



# Effects of the reinforcement content and reinforcement scale on the shear strength characteristics of mechanically biologically treated waste

Bang Wang<sup>1</sup> · Zhenying Zhang<sup>1</sup> · Hui Xu<sup>1</sup> · Menghe Huang<sup>1</sup> · Chengyu Nie<sup>1</sup> · Tuo Li<sup>1</sup>

Received: 19 November 2021 / Accepted: 16 February 2022 / Published online: 14 March 2022  
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

## Abstract

Mechanical and biological treatment (MBT), which can be used for waste reduction and for the burning of methane from biological treatments to generate electricity and heating, has become a popular research topic in environmental geotechnical engineering. This study investigated the mechanical behaviour of MBT waste and the effects of different reinforcement contents and reinforcement scales on its shear strength characteristics, and 68 groups of MBT waste samples from the Hangzhou Tianziling landfill were tested in the laboratory with a direct shear test apparatus. The samples exhibited displacement hardening behaviour in their mechanical response. The results show that the content and scale of the reinforced materials in MBT waste play an important role in the strength characteristics of MBT waste, and graphs showing the variation of the MBT waste shear strength and shear strength parameters with different reinforcement contents and reinforcement scales are shown. The range of cohesion  $c$  is 6.0–12.0 kPa, and the internal friction angle  $\varphi$  is 15.6–26.6°, respectively. The results of this study provide a reference for the assessment of slope stability at MBT landfills.

**Keywords** Mechanically biologically treated waste · Direct shear test · Reinforcement content · Reinforcement scale · Shear strength · Shear strength parameters

## Introduction

Landfilling is the main method used to treat municipal solid waste (MSW) (Eskandari et al. 2016; Falamaki et al. 2018). The increasing population and rapid urbanisation have led to an increase in the MSW output and thus to great challenges with respect to environmental protection (Blight 2008; Reddy and Basha 2014; Chaudhary et al. 2021). To reduce the landfill volume of MSW, pretreatment technology for solid waste has gradually attracted attention. On 26 April 1999, the European Union (EU) issued a Council Directive (1999/31/EC) for MSW landfills, which stipulates that EU member states must reduce the amount of biodegradable waste transported to landfills. To achieve this goal, the member states use mechanical biological treatment (MBT)

technology for the MSW treatment. The MBT can be divided into two parts: firstly, biodegradable and non-biodegradable materials are separated by mechanical treatment (e.g. crushing, screening, centrifugation, and selection) and large-sized materials are screened or chopped into small-sized materials to facilitate the biological treatment. Secondly, the degradation of organic matter in MSW is accelerated by biological treatment (aerobic and anaerobic). The waste treated by MBT technology consists of plastic, textile, wood, rubber, stone, ceramic, glass, metal, soil (< 5 mm), and other indistinguishable materials, which will be filled. Among them, the degradable materials are textile and wood, and the remaining physical materials are basically non-degradable. The MBT technology can be used to recover reusable MSW resources, and the methane produced by biological treatment can be utilised for incineration, power generation, and heating to reduce the amount of waste in landfills. The MSW is converted into a new material, that is, MBT waste, by using MBT technology, and its physical properties (e.g. particle size, composition, moisture content, density, void ratio) and mechanical properties (e.g. shear strength, compression consolidation, and permeability) change (Zhang et al. 2018). In

---

Responsible Editor: Philippe Garrigues

✉ Zhenying Zhang  
zhangzhenyinga@163.com

<sup>1</sup> School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou 310018, China

addition, the strength, stiffness, and stability of the landfill are affected (Jones and Dixon 2015). Therefore, it is necessary to study the physical and mechanical properties of MBT waste.

In the past 30 years, many researchers have studied the shear strength of MSW (Landva and Clark 1986, 1990; Singh and Murphy 1990; Kölsch 1993, 1995; Kavazanjian et al. 1995; Kavazanjian 1999; Eid et al. 2000; Machado et al. 2002, 2008, 2010; Caicedo et al. 2002a, 2002b; Reddy et al. 2009; Stark et al. 2009; Shariatmadari et al. 2009, 2011, 2014, 2017; Karimpour-Fard 2009, Karimpour-Fard et al. 2011, 2013, Karimpour-Fard 2018; Bray et al. 2009; Zekkos et al. 2010; Bareither et al. 2012; Zekkos and Fei 2016; Fei and Zekkos 2017; Abreu and Vilar 2017; Ramaiah et al. 2017; Falamaki et al. 2019; Keramati et al. 2020). Landva and Clark (1990) reported the results of direct shear tests on MSW samples collected from different regions of Canada and concluded that samples with higher plastic contents exhibit a lower shear strength. However, Machado et al. (2002) considered that plastics may improve the cohesion and internal friction angle. Shariatmadari et al. (2009) and Karimpour-Fard et al. (2011) conducted large-scale triaxial tests of fresh MSW with a plastic content of 0%, 6.25%, 12.5%, and 25% and found that the shear strength increases with increasing plastic content. Zekkos et al. (2010) observed that the increase in the fibre content slightly reduces the shear strength of MSW samples. Karimpour-Fard et al. (2013) reported that the internal friction angle of samples with plastic contents of 6% and 12% reaches a maximum when the fibres are placed at an angle of 60°. Shariatmadari et al. (2017) conducted direct shear and triaxial tests on MSW samples with the same fibre content and concluded that the use of different shear test apparatuses leads to different shear strength parameters. Based on the above-mentioned literature, the shear strength of MSW is not only controlled by the friction between solid particles but also by internal reinforced materials.

Mahler and Neto (2006) conducted a direct shear test on MBT waste with different particle sizes and found that the shear strength of the 0.42-mm particle size group is smaller than that of the 9.52-mm particle size group. They also observed fibre components in the MBT waste group with the large particle size. Fucale (2005) performed direct shear tests on MBT waste with different fibre contents (0%, 10%, and 20%) and reported an optimal value (10%) which reached the highest shear strength. Fernando et al. (2009) prepared the MBT waste samples with the reinforced material content changing from 2 to 6% and observed an enhancement in both the peak and residual shear strengths. Bhandari and Powrie (2013) conducted triaxial tests on MBT waste with different particle sizes and shapes and observed that small reinforced materials enhanced the resistance of the sample to lateral deformation and volume deformation under high confining

pressure. Pimolthai and Wagner (2014) used direct shear test equipment to test the shear strength of MBT waste (from Luxembourg, Germany, and Thailand) with a particle size below 10 mm and observed that the shear strength increases with increasing content of reinforced material. Babu et al. (2015) conducted direct shear and triaxial tests on waste samples from the Mavallipura landfill in Bangalore to study the effects of the particle size, unit weight, and drainage and undrained conditions on the MBT waste. They reported that the higher shear strength was achieved by the waste samples with larger unit weight, higher density, and smaller particle size. Fucale et al. (2015) carried out experiments and reported that reinforced materials (e.g. plastics, textiles, and fibres) in landfills can improve the shear strength of MBT waste by mobilising the tensile strength. Relevant literature on the shear strength characteristics of reinforced MSW and MBT waste is presented in Table 1.

Compared with MSW landfills, MBT landfills have a low content of organic matter and high content of reinforced materials such as plastics and textiles. The content and scale of reinforced materials in MBT landfills affect their stability. When the content and scale of reinforced materials are too large, the internal gap of the landfill will become larger, which will lead to instability or sliding of the pile. Reinforced materials with a too small content or scale may not perform its reinforcement effect. According to the above literature summary, there is still a lack of systematic research on the influence of reinforced material content and reinforced material scale on the shear strength characteristics of MBT waste. In this paper, the shear strength characteristics of MBT waste with different contents (0%, 5%, 10%, 15%, 20%) and different scales (5, 10, 15, 20 mm) of reinforced materials were studied by using a direct shear test apparatus. The test results provide a reference for the analysis of the stability of MBT waste landfills.

## Materials, test apparatus, and process

### Materials

The MBT waste was collected from the Hangzhou Tianziling pilot project, put into a sealed plastic bucket, and transported to the Geoenvironmental Laboratory at Zhejiang Sci-Tech University. The original MBT waste is shown in Fig. 1.

Figure 2 shows the composition of the original MBT waste. The Hangzhou Tianziling MBT waste consists of plastic, textile, wood, rubber, stone, ceramic, glass, metal, soil (< 5 mm), and other indistinguishable materials. The plastic content is high, accounting for 22.5%. The initial unit weight of the MBT waste can be determined based on the volume and weight of the materials obtained from the MBT plant. The average unit weight of the MBT waste was

**Table 1** Reference summary

Reference	Waste origin and types of waste	Testing method	Sample size (mm)	Pressure (kPa)	Shear displacement or strain
Landva and Clark (1990)	Various Canadian Landfills (MSW)	L-DS	434×287	PS, 30.3–565	NI
Machado et al. (2002)	Tri-Cities, Northern California (MSW)	L-DS	300×300×180(H)	1.8–700	PD (55 mm)
Mahler and Neto (2006)	Brazil (MBT)	L-DS	NI	25–100	PD (12 mm)
Fucale (2007)	Germany (MBT)	L-DS	300×300×150(H)	100–300	PD (20%)
Fernando et al. (2009)	UK (MBT)	L-DS	NI	50–100	PD (3%, 4%)
Shariatmadari et al. (2009)	Metropolitan Center landfill in Salvador (MSW)	L-TT	$D=200, H=350$	100–400	PD (30%)
Zekkos et al. (2010)	Tri-Cities, N. California (MSW)	L-DS	300×300×180(H)	1.8–700	PD (55 mm)
Shariatmadari et al. (2011)	The Kahrizak Center Landfill (MSW)	L-DS	300×300×150(H), 2000×1000×1500(H)	20–200	PD (45 mm)
Karimpour-Fard et al. (2011)	Metropolitan Center Landfill (MSW)	L-TT	$D=200, H=350$	50–300	PD (30%)
Karimpour-Fard et al. (2013)	Kahrizak Center Landfill Tehran, Iran (MSW)	L-DS	300×300×150(H)	20–200	PD (45 mm)
Bhandari and Powrie (2013)	Dorset, England (MBT)	L-TT	NI	25–200	PD (50%)
Pimolthai and Wagner (2014)	Luxembourg; Germany; Thailand (MBT)	L-DS	$D=94, H=20$	20–100	NI
Fucale et al. (2015)	Germany (MBT)	L-DS	300×300×150(H)	100–300	PD (20%)
Babu et al. (2015)	Mavallipura, India (MBT)	L-DS	60×60×30(H)	50–150	PD (20%)
Shariatmadari et al. (2017)	Kahrizak landfill in Tehran (MSW)	L-DS; L-TT	300×300×150(H); $H=350$	25–10; 25–100	PD (20%)
Pulat and Yukselen-Aksoy (2017)	Europe, Turkey; USA (MSW)	L-DS	300×300×150(H)	50–200	PD (20%)

*L* laboratory tests, *DS* direct shear, *TT* triaxial text, *D* diameter, *H* height, *PS* peak stress, *PD* peak displacement, *NI* not involved.

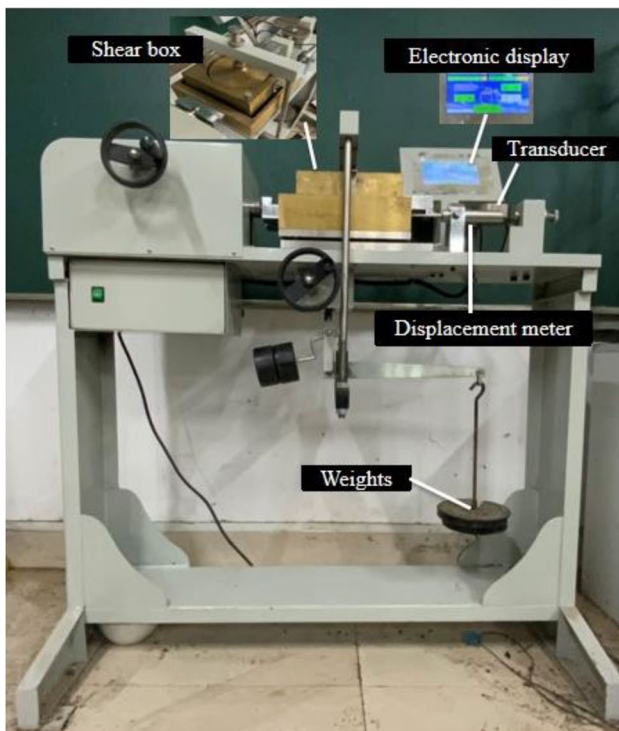
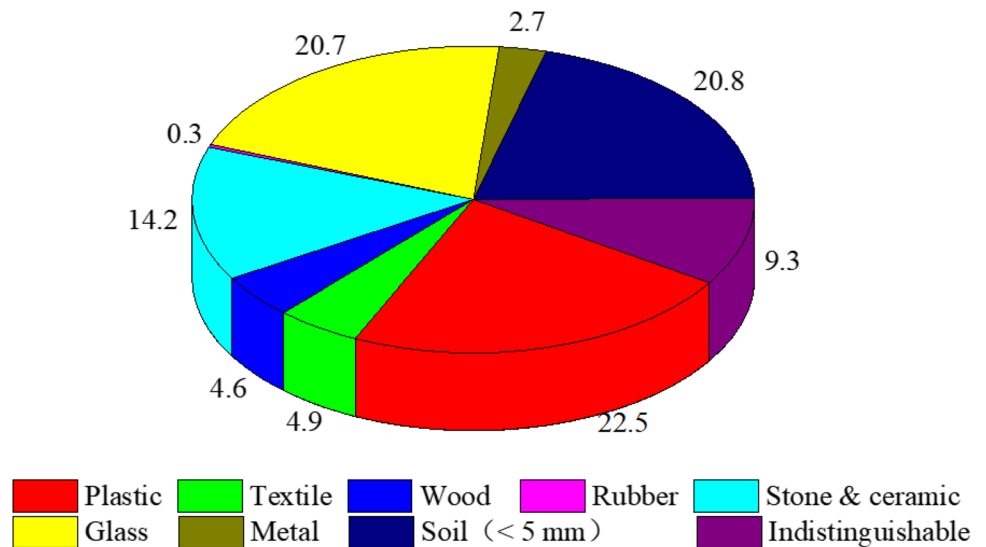
**Fig. 1** Original MBT waste

determined to be  $4 \text{ kN/m}^3$ . Therefore, we set the initial unit weight of the MBT waste to  $4 \text{ kN/m}^3$ . After drying the original MBT waste at a constant temperature (oven temperature of  $65 \text{ }^\circ\text{C}$ ) for 24 h, the moisture content of the original MBT waste was obtained as 20%.

### Direct shear test apparatus

A direct shear test apparatus was used in this study, as shown in Fig. 3. The apparatus consists of a shear box, loading device, displacement metre, electronic display, and motor. The diameter and height of the shear box are 185 and 60 mm, respectively. The loading device can be used for load application in both vertical and horizontal directions. The maximum vertical and horizontal load is 400 kPa and 50 kN, respectively. The displacement metre is used to measure the compression and shear displacement of the sample (the maximum displacement was determined to be 40 mm), and the data can be directly read on the electronic display.

**Fig. 2** MBT composition in the Tianziling (dry weight, %)



**Fig. 3** Direct shear test apparatus

**Test process**

To study the reinforced effects on the shear strength characteristics of MBT waste, 68 groups of MBT waste samples with different reinforcement contents (RCs; 0%, 5%, 10%, 15%, and 20%) and reinforcement scales (RSs: 5, 10, 15, and 20 mm) were prepared. The test conditions are shown in Table 2.

The test was carried out in accordance with the technical specifications for geotechnical waste tests (CJJ/T 2013). Firstly, large pieces of reinforced materials (e.g. plastics and textiles) were selected and manually sorted. The remaining parts were then placed into the oven and dried to a constant weight at a temperature of 65 °C. Material with a size below 5 mm was separated from the dry remaining material as non-reinforced MBT waste, and the selected reinforced materials (plastics and textiles) were cut into square sheets (5, 10, 15, and 20 mm).

Sample preparation and test process are described by using the DS2-1 group as an example. In total, 26.9 g dry 5-mm reinforced materials were added to 510.6 g of dry non-reinforced MBT waste material (the total dry mass of the MBT waste is the sum of the dry reinforced materials and dry non-reinforced MBT waste) and mixed. Subsequently, 107.5 g purified water was sprayed on the sample with a watering can, and the sample was stirred. After the preparation, 645.0 g sample was obtained, which was allowed to stand in the laboratory for 24 h.

The prepared MBT waste sample was placed into the shear box in 10-mm layers, and then a simple tamping hammer was used to evenly compact the sample to ensure the same vertical settlement in the same plane to reach an initial unit weight of 4 kN/m<sup>3</sup>. The sample was continuously compressed for 1440 min under a vertical pressure of 25 kPa, and the compression of the test sample was measured. The direct shear test was carried out at a constant shear rate of 1 mm/min, and the shear force was recorded every 1 mm displacement during the shear process. The test was stopped when the shear force no longer increased nor decreased.

After the direct shear test of the DS2-1 sample was completed, sample DS2-2 was prepared by using the same method. A vertical pressure of 50 kPa was applied, the sample was continuously compressed for 1440 min, and

**Table 2** Test conditions

Specimen number	Reinforcement content (%)	Reinforcement scale (mm)	Vertical pressure during compression ( $\sigma$ , kPa)	Vertical pressure duration (min)	Unit weight after compression ( $\gamma$ , kN/m <sup>3</sup> )
DS1-1	0	0	25	1440	5.99
DS1-2	0	0	50	1440	6.45
DS1-3	0	0	75	1440	7.01
DS1-4	0	0	100	1440	7.22
DS2-1	5	5	25	1440	5.85
DS2-2	5	5	50	1440	6.16
DS2-3	5	5	75	1440	6.68
DS2-4	5	5	100	1440	6.80
DS3-1	5	10	25	1440	5.76
DS3-2	5	10	50	1440	6.10
DS3-3	5	10	75	1440	6.44
DS3-4	5	10	100	1440	6.71
DS4-1	5	15	25	1440	5.60
DS4-2	5	15	50	1440	5.81
DS4-3	5	15	75	1440	5.99
DS4-4	5	15	100	1440	6.06
DS5-1	5	20	25	1440	5.19
DS5-2	5	20	50	1440	5.61
DS5-3	5	20	75	1440	5.74
DS5-4	5	20	100	1440	5.85
DS6-1	10	5	25	1440	5.71
DS6-2	10	5	50	1440	6.14
DS6-3	10	5	75	1440	6.60
DS6-4	10	5	100	1440	6.73
DS7-1	10	10	25	1440	5.63
DS7-2	10	10	50	1440	6.07
DS7-3	10	10	75	1440	6.38
DS7-4	10	10	100	1440	6.62
DS8-1	10	15	25	1440	5.41
DS8-2	10	15	50	1440	5.75
DS8-3	10	15	75	1440	5.81
DS8-4	10	15	100	1440	5.99
DS9-1	10	20	25	1440	5.11
DS9-2	10	20	50	1440	5.58
DS9-3	10	20	75	1440	5.71
DS9-4	10	20	100	1440	5.79
DS10-1	15	5	25	1440	5.66
DS10-2	15	5	50	1440	6.13
DS10-3	15	5	75	1440	6.58
DS10-4	15	5	100	1440	6.70
DS11-1	15	10	25	1440	5.61
DS11-2	15	10	50	1440	6.06
DS11-3	15	10	75	1440	6.36
DS11-4	15	10	100	1440	6.56
DS12-1	15	15	25	1440	5.25
DS12-2	15	15	50	1440	5.55
DS12-3	15	15	75	1440	5.77
DS12-4	15	15	100	1440	5.94

**Table 2** (continued)

Specimen number	Reinforcement content (%)	Reinforcement scale (mm)	Vertical pressure during compression ( $\sigma$ , kPa)	Vertical pressure duration (min)	Unit weight after compression ( $\gamma$ , kN/m <sup>3</sup> )
DS13-1	15	20	25	1440	4.98
DS13-2	15	20	50	1440	5.48
DS13-3	15	20	75	1440	5.64
DS13-4	15	20	100	1440	5.75
DS14-1	20	5	25	1440	5.61
DS14-2	20	5	50	1440	6.09
DS14-3	20	5	75	1440	6.51
DS14-4	20	5	100	1440	6.65
DS15-1	20	10	25	1440	5.51
DS15-2	20	10	50	1440	5.97
DS15-3	20	10	75	1440	6.31
DS15-4	20	10	100	1440	6.49
DS16-1	20	15	25	1440	4.98
DS16-2	20	15	50	1440	5.39
DS16-3	20	15	75	1440	5.70
DS16-4	20	15	100	1440	5.80
DS17-1	20	20	25	1440	4.78
DS17-2	20	20	50	1440	5.36
DS17-3	20	20	75	1440	5.62
DS17-4	20	20	100	1440	5.68

DS direct shear test.

the compression of the test sample was measured. Subsequently, a direct shear test was conducted at a constant shear rate of 1 mm/min, and the shear force was recorded every 1-mm displacement until the shear force did not increase nor decrease. The above-mentioned sample preparation and test process was repeated until whole test was completed and all test data were recorded.

## Results and analysis

### Shear stress–displacement behaviour

Fig. 4 shows the correlation between the shear stress and shear displacement of MBT waste with different RCs for a reinforcement scale of 15 mm. It is observed that the shear stress increases with an increase in the horizontal shear displacement. Even though the horizontal displacement reached the maximum limit value, the shear stress did not show a notable peak. The shear stress–shear displacement curve of MBT waste shows a typical characteristic of displacement hardening, which is similar to that of MSW (Zhang 2018). The underlying mechanism can be explained as follows: in the early stage of the shear process, friction between solid particles is the main reason for the increase in the shear stress. When the shear displacement reaches a certain value,

the tensile forces and friction between the reinforced materials and solid particles improve the shear stress of the MBT waste.

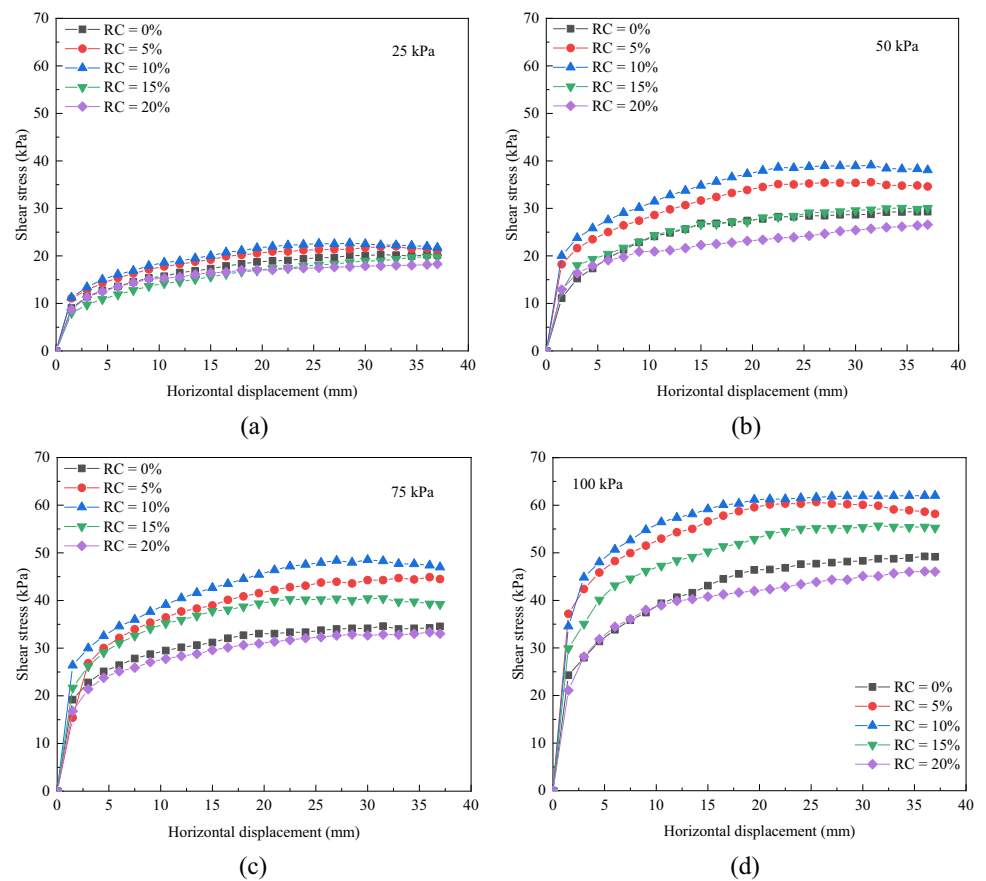
### Shear strength and vertical pressure

Taking the reinforcement scale of 15 mm as an example, the correlation between the shear strength and vertical pressure of MBT waste for different RCs is shown in Fig. 5. It is observed that the shear strength of the sample increases with the increase in the vertical pressure and the correlation can be fitted with a straight line, which conforms to the Coulomb strength theory.

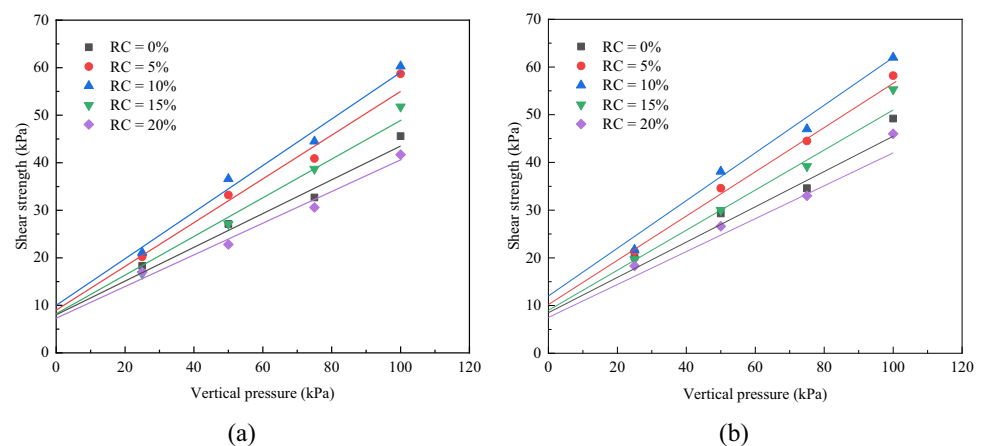
### Effect of the reinforcement content on the shear strength

Because the shear stress–shear displacement curve of MBT waste has no obvious peak value, the shear strength is determined as the shear stress at the ratio of the horizontal displacement to sample diameter is 10% or 20%. Fig. 6 shows the variation between shear strength and reinforcement content at a fixed reinforcement scale of 15 mm. When the ratio of the horizontal displacement to sample diameter increases from 10 to 20%, the shear strength increases. Fig. 6 also shows that the shear strength first increases and

**Fig. 4** Correlation between the shear stress and horizontal displacement of MBT waste for different reinforcement contents (reinforcement scale: 15 mm). The vertical pressure is **a** 25 kPa, **b** 50 kPa, **c** 75 kPa, and **d** 100 kPa (Note: RC represents the reinforcement content)

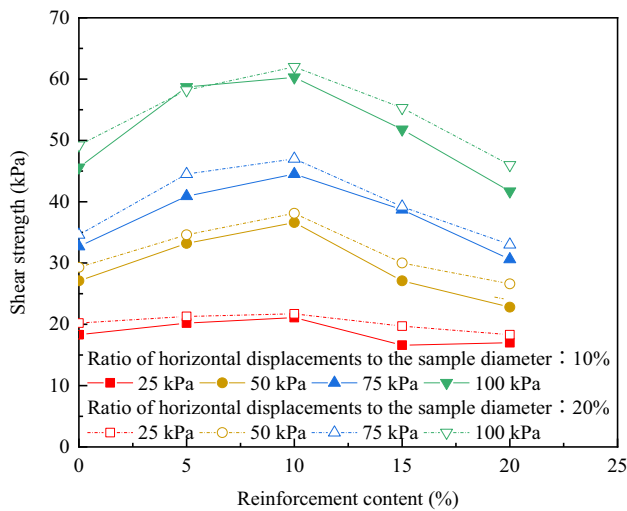


**Fig. 5** Shear strength envelope of MBT waste (reinforcement scale: 15 mm): **a** the ratio of the horizontal displacement to sample diameter is 10%; **b** the ratio of the horizontal displacement to sample diameter is 20%

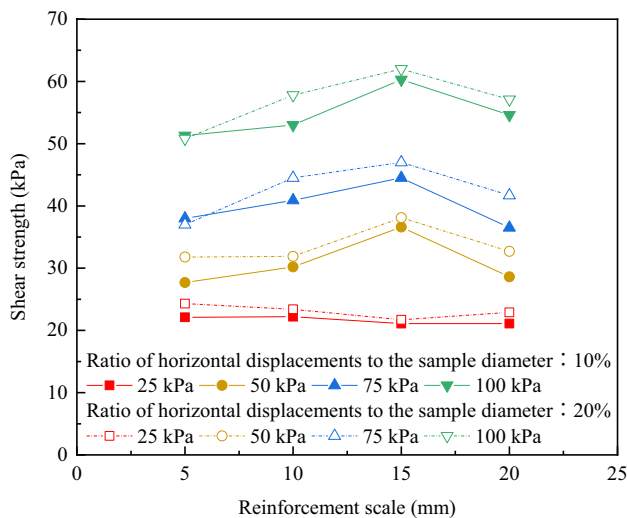


then decreases with increasing RC. When the RC reaches 10%, the shear strength is maximal at a given vertical pressure. Further, the shear strength is the minimum at an RC of 20%. When the RC is less than 10%, the reinforced materials and the solid particles are fully mixed and interact well to provide tensile forces during the shear process. When the reinforced material is in tension or shear in the soil, an equivalent confining pressure will act on the soil. With increasing RC, the tensile forces provided by the reinforced materials increases, and thus the shear strength increases.

Since the volume of solid particles is less than that of reinforced materials of the same mass and the initial mass of all samples placed into the shear box remains unchanged, when the RC exceeds 10%, a large amount of reinforced material will occupy the interior of the sample when the RC increases. This will lead to an excess of reinforced material in the sample and an increase in the void, which will affect the distribution uniformity of the reinforced materials and reduce the contact between the reinforced materials and solid particles. In contrast, there is an increased contact



**Fig. 6** Variation between the shear strength and reinforcement content of MBT waste (reinforcement scale: 15 mm)



**Fig. 7** Variation between the shear strength and reinforcement scale of MBT waste (reinforcement content: 10%)

among reinforced materials, which is conducive to creep. Therefore, the shear strength of the sample decreases; it is even lower than that of unreinforced MBT waste.

### Effect of the reinforcement scale on the shear strength

Fig. 7 shows the variation between the shear strength of MBT waste and the reinforcement scale at a fixed RC of 10%. It shows that the reinforcement scale insignificantly affects the shear strength at the vertical pressure of 25 kPa. When the vertical pressure is too small, the anchorage between the reinforced materials and solid particles is insufficient, and

thus the tensile forces between the reinforced materials and solid particles are weak. When the vertical pressure exceeds 25 kPa, the shear strength gradually increases with increasing reinforcement scale. When the reinforcement scale reaches 15 mm, the shear strength is maximal at a given vertical pressure. When the reinforcement scale exceeds 15 mm, the shear strength gradually decreases. Under large vertical pressure, large-scale reinforced materials strengthen the MBT waste. When the vertical pressure is large enough, the anchoring effect between the reinforced materials and solid particles is strong. The large-scale reinforced materials can be fully wound, interwoven, and bonded with solid particles to strengthen the interaction between the reinforced materials and solid particles. Therefore, the reinforced materials provide stronger and longer-lasting traction in the shear process, which improves the strain hardening level and the shear strength at a large displacement. During the preparation of MBT waste samples, the reinforced materials may change from flakes to rods, strips, and mass due to the stirring effect. The reinforced materials with a scale of 20 mm or larger are easier to wrap the solid particles with the materials, resulting in larger pores in the MBT waste and the smaller shear strength of the samples.

### Shear strength parameters

Table 3 shows the shear strength parameters  $c$  and  $\phi$  of MBT waste for different RC and reinforcement scales. When the ratio of the horizontal displacement to sample diameter is 10%, the cohesion  $c$  ranges from 0.3 kPa to 10.0 kPa, and the internal friction angle  $\phi$  varies from 14.0 to 26.6°. When the ratio of the horizontal displacement to sample diameter is 20%, the cohesion  $c$  ranges in 6.0–12.0 kPa, and the internal friction angle  $\phi$  varies in 15.6–26.6°.

### Correlation between the shear strength parameters and ratio of the shear displacement to specimen diameter

Fig. 8 shows the correlation between shear strength parameters and the ratio of the horizontal displacement to sample diameter at a fixed reinforcement scale of 15 mm. The shear strength parameter increases with increasing ratio of the horizontal displacement to sample diameter. The shear strength parameters first increase and then decrease with increasing RC.

Fig. 9 shows the correlation between the shear strength parameters and ratio of the shear displacement to sample diameter at a fixed RC of 10%. The shear strength parameter increases with increasing ratio of the shear displacement to specimen diameter. The shear strength parameters first increase and then decrease with the increase in the reinforcement scale.



**Table 3** Shear strength parameters

Reinforcement content (%)	Reinforcement scale (mm)	Ratio of the horizontal displacement to sample diameter of 10%		Ratio of horizontal displacement to sample diameter of 20%	
		$c$ (kPa)	$\varphi$ (°)	$c$ (kPa)	$\varphi$ (°)
0	0	8.0	19.5	8.5	20.3
5	5	7.2	18.3	8.0	19.8
5	10	8.0	22.3	9.0	22.8
5	15	9.1	24.7	10.2	25.1
5	20	7.3	19.8	9.0	21.3
10	5	8.0	18.8	10.0	19.8
10	10	9.0	21.8	11.1	23.3
10	15	10.0	26.6	12.0	26.6
10	20	8.1	19.8	10.7	22.4
15	5	4.7	17.7	6.0	18.8
15	10	5.4	21.3	6.3	24.7
15	15	8.2	22.2	9.0	22.8
15	20	5.1	18.8	6.2	20.8
20	5	0.3	14.0	6.9	15.6
20	10	5.1	18.8	6.6	19.3
20	15	7.3	18.5	7.5	19.0
20	20	5.4	17.9	6.4	18.8

These trends of the shear strength parameters are consistent with those reported by Fucale et al. (2015). The change of the shear strength parameters can be explained as follows: the larger RC means more reinforced materials in the sample, which results in more traction can be provided in the shear process, and thus the shear strength parameters improve. However, when the RC is too high, the contact among reinforced materials in the sample increases, and the friction decreases. Therefore, the shear strength parameters of the sample decrease.

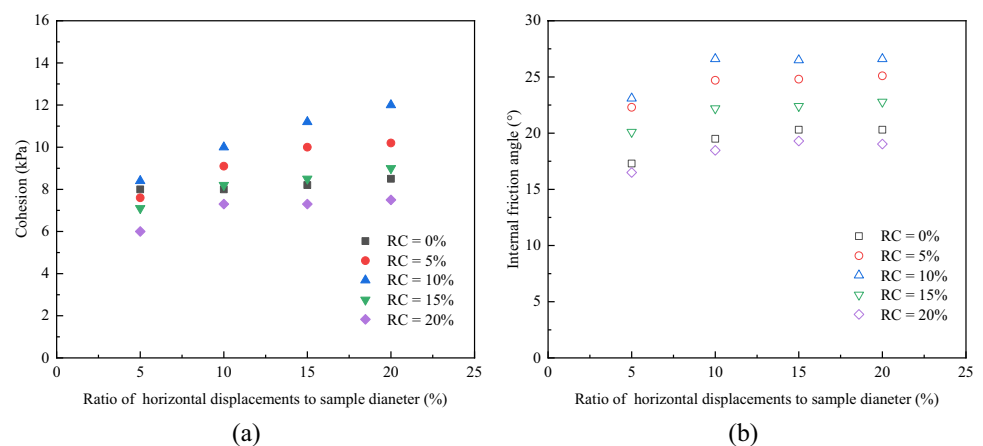
### Correlations between shear strength parameters and the reinforcement content and scale

Figure 10a shows the correlations among the cohesion  $c$  of MBT waste and RC and reinforcement scale for a fixed ratio of the shear displacement to sample diameter of 20%. The correlations among the internal friction angle  $\varphi$  of MBT waste and the RC and reinforcement scale are shown in Fig. 10b. The results show that the cohesion  $c$  and internal friction angle  $\varphi$  are the largest when the reinforcement scale is 15 mm at a given RC. When the RC is 10% at a given reinforcement scale, the cohesion  $c$  and internal friction angle  $\varphi$  of MBT waste are the largest. When the RC is 10% and the reinforcement scale is 15 mm, the cohesion  $c$  and internal friction angle  $\varphi$  of MBT waste are maximal, that is, 12.0 kPa and 26.6°, respectively.

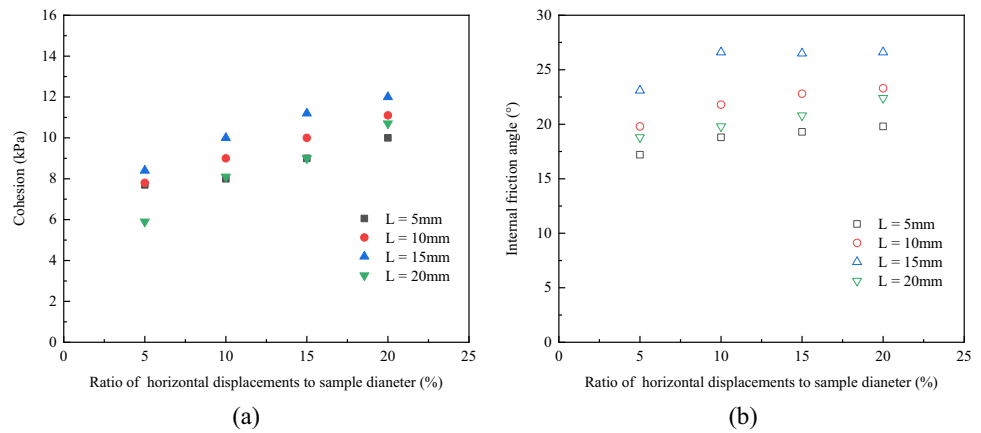
### Discussion

To study the shear strength behaviour of MBT waste, the shear strength of MBT waste in this study was compared with that reported in previous studies (Fig. 11). Based on Fucale et al. (2015), the shear strength envelope at a RC of 10%, 0%, and 20% is at the top, bottom, and in the middle, respectively (Fig. 11). This shows that the effect of the RC on the shear strength is limited. Based on the results of the present study, the shear strength envelope at a RC of 20% and 10% is at the bottom and top, respectively. At a RC of 0%, 5%, and 15%, the shear strength envelope is in the middle, which also indicates a limit of the effect of the RC on the shear strength. The results of the present study are similar to those of Fucale et al. (2015). Fig. 11 also shows that the shear strength envelope in this study is close to that reported by Pimolthai and Wagner (2014). The variation of the shear strength of MBT waste depending on the RC can be explained as follows. In the absence of reinforced materials, the shear strength of MBT waste is mainly provided

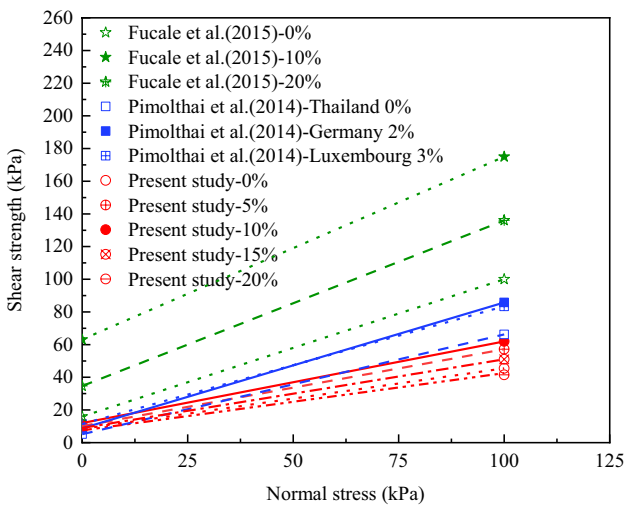
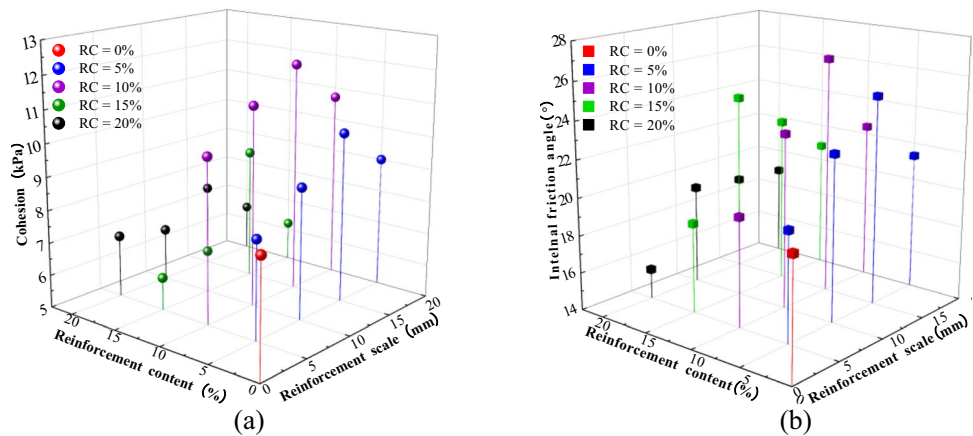
**Fig. 8** Correlation between the shear strength parameters of MBT waste and the ratio of the horizontal displacement to sample diameter (reinforcement scale: 15 mm): **a** cohesion and **b** internal friction angle



**Fig. 9** Correlation between the shear strength parameters of MBT waste and the ratio of the horizontal displacement to sample diameter (reinforcement content: 10%): **a** cohesion and **b** internal friction angle (Note: L represents the reinforcement length)



**Fig. 10** Correlations between the shear strength parameters and reinforcement content and reinforcement scale: **a** cohesion and **b** internal friction angle



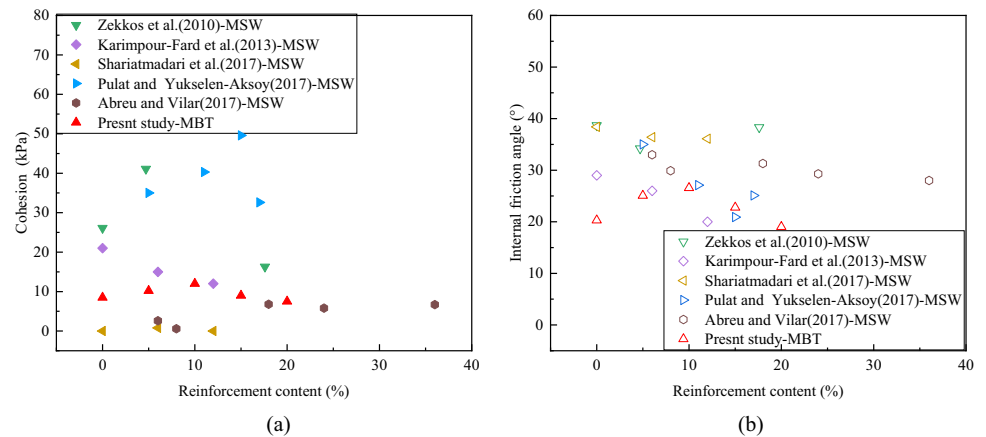
**Fig. 11** Comparison of the shear strength envelopes between the present study and previous work

by the friction between solid particles. When the RC is low, the shear strength of MBT waste is controlled by the friction between solid particles as well as the force of reinforced

materials. With the increase in the RC, the force of reinforced materials increases, and the shear strength of MBT waste increases. When the RC is too high, the interactions among reinforced materials increase, and the tensile forces between solid particles and reinforced materials weaken, resulting in the reduction of the shear strength of MBT waste. Considering the types of reinforced materials, Fucale et al. (2015) included plastics, textiles, threads, filaments, and branches (all components' size < 40 mm); Pimolthai and Wagner (2014) used light plastics (size < 10 mm); and plastics and textiles were used in this study. Different reinforcement materials have different reinforcement effects, leading to different shear strengths of MBT waste.

The comparison between the shear strength parameters of MBT waste and relevant reinforced MSW is shown in Fig. 12. The shear strength parameters  $c$  and  $\phi$  of MBT waste and MSW depend on the RC. With the increase in the RC, the shear strength parameters of MBT waste first increase and then decrease (Fucale et al. 2015, present study). It can also be seen that the cohesion  $c$  of MSW first increases and then decreases with the increase in the RC (Zekkos et al. 2010; Shariatmadari et al. 2017; Pulat and Yukselen-Aksoy 2017) and the internal friction angle  $\phi$  of

**Fig. 12** Comparison of the shear strength parameters between the present study and previous work: **a** cohesion and **b** internal friction angle



MSW decreases (Karimpour-Fard et al. 2013; Pulat and Yukselen-Aksoy 2017). Karimpour-Fard et al. (2013) analysed the differences between the changes of the MSW shear strength parameters and increase in the RC. In direct shear tests, the directions of the shearing plane and fibrous particles, which tend to align themselves in the horizontal direction, are the same. When the RC increases, the interaction between solid particles and reinforced materials weakens, and the contact among reinforced materials increases. Therefore, the presence of several sliding planes due to horizontally oriented plastic fractions could affect the shear strength of the samples. Pulat and Yukselen-Aksoy (2017) reported that the shear strength parameters  $c$  and  $\phi$  increased after the plastics (12%) were removed from MSW U-1 (USA). This can also be explained by interactions between solid particles, between reinforced materials and solid particles, and among reinforced materials.

The cohesion  $c$  of MSW ranges from 0 to 49.6 kPa and  $\phi$  varies from between 20 and 38.7°. The cohesion  $c$  of MBT waste ranges from 5.4 to 63.1 kPa, and the internal friction angle  $\phi$  varies between 19.0 and 48.1°. The main reasons for the differences in  $c$  and  $\phi$  between MBT waste and MSW are the high content of organic matter, high moisture content, uneven composition, and strong anisotropy of MSW. After the MSW is mechanically sorted and biologically treated, its composition, moisture content, and density change and the particle sizes of its constituents become relatively uniform.

## Conclusion

In this paper, five reinforcement contents (0%, 5%, 10%, 15%, 20%) and four reinforcement scales (5, 10, 15, 20 mm) were considered, and the shear strength characteristics and variation of MBT waste were obtained using a direct shear test apparatus. The results show that (1) with the increase in the shear displacement, the shear

stress of MBT waste gradually increases, a peak value cannot be observed, representing displacement hardening; (2) the shear strength of MBT waste depends on the content of reinforced materials. With the increase in the RC, the shear strength of MBT waste first increases and then decreases. The optimal RC is 10%; (3) the shear strength of MBT waste depends on the scale of the reinforced materials. With the increase in the reinforcement scale, the shear strength of MBT waste first increases and then decreases. The optimal reinforcement scale is 15 mm; (4) the ranges of the shear strength parameters of MBT waste were determined. When the ratio of the shear displacement to the sample diameter is 10%,  $c$  ranges from 0.3 to 10.0 kPa, and  $\phi$  varies from 14.0 to 26.6°. When the ratio of the shear displacement to the sample diameter is 20%, the range of  $c$  is 6.0–12.0 kPa, and that of  $\phi$  is 15.6–26.6°; (5) the shear strength parameters of MBT waste depend on the RC and reinforced scale. The optimal RC is 10%, and the optimal scale of the reinforced materials is 15 mm; and (6) the shear strength parameters of MBT waste, reinforced MBT waste, and reinforced MSW were compared and discussed.

**Acknowledgements** We thank the Hangzhou Environmental Group for their assistance.

**Author contribution** BW conducted the direct shear test on Hangzhou Tianziling MBT waste and analysed and interpreted the effects of the RC and reinforcement scale on the shear strength of MBT waste. HX, MH, CN, and TL conducted the direct shear test on Hangzhou Tianziling MBT waste; ZZ analysed the test data and reviewed and revised the manuscript. All authors read and approved the final manuscript.

**Funding** This research was funded by the National Natural Science Foundation of China (Grant numbers 51978625 and 51678532) and Zhejiang Provincial Natural Science Foundation of China (Grant number LZ21E080003).

**Data availability** The datasets used and analysed in the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

## References

- Abreu AES, Vilar OM (2017) Influence of composition and degradation on the shear strength of municipal solid waste. *Waste Manag* 68(10):263–274. <https://doi.org/10.1016/j.wasman.2017.05.038>
- Babu GLS, Lakshmikanthan P, Santhosh LG (2015) Shear strength characteristics of mechanically biologically treated municipal solid waste (MBT-MSW) from Bangalore. *Waste Manag* 39(5):63–70. <https://doi.org/10.1016/j.wasman.2015.02.013>
- Bareither CA, Benson CH, Edil TB (2012) Effects of waste composition and decomposition on the shear strength of municipal solid waste. *J Geo-Tech Geoenviron Eng* 138(10):1161–1174. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000702](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000702)
- Bhandari AR, Powrie W (2013) Behavior of an MBT waste in monotonic triaxial shear tests. *Waste Manag* 33(4):881–891. <https://doi.org/10.1016/j.wasman.2012.11.009>
- Blight G (2008) Slope failures in municipal solid waste dumps and landfill—a review. *Waste Manage Res* 26(5):448–463. <https://doi.org/10.1177/0734242X07087975>
- Bray JD, Zekkos D, Kavazanjian E, Athanasopoulos GA, Riemer MF (2009) Shear strength of municipal solid waste. *Int Symp Waste Mechan* 135(6):709–722. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000063](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000063)
- Caicedo B, Giraldo E, Yamin L, Soler N (2002) The landslide of Dona Juana landfill in Bogota: a case study. In: *Proc 4th Int Congress Environ Geotech Brazil* 1:171–175
- Caicedo B, Yamin L, Giraldo E, Coronado O (2002) Geomechanical properties of municipal solid waste in Dona Juana sanitary landfill. *Proc 4th Int Congress Environ Geotech Brazil* 1:177–182
- Chaudhary R, Nain P, Kumar A (2021) Temporal variation of leachate pollution index of Indian landfill sites and associated human health risk. *Environ Sci Pollut Res* 28:28391–28406. <https://doi.org/10.1007/s11356-021-12383-1>
- Eid H, Stark T, Evans W, Sherry P (2000) Municipal solid waste slope failure. I: Waste and foundation soil properties. *J Geotech Geoenviron Eng* 126(5):397–407. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2000\)126:5\(397\)](https://doi.org/10.1061/(ASCE)1090-0241(2000)126:5(397))
- Eskandari M, Homae M, Falamaki A (2016) Landfill site selection for municipal solid wastes in mountainous areas with landslide susceptibility. *Environ Sci Pollut Res* 23(12):12423–12434. <https://doi.org/10.1007/s11356-016-6459-x>
- Falamaki A, Eskandari M, Homae M, Gerashi M (2018) An improved multilayer compacted clay liner by adding bentonite and phosphate compound to sandy soil. *KSCE J Civ Eng* 22(10):3852–3859. <https://doi.org/10.1007/s12205-018-1554-9>
- Falamaki A, Ghareh S, Homae M, HamtaeipourShirazifard A, Abedpour S, Kiani S, Mousavi N, Rezaei M, Motlagh MT, Nouri A (2019) Laboratory shear strength measurements of municipal solid waste at room and simulated in situ landfill temperature, Barmshoor Landfill. *Iran Int J Civil Eng* 18(2):185–197. <https://doi.org/10.1007/s40999-019-00446-x>
- Fei XH, Zekkos D (2017) Comparison of direct shear and simple shear responses of municipal solid waste in USA. *J Environ Geotech* 5(3):158–167. [https://www.researchgate.net/publication/320661378\\_Comparison\\_of\\_direct\\_shear\\_and\\_simple\\_shear\\_responses\\_of\\_municipal\\_solid\\_waste\\_in\\_USA](https://www.researchgate.net/publication/320661378_Comparison_of_direct_shear_and_simple_shear_responses_of_municipal_solid_waste_in_USA). Accessed 1 June 2021
- Fernando S, Powrie W, Wastson G, Richards DJ (2009) The impact of the reinforce content on the shear strength of mechanically biologically treated waste. In: *Third International Workshop “Hydro-Physico-Mechanics of Landfills”* 3:10–13. [https://www.researchgate.net/publication/268176078\\_THE\\_IMPACT\\_OF\\_THE\\_REINFORCING\\_CONTENT\\_ON\\_THE\\_SHEAR\\_STRENGTH\\_OF\\_MECHANICALLY\\_BIOLOGICALLY\\_TREATED\\_WASTE](https://www.researchgate.net/publication/268176078_THE_IMPACT_OF_THE_REINFORCING_CONTENT_ON_THE_SHEAR_STRENGTH_OF_MECHANICALLY_BIOLOGICALLY_TREATED_WASTE). Accessed 30 May 2021
- Fucale SP (2005) Influência dos componentes de reforço na resistência de resíduos sólidos urbanos. Dissertation, Federal University of Pernambuco, Brazil. <http://livros01.livrosgratis.com.br/cp028574.pdf>. Accessed 17 June 2021
- Fucale S, Juca JFT, Muennich K (2015) The mechanical behavior of MBT waste. *Electron J Geotech Eng* 20(13):5927–5931. [https://www.researchgate.net/profile/Jose-Fernando-Juca/publication/286124763\\_The\\_mechanical\\_behavior\\_of\\_MBT-waste/links/57d411af08ae5f03b4915b6d/The-mechanical-behavior-of-MBTwaste.pdf](https://www.researchgate.net/profile/Jose-Fernando-Juca/publication/286124763_The_mechanical_behavior_of_MBT-waste/links/57d411af08ae5f03b4915b6d/The-mechanical-behavior-of-MBTwaste.pdf). Accessed 18 June 2021
- Jones D, Dixon N (2015) Landfill lining stability and integrity: the role of waste settlement. *Geotext Geomembr* 23(1):27–53. <https://doi.org/10.1016/j.geotextmem.2004.08.001>
- Karimpour-Fard M (2009) Mechanical behavior of MSW materials with different initial state under static loading. Dissertation, Iran University of Science and Technology (In Persian)
- Karimpour-Fard M (2018) Rehabilitation of Saravan dumpsite in Rasht, Iran: geotechnical characterization of municipal solid waste. *Int J Environ Sci Technol* 16(8):4419–4436. <https://doi.org/10.1007/s13762-018-1847-z>
- Karimpour-Fard M, Machado SL, Shariatmadari N, Noorzad A (2011) A laboratory study on the MSW mechanical behavior in triaxial apparatus. *Waste Manag* 31(8):1807–1819. <https://doi.org/10.1016/j.wasman.2011.03.011>
- Karimpour-Fard M, Shariatmadari N, Keramati M, Jafari Kalarijani H (2013) An experimental investigation on the mechanical behavior of MSW. *Int J Civ Eng* 12(4):292–303. <http://www.iust.ac.ir/ijce/article-1-918-en.pdf>. Accessed 10 June 2021
- Kavazanjian E (1999) Seismic design of solid waste containment facilities. In: *Proceedings of the 8th Canadian conference on earthquake engineering*, Vancouver, BC, 51–89
- Kavazanjian N, Matascovic R, Bonaparte GR, Schmertmazin E (1995) Evaluation of evaluation of MSW properties for seismic analysis. *Geoenviron*. 2000, *Geotech. Special Publ. ASCE*.46,1126–1141. [https://www.researchgate.net/profile/Neven-Matasovic/publication/279854270\\_Evaluation\\_of\\_MSW\\_Properties\\_for\\_Seismic\\_Analysis/links/559c61f908ae898ed651efc6/Evaluation-of-MSW-Properties-for-Seismic-Analysis.pdf](https://www.researchgate.net/profile/Neven-Matasovic/publication/279854270_Evaluation_of_MSW_Properties_for_Seismic_Analysis/links/559c61f908ae898ed651efc6/Evaluation-of-MSW-Properties-for-Seismic-Analysis.pdf). Accessed 20 May 2021
- Keramati M, Shahedifar M, Aminfar MH, Alagipour H (2020) Evaluation the shear strength behavior of aged MSW using large scale in situ direct shear test, a case of Tabriz Landfill. *Int J Civil Eng* 18(2):717–733. <https://doi.org/10.1007/s40999-020-00499-3>
- Kölsch F (1993) The bearing behaviour of domestic waste and related consequences for stability. *CISA (Hrsg.): Proc 4th Int Landfill Symp Cagliari (Italy)* 2:1393–1410
- Kölsch F (1995) Material values for some mechanical properties of domestic waste. *CISA (Hrsg.): Proc 5th Int Landfill Symp Cagliari (Italy)* 2:711–729
- Landva A, Clark J (1986) Geotechnical testing of waste fill. In: *Proceedings of the 39th Canadian geotechnical conference Ottawa, Ontario*, 371–385. <https://www.researchgate.net/publication/291858826>
- Landva AO, Clark JI (1990) Geotechnics of waste fill. In: *Landva A, Knowles D (eds) Geotechnics of waste fill: theory and practice*. STP No. 1070. ASTM, Philadelphia, PA, pp 86–103.

- [https://www.astm.org/DIGITAL\\_LIBRARY/STP/SOURCE\\_PAGES/STP1070\\_foreword.pdf](https://www.astm.org/DIGITAL_LIBRARY/STP/SOURCE_PAGES/STP1070_foreword.pdf). Accessed 18 May 2021
- Machado SL, Carvalho MF, Vilar OM (2002) Constitutive model for municipal solid waste. *J Geo-Tech Geoenviron Eng* 128(11):940–951. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2002\)128:11\(940\)](https://doi.org/10.1061/(ASCE)1090-0241(2002)128:11(940))
- Machado SL, Vilar OM, Carvalho MF (2008) Constitutive model for long term municipal solid waste mechanical behavior. *Comput Geotech* 35(5):775–790. <https://doi.org/10.1016/j.compgeo.2007.11.008>
- Machado SL, Karimpour-Fard M, Shariatmadari N, Carvalho FM, Nascimento JCF (2010) Evaluation of the geotechnical properties of MSW in two Brazilian landfills. *Waste Manag* 30(12):2579–2591. <https://doi.org/10.1016/j.wasman.2010.07.019>
- Mahler CF, Neto ADL (2006) Effect of fiber on shear strength of residue from mechanical biological pretreatment of waste. *Int J Environ Waste Manag* 1(1):85–93. <https://doi.org/10.1504/ijewm.2006.011133>
- Pimolthai P, Wagner JF (2014) Soil mechanical properties of MBT waste from Luxembourg, Germany and Thailand. *Songklanakarin J Sci Technol* 36(6):701–709. <https://www.thaiscience.info/Journals/Article/SONG/10968362.pdf>. Accessed 17 June 2021
- Pulat HF, Yukselen-Aksoy Y (2017) Factors affecting the shear strength behavior of municipal solid wastes. *Waste Manag*:215–224. <https://doi.org/10.1016/j.wasman.2017.08.030>
- Ramaiah BJ, Ramana GV, Datta M (2017) Mechanical characterization of municipal solid waste from two waste dumps at Delhi. *India Waste Manag* 68(10):275–291. <https://doi.org/10.1016/j.wasman.2017.05.055>
- Reddy KR, Hettiarachchi H, Parakalla NS, Gangathulasi J, Bogner JE (2009) Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA. *Waste Manag* 29(2):952–959. <https://doi.org/10.1016/j.wasman.2008.05.011>
- Reddy KR, Basha BM (2014) Slope stability of waste dumps and landfills: state-of-the-art and future challenges. In: *Proc. of Indian Geotechnical Conference (IGC-2014)*, pp. 2311–2337. <https://doi.org/10.13140/2.1.4186.5283>
- Shariatmadari N, Machado SL, Noorzad A, Karimpour-Fard M (2009) Municipal solid waste effective stress analysis. *Waste Manag* 29(12):2918–2930. <https://doi.org/10.1016/j.wasman.2009.07.009>
- Shariatmadari N, Sadeghpour AH, Razaghian F (2014) Effects of aging on shear strength behavior of municipal solid waste. *Int J Civ Eng* 12(3 and B):226–237
- Shariatmadari N, Karimpour-Fard M, Keramati M, Kolarijani HJ, Naebi A (2011) Fiber content impact on the shear strength of MSW materials in direct shear tests. *Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium*. <https://www.researchgate.net/publication/272162570>, <https://doi.org/10.13140/2.1.5061.7125>
- Shariatmadari N, Asadi M, Karimpour-Fard M (2017) Investigation of fiber effect on the mechanical behavior of municipal solid waste by different shearing test apparatuses. *Int J Environ Sci Technol*. <http://link.springer.com/content/pdf/https://doi.org/10.1007/s13762-017-1297-z.pdf>. Accessed 10 June 2021
- Singh S, Murphy B (1990) Evaluation of the stability of sanitary landfills. *Geotech. Waste Fills – Theory Pract. ASTM STP 1070*:240–258. <https://doi.org/10.1520/STP25310S>
- Stark TD, Sarihan NH, Li G (2009) Shear strength of municipal solid waste for stability analyses. *Environ Geol* 57(8):1911–1923. <https://doi.org/10.1007/s00254-008-1480-0>
- Zekkos D, Fei XH (2016) Constant load and constant volume response of municipal solid waste in simple shear. *Waste Manag* 63(5):380–392. <https://doi.org/10.1016/j.wasman.2016.09.029>
- Zekkos D, Athanasopoulos GA, Bray JD, Grizi A, Theodoratos A (2010) Large-scale direct shear testing of municipal solid waste. *Waste Manag* 30(8–9):1544–1555. <https://doi.org/10.1016/j.wasman.2010.01.024>
- Zhang Y (2018) Research on municipal solid waste output forecast and MBT volume reduction technology, Dissertation. Zhejiang Sci-tech University. [https://link.springer.com/chapter/10.1007/978-981-13-0128-5\\_46](https://link.springer.com/chapter/10.1007/978-981-13-0128-5_46) (in Chinese)
- Zhang ZY, Zhang JH, Wang QN, Wang M (2021) Nie CY (2021) Research on direct shear strength characteristics of mechanically biologically treated waste. *Environ Sci Pollut Res* 28(112):59844–59857. <https://doi.org/10.1007/s11356-021-14935-x>
- Zhang ZY, Zhang YX, Wang YF, Xu H, Guo WQ, Wu DZ, Fang YH (2018a) Physical and mechanical characteristics of MBT Waste in China. In: Farid A., Chen H. (eds) *Proceedings of GeoShanghai 2018 International Conference: Geoenvironment and Geohazard*. GSIC 2018. Springer, Singapore. [https://doi.org/10.1007/978-981-13-0128-5\\_46](https://doi.org/10.1007/978-981-13-0128-5_46)

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.