridharan, A. & Bindumadhava (1993) Evaluation of interfacial frictional resistance. *Geotextiles and Geomembranes,* 12(235-253.

Sivakumar Babu, G. L., Vasudevan, A. K. & Haldar, S. (2008) Numerical simulation of fiber-reinforced sand behavior. *Geotextiles and Geomembranes,* 26(181-188.

Sobhi, S. & Wu, J. T. H. (1996) An interface pullout formula for extensible sheet reinforcement. *Geosynthetics internationals* 3(5)**,** 565-582.

Tang, C., Bin, S., Gao, W., Chen, F. & Cai, Y. (2007) Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotextiles and Geomembranes,* 25(194-202.

Tang, C., Shi, B. & Zhao, L. (2010) Interface shear strength of fiber reinforced soil. *Geotextiles and Geomembranes,* 28(54-62.

Thomas, T., Aboura, A. A., Gourc, J. P., Gotteland, P., Billard, H., Delineau, T., Gisbert, T., Ouvry, J. F. & Vuillemin, M. (1999) An in situ waste mechanical experimentation on a french lndfill. *Proceedings Sardinia 1999, Seventh International Waste Management and Landfill Symposium* S. Margherita di Pula, Cagliari, Italy CISA, Environmental Sanitary Engineering Centre, Italy

Vanapalli, S. K., Fredlund, D. G., Puhafl, D. E. & Clifton, A. W. (1996) Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal,* 33(379-392.

Velkushanova, K., Caicedo, D., Richards, D. & Powrie, W. (2009) A detailed characterisation of an mbt waste. *Sardinia 2003, 12th International Waste Management and Landfill Symposium*

S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, Italy. Webster, S. L. & Santoni, R. L. (1997) *Contingency airfield and road construction using geosynthetic fiber stabilization of sands.* Report for Tech. Rep. GL-97-4, U.S. Army Engr. Waterways Experiment Station (Vicksburg, Miss.).

Wilson-Fahmy, R. F., Narejo, D. & Koerner, R. M. (1996) Puncture protection of geomembranes part 1:Theory. *Geosyntehtices International* 3(5)**,** 605-627.

Wrap Available online at: http://www.wasteonline.org.uk/resources/InformationSheets/HouseholdersRecycling.htm).

Yetimoglu, T., Inanir, M. & Inanir, I. E. (2005) A study on bearing capacity of random;y distributed fiber reinforced sand fills overlying soft clay. *Geotextiles and Geomembranes,* 23(2005)**,** 174-183.

Zekkos, D., Bray, J. D., Athanasopoulos, G. A., Michael, F., Kavazanjian Jr., E., Founta, P. A., Grizi, A. F. & (2007) Compositional and loading rate effects on the shear strength of municipal solid waste, paper presented at the *4th International Conference on Earthquake Geotechnical Engineering*, City, 25-28 June 2007.

Zekkos, D. P. (2005) *Evaluation of static and dynamic properties of municipal solid-waste.* University of California.