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SHEAR STRENGTH OF BIODRIED MUNICIPAL SOLID WASTE

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ABSTRACT: In this paper, the shear strength of biodried and then subsequently mechanically treated (BMT) municipal solid waste (MSW) is presented. For the purposes of the presented research, the BMT waste samples, with maximum particle size of 25 mm, were obtained from the Croatian Regional Waste Management Centre, Marišćina. Biodrying is an aerobic process, the main purpose of which is to bring the biodegradation of organic waste to an extent sufficient to produce biologically induced heat to dry the waste via evaporation. During the life-time of the bioreactor landfill, the landfill operator disposes BMT waste in its dry state. Once the landfill is closed, the landfill operator will initiate the recirculation of leachate through the landfill body in order to induce intensive gas production and energy recovery. For the design purposes of bioreactor landfill, three dry BMT samples were tested a large direct shear box and in a triaxial testing device as well. The initial dry density of the installed samples in both devices was 380 kg/m^3. The initial density of the installed samples is close to the density values achieved on the Marišćina landfill, as was reported by the landfill operator. The design height of landfill Mariscina after closure is 21 metres. Based on the closure height and initial waste unit weight of about 3.9 kN/m^2, the vertical stress at the landfill bottom should be close to 80 kPa. Therefore, the selected normal stress levels for direct shear tests were 75, 100 and 125 kPa. The cell pressures in the triaxial tests were 50, 100 and 200 kPa. The obtained results show that BMT waste materials aimed for disposal in bioreactor landfill have a shear friction angle significantly lower than the similar waste materials, e.g., biostabilised MBT waste. Therefore, special care has to be taken in the design process of the bioreactor landfill.

Keywords: BMT waste, shear strength, bioreactor landfill, direct shear test

1. INTRODUCTION

As the population continuously increases and our daily lives become more dependent on various products, creating large amounts of waste and its disposal are the main concerns of the quality waste management system.

In order to achieve efficient waste management, it is necessary to understand the variability of waste parameters and waste properties. With respect to the sanitary landfills, as one of the final steps in the waste management cycle, one of the most important properties of municipal solid waste (MSW) is its shear strength.

In order to assess the slope stability of open and closed landfills it is necessary to understand the shear strength phenomena of waste material. The shear strength of waste material is influenced by various factors: waste composition, particle size, age, pre-treatment process, percentage of fibre components, heterogeneous nature of waste material, and unit weight. It is also dependent on the type of shear test device used, and the applied shear rate.

Shear strength of waste material has been the subject of interest of various researchers. For example, Bareither et al. (2012) examined effects of waste composition and decomposition on the shear strength of MSW. They found that a friction angle of 37^0 and cohesion of 20 kPa can be considered as general shear strength parameters in conventional and bioreactor landfills in a range of vertical stress from 12 to 90 kPa.

Zekkos et al. (2010) investigated the shear strength of MSW in a large direct shear device. They recommended a shear strength envelope with a cohesion intercept at 15 kPa and shear friction angle of 36^0 at a normal stress of 1 atm.

The drained response of MSW in a large-scale triaxial device was examined by Zekkos et al. (2012). Results from triaxial compression test at cell pressure of about 100 kPa yielded secant shear friction angles in a range between 36 and 41^0.

Karimpour Fard et al. (2013) examined the shear properties of MSW using a large direct shear apparatus. They concluded that the mechanical response of MSW is rate dependent. The obtained results showed that MSW shear strength increases with an increase of shear rate.

Reddy et al. (2011, 2015) examined the shear strength of bioreactor waste at various degrees of decomposition. Experiments were conducted on raw synthetic waste (Reddy et al., 2011) and raw real waste (Reddy et al., 2015) using a direct shear device. In both cases their findings showed a general decreasing trend of shear friction angle with degree of decomposition. With respect to cohesion, their earlier research showed an increasing trend with degree of decomposition, while in the latest research they did not obtain a consistent trend.

This paper presents shear strength parameters of biologically and mechanically treated (BMT) municipal solid waste (MSW) suitable for landfilling into the bioreactor landfill. In addition, the obtained shear strength parameters are compared with results published by other researchers.

2. MATERIALS AND METHODS

2.1 Tested waste material

2.1.1. Sample's origin

Fresh samples of the mechanically and biologically treated waste material with particle size less than 25 mm were obtained from the waste management centre (WMC) Marišćina in Istria, Croatia (Figure 1).

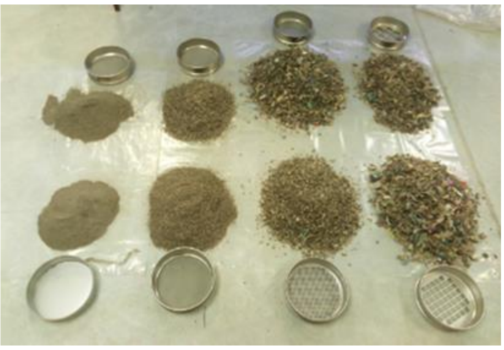

Figure 1. Sieved fractions of BMT waste obtained from WMC Marišćina.

The WMC Marišćina consists of several technical-technological units and facilities, but can generally be divided into the entrance area, disposal area, and working area. Outputs of the BMT Plant Marišćina are reusable waste fraction – metals; solid recovered fuel (SRF), and biodegradable fraction of municipal waste. Biodegradable fraction of waste is disposed in the controlled bio-reactive landfill cell, where the biogas production takes place under controlled conditions with the aim of energy recovery. Waste flow at WMC Marišćina is shown in Figure 2.

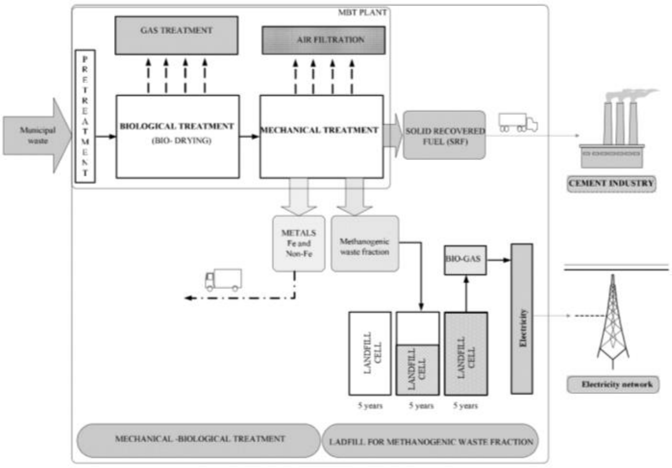

Figure 2. Waste flow at the CWMC Marišćina (Ekoplus Ltd, 2009)

2.1.2. Basic geotechnical properties of tested material

Waste composition

The mass percentages of each individual constituent of the sampled waste material (Figure 3) was determined as follows: plastics 6.43%, textiles 0.22%, glass 10.62%, metals 0.94%, paper/cardboard 4.71%, wood 1.18%, bones/skin 0.20%, stones 2.76%, ceramics 0.46%, rubber 0.13%, and kitchen waste 2.15%. The main components of the examined material were plastics, paper/cardboard, and glass, while more than 70% of the tested material could not be identified. The unidentified particles are classified into a miscellaneous category and divided into particles larger than 2 mm (42.48%) and particles smaller than 2 mm (27.71%). The high percentage of unidentified particles larger than 2 mm suggests that the examined material might show a reinforcing effect during the shearing process.

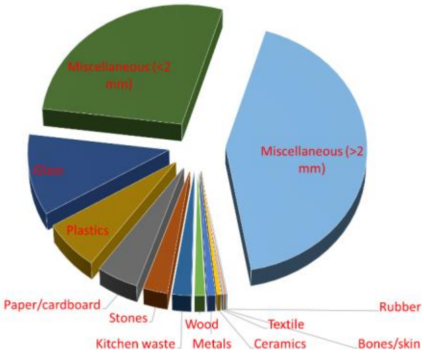

Figure 3. Composition of tested BMT waste material from WMC Marišćina.

Moisture content, organic content, and solid particle density

The average in-situ moisture content of 9.60% was determined in accordance with the ASTM D 2216 standard. The organic portion of 51.60% was determined in accordance with the ASTM D 2974 standard. The average solid particle density value obtained with the gas pycnometry method was 1.89 g/cm^3.

Granulometric properties

Figure 4 shows the averaged granulometric curve obtained for 25 BMT waste samples. The obtained averaged granulometric curve reveals that more than 92% of the tested samples have particles smaller than 31.5 mm. The determined coefficient of curvature and uniformity are 0.86 and 15.8, respectively. Thus, according to the unified soil classification system, the examined BMT waste corresponds to a well graded coarse-grained material.

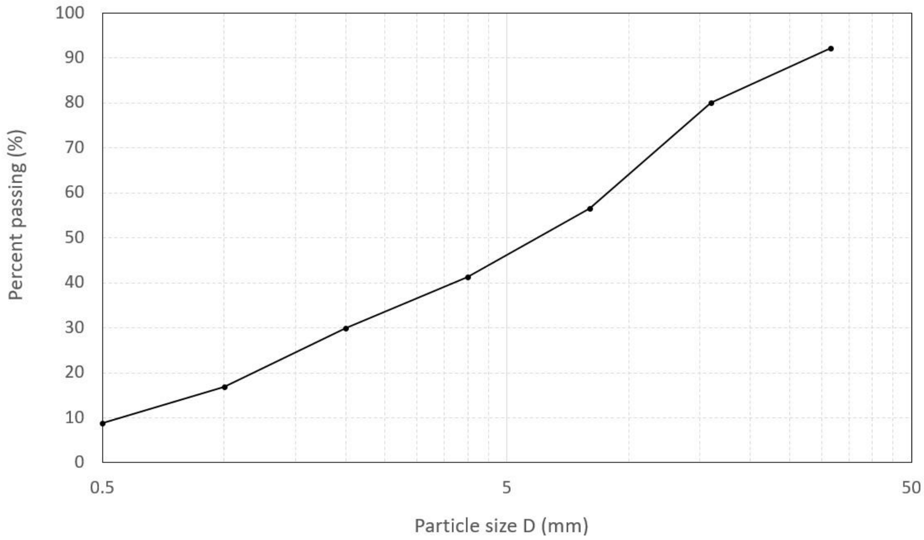

Figure 4. Averaged particle size distribution curve of tested BMT waste material

Maximum dry density

The maximum dry densities of the tested BMT waste material under atmospheric pressure were determined in accordance with the ASTM D 4253 standard. The volume of the used cylindrical metal mould, determined with water–filling method, was 2832.2 cm^3. The mould was filled with waste samples with a plastic scoop in a spiral path (Figure 5). The distance between specimen and plastic scoop was continuously adjusted and kept constant at approximately 13 mm. After sample installation, the samples were compacted using a vibratory table at 50 Hz for 12 minutes. In total, seven samples were tested. The mass of the installed samples varied from 577 to 871 g. Thus, even though the sample installation procedure was the same in all seven cases, the obtained samples mass varied significantly which indicates a strong inhomogeneity of the tested waste material. The maximum dry density of the tested BMT waste under atmospheric pressure lies in range from 340.2 kg/m^3 to 424 kg/m^3, with an average value of 383 kg/m^3.

Figure 5. Filling the mould with waste sample.

2.2 Direct shear device

A large, direct shear apparatus with a shear box with dimensions of 350×350×220 mm was used to perform the shear test. The device has the capability of applying shearing force of up to 50 kN and a maximum vertical load of 400 kPa. An electrical motor applied the horizontal displacement to produce shearing stress at a constant rate of 1 mm/min, or optionally 0.1 mm/min. The shear displacement of the specimen was measured by LVDT with a travelling course of 100 mm. The shear load is measured by a load cell of 50 kN capacity. The vertical force is applied through a pneumatic system using a rubber bladder. The device was originally designed for testing interface shear strengths. However, since the tested material was very compressible, the stretching of the bladder in the vertical direction becomes an important issue. In the case of high vertical stresses and consequently large sample deformations, there was a risk that the bladder would not be able to stretch enough to provide the necessary vertical force. Thus, in order to overcome the possible loss of vertical force, samples were submitted to relatively low vertical stresses in order to keep vertical deformations within the acceptable limits. The chosen vertical stresses were high enough to simulate pressures at the landfill bottom realistically. Moreover, in order to prevent bursting of the bladder with sharp objects in the tested materials, a geotextile was placed between the bladder and waste sample. The direct shear apparatus is presented in Figures 6, 7 and 8.

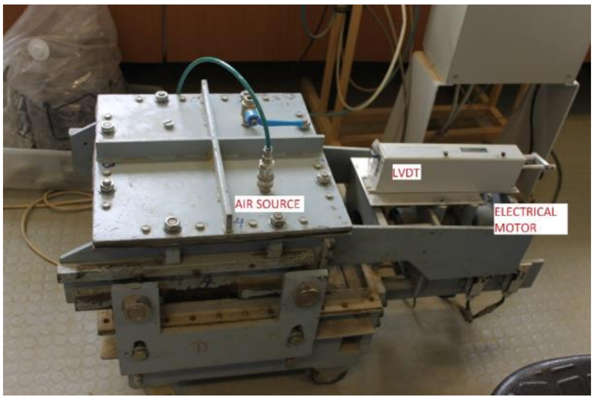

Figure 6. Direct shear device fully assembled.

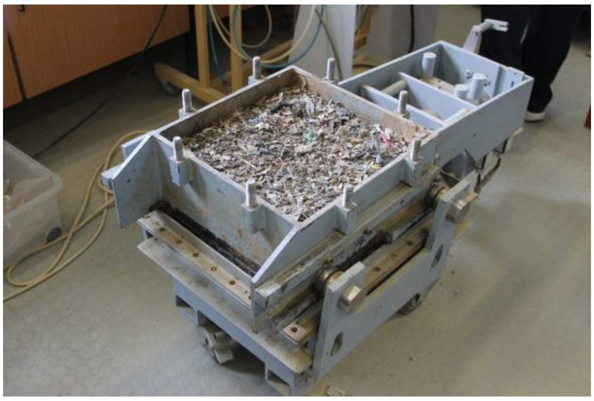

Figure 7. Installed sample.

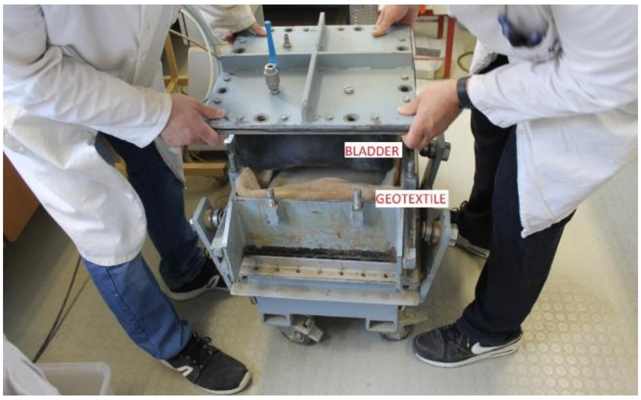

Figure 8. Position of bladder and geotextile.

Triaxial device

A conventional triaxial device with a passive triaxial cell in which samples of 100 mm in diameter can

Figure 9. Triaxial device.

Specimen preparation and test schedule

2.4.1. Direct shear test samples

The initial density of installed samples was 380 kg/m^3. The initial density was selected in accordance with results obtained from a vibratory plate test. Moreover, the initial density value is in good agreement with density values of dry waste material placed on Marišćina landfill, as reported by the landfill operator.

In order to achieve the target density, 10.71 kg of dried waste material was placed into the shear box. The sample height was 230 mm. Samples were placed into the box in five consecutive layers. Each layer had the same mass of 2.14 kg. The samples were slightly compacted with a wooden plate using body self-weight.

The samples were consolidated for two hours prior to shearing tests. The duration of the consolidation phase was determined on the basis of the conducted oedometric tests on the same type of waste material which showed that after two hours the majority of the settlements was achieved.

The adopted shear rate was 1 mm/min. The normal stress levels were selected based on the design height of the Marišćina landfill, which should be about 21 metres. Based on the final landfill height and unit weight of implaced waste (3.9 kN/m^2), the vertical stress at the bottom of the landfill is about 80 kPa. Therefore, in order to simulate the stress conditions at the landfill bottom, three levels of normal stress, 75, 100 and 125 kPa, were selected to perform shear tests.

For the purposes of this research three samples, each at a different vertical stress level, were tested.

2.4.2 Triaxial test samples

Consolidated undrained tests were conducted on three samples at cell pressures of 50, 100 and 200 kPa. The adopted strain rate was 0.021 mm/min. The initial density of installed samples was 380 kg/m^3. In order to achieve the target density, 298.4 g of dried waste material was placed into the suction sleeve stretcher. During assembly of the specimen, water mixed with 10 g/l of acid and propionic acid were added to the specimen by means of a pressure/volume controller. The acids were added in order to prevent microbial activities and sample decomposition during the test. Further saturation was accomplished through the application of a backpressure until the B-parameter value of 0.95 was reached. The initial moisture content of tested samples before additional saturation, on a wet matter basis, was about 59%. In order to reduce the occurrence of sample buckling and barreling, the sample height was reduced from 200 to 100 mm.

3. RESULTS AND DISCUSSION

Figure 9 presents the shear strain – shear strength relationship obtained in direct shear tests. As can be seen from Figure 9, an increase in vertical stress is followed by a corresponding increase in shear strength. In the direct shear device, the tested samples show a hyperbolic trend, only approaching failure shear stresses at very large displacements. The tested samples did not show any hardening phenomena. Moreover, the obtained results are typical for a direct shear test where shear plane is artificially induced in the horizontal direction.

Due to the fact that the bottom shear box is longer by 75 mm than the top box, the contact shear area, and thus the shear and normal stresses, remain constant during the test.

Contrary to the results obtained in the direct shear tests, the results obtained in the triaxial testing device, presented in Figure 10, show strength hardening behaviour for all three specimens. The obtained results are typical for triaxial tests where the shear plane is not artificially induced, and the fibre component can be activated during the shearing process.

The observations obtained in the direct shear and triaxial devices are in good agreement with results published from various researchers (Karimpour Fard et al., 2013; Shariatmadari et al., 2017) who also confirmed similar behaviour of waste material in direct shear and triaxial devices.

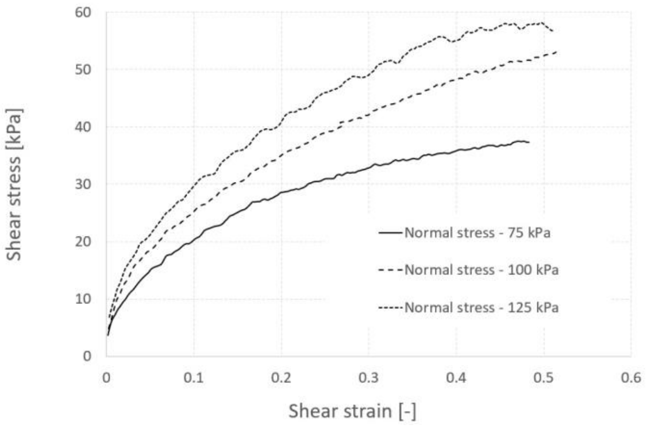

Figure 9 – Shear deformation – shear strength curves obtained in direct shear device

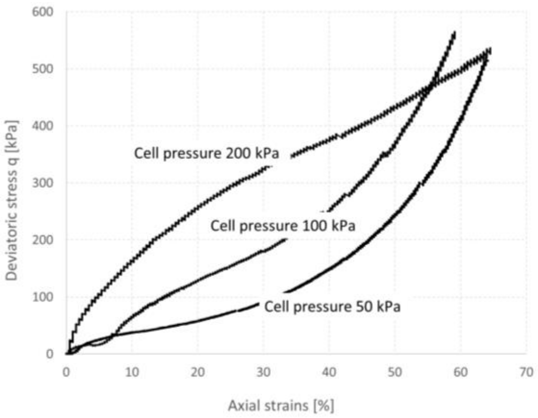

Figure 10. Axial strain – deviatoric stress curves obtained in triaxial device

Based on the obtained results, the virtual shear strength parameters in accordance with the Mohr-Coulomb theory were established at shear/axial strain levels of 30%, 40% and 50%. The obtained shear strength parameters are presented in Table 1.

Table 1. Virtual shear strength parameters at various levels of shear (DS) / axial (TX) strains

Shear (DS) / Axial (TX) strain level [%]	**Apparent cohesion [kPa]**	**Shear friction angle [^{0}]**	**Apparent cohesion [kPa]**	**Shear friction angle [^{0}]**
	Direct shear test		**Triaxial test**	
30	8.7	18.2	5.5	25.8
40	8.2	20.9	27.6	25
50	8.2	22.1	71.4	21.6

As can be seen from Table 1 the cohesion obtained in direct shear tests varied within a small range of values, while the shear friction angle increased by 17.6 % with the increase of shear strain level from 30 to 50%. In the triaxial tests an opposite trend was observed. Apparent cohesion was significantly increased with the increase in strain levels while the shear friction angle varied slightly. Figure 11 presents virtual failure envelopes which correspond to relative strains of 30, 40 and 50% obtained from the direct shear and triaxial test results. As can be noticed from Figure 10, the shear strength obtained in the triaxial test, for the same level of deformation, is higher than the corresponding shear strength obtained in the direct shear device. The most probable reason for this is the different orientation of the shearing plane. In direct shear tests the shear plane is induced artificially in the horizontal direction. As a consequence, fibre components cannot be activated during the shearing process.

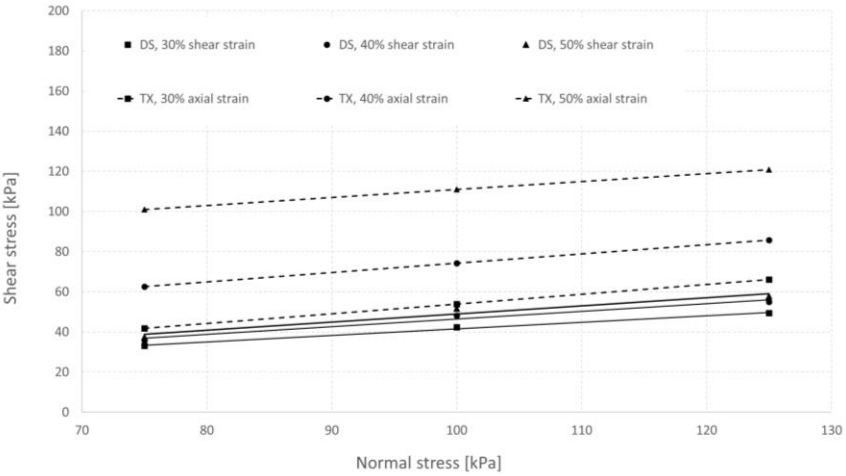

Figure 11. Strength envelopes obtained with direct shear and triaxial tests

For comparison purposes Figure 12 presents upper and lower limit envelopes published by Shariatmadari (2017), and failure envelopes for untreated municipal solid waste published by Kavazanjian (2001) and Van Impe (1998) at the same vertical stress levels. It can be noticed that the failure envelopes obtained on the tested materials fit well within the failure envelope limits published by Shariatmadari (2017). With respect to the raw waste material, it can be noticed that the obtained shear strength of BMT waste in the direct shear, at the same level of normal stress, and even at large strains, produces a smaller shear strength than the raw waste material. The most probable reason is due to a smaller amount, or total absence, of fibrous components in BMT waste materials. However, in the triaxial device, the obtained shear strength is comparable, and at very large strains, even higher than the shear strength of the raw waste material.

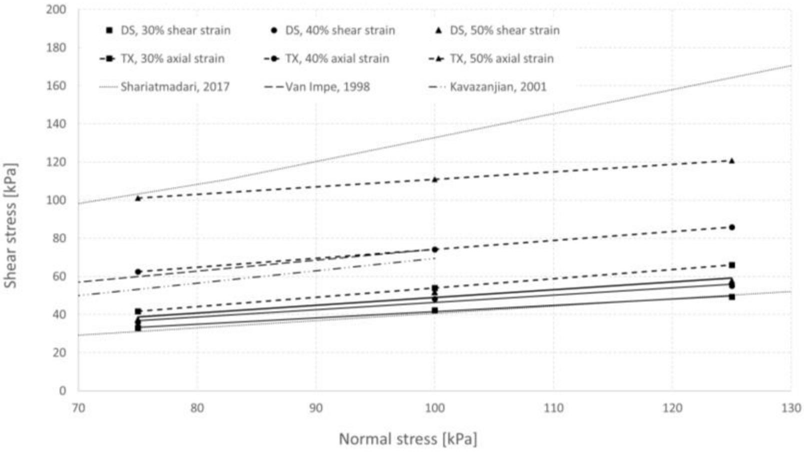

Figure 12. Strength envelopes

Figure 13 presents comparisons of the obtained values with proposed ranges of shear strength parameters of bio-stabilised MBT waste material published by Kuehle-Weidemeier (2007) and Bauer et al. (2009). As can be seen, the obtained cohesions fit reasonably well within the suggested limits while the obtained shear friction angles are significantly smaller than the ranges of shear friction angle values suggested by Kuehle-Weidemeier (2007) and Bauer et al. (2009).

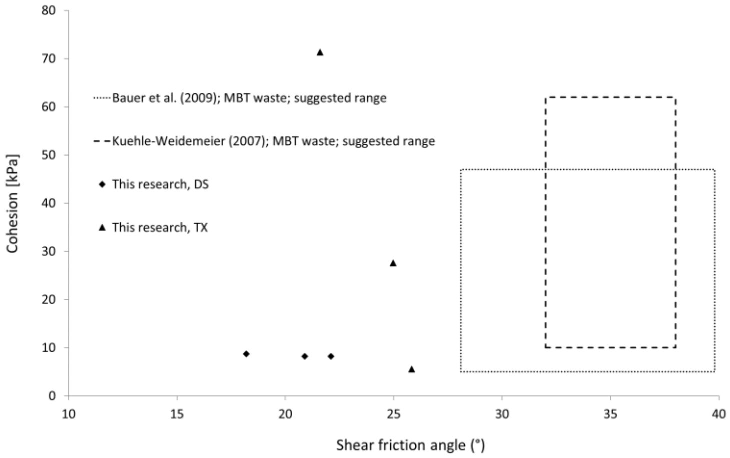

Figure 13. Suggested range of shear strength parameters of bio-stabilised MBT waste material

4. CONCLUSIONS

It is shown that the mechanical behaviour of BMT waste in direct shear tests follows a hyperbolic trend approaching a horizontal asymptote, which is the opposite of the mechanical response of BMT waste in the triaxial apparatus, which exhibits strain hardening in the form of an upward concave curve.

In direct shear tests the shearing mechanism is such that it creates a shearing plane parallel to the horizontally oriented fibres inside the BMT. As a consequence, the reinforcement action of the fibrous particles could not be activated and as a result the mechanical behaviour does not show a strain hardening phenomena.

Through conducted experiments in direct shear tests, the friction angle and cohesion varied from 18.2 to 22.1 degrees, and 8.7-8.2 kPa for the strain range from 30 to 50%. In triaxial tests, for the same strain levels, the friction angle and cohesion varied from 21.6 to 25.8 degrees, and 5.5-71.4 kPa.

However, since landfills are composed of various components which show strain-softening behaviour, it is advisable to further reduce the obtained shear strength parameters to conform the smaller strain levels. Thus, the obtained results show that BMT waste material aimed for disposal in bioreactor landfill gas, with exception at the very large strains, has a low shear strength. Therefore, special care in the design process of a bioreactor landfill is necessary.

With respect to the proposed range of shear strength parameters for biostabilised MSW, which is a different type of pre-treatment process then the biodrying process, the cohesion obtained within this research fits reasonably well within the suggested ranges, while the obtained shear friction angles of biodried waste are significantly smaller than the shear friction angles of the biostabilised waste material.

ACKNOWLEDGEMENTS

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