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RESEARCH PAPER

Evaluation the Shear Strength Behavior of aged MSW using Large Scale In Situ Direct Shear Test, a case of Tabriz Landfill

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Abstract

The current study presents the physical and mechanical properties of municipal solid waste (MSW) with different ages of new and old Tabriz landfill. Although there are several theoretical and laboratory methods to investigate the shear strength parameters of MSW, field methods provide more accurate results due to the minimum MSW disturbance and changes, so in this study the shear strength parameters of MSW Tabriz landfill were evaluated using the "Large Scale in Situ Direct Shear Device" with the cross-sectional dimensions 122 × 122 cm. In spite of difficulties related to conducting tests such as potential exposure to various contaminations and the lack of specific equipment in the beginning, it provided more realistic results of the geotechnical behavior of municipal solid waste compared to other methods. Moreover, the in situ unit weight, physical analysis, moisture and organic content at different ages were evaluated to better understand the mechanical response with increase in the age of MSW. The results showed the cohesion and friction angle of 5- and 16-year-old MSW was estimated as 1.17, 2.215 kPa and 31.51°, 21.51°, respectively; According to the results, the shear strength of 5- and 16-year-old MSW is mainly controlled by the friction angle which seems due to the MSW composition as a function of the consumption pattern. The physical analysis of fresh MSW from 2005 to 2017 showed an increase in the fiber content including plastics and textiles. Moreover, studies on MSW mechanical responses over the time revealed a decrease in the shear strength because of the raise in the fiber and plastic content.

Keywords Shear strength · Municipal solid waste · Landfill · Mechanical response · Aging

1 Introduction

Rapid urbanization has led to an enormous increase in the production of municipal solid wastes (MSW) in many large cities. On the other hand, the occurrence of several landslides all over the world has caused devastating environmental, economical, and financial problems in sites like the United States Rumpke Waste Management (1996), Dona Juanna, Colombia (1997) [1], Payatas, Philippines (2000), Leuwigajah, Indonesia (2005) [2], and Barmshoor, Shiraz, Iran (2013) [3].

It should be ensured that some factors such as stability and integrity of waste mass and waste containment system are provided during and after the operation of landfills. Therefore, designing, constructing, and safe utilization of such structures need a thorough understanding of the geotechnical behavior of the MSW. However, appropriate data about the mechanical properties of MSW as prerequisites of such studies were not available for many landfills

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such as Tabriz landfill (TL). It is important to note that local measurement should always be carried out to examine these properties because they are highly dependent on the physical and mechanical characteristics of the MSW, which depend on the consumption pattern of the community. According to the above, the present study was conducted to examine the physical and mechanical properties of MSW in the Tabriz landfill, Iran.

1.1 Shear Strength Parameters

Several researches have investigated the effects of various factors such as density, composition, age and degradation, loading rate, limiting stress, and moisture on the strength and stiffness of MSW materials. The mechanical response of MSW is significantly influenced by fibrous materials such as plastics, paper, fabric and wood [4], and the presence of the fiber content leads to the non-isotropic behavior of MSW [5]. In addition, the shear strength of MSW depends on the direction of fiber elements and the device used for testing [6].

In this regard, Richardson et al. [7] used a shear box (122 × 122 cm) to conduct the large-scale in situ direct shear test on the MSW of Central Mine Landfill.

Houston et al. [8] studied the mobilized shear strength of an MSW sample at a 2.5 cm displacement, using a 120 × 120 cm in situ direct shear device. They increased the normal stress and carried out the test when the variation of shear stress was close to zero. Then the tests were repeated at three different normal stresses and 33°–35° was reported as the friction angle and approximately 5 kPa for cohesion.

Witiam et al. [9] used a direct shearing device (150 × 150 × 150 cm) on MSW materials including glass, paper, ash, plastics, and metal. Using a step loading technique, they performed five experiments at three different normal stresses ranging from 0 to 21 kPa. The shear strength parameters were reported as cohesion of 10 kPa and internal friction angle of 30°.

Mazzucato et al. [10] conducted an experiment using 80-cm-diameter cylindrical direct shearing device. In this study, a displacement of 2.5 cm was the criteria for determining the samples' shear strength and cohesion of 43 kPa and friction angle of 31° was reported.

Thomas et al. [11] conducted a direct shearing test using a mobilized shear strength of MSW at a 2.5 cm displacement by a 100 × 100 cm in situ direct shear device. They reported cohesion and friction angle as 23.4 kPa and 29.6°, respectively. They also showed that the waste shear strength decreased by increasing the plastic percentage. According to the findings, through the decomposition process, the percentage of paper decreases which results in increasing the percentage of plastic. Hence, the decomposition process decreases the MSW shear strength.

Using the direct laboratory shearing device (30 × 45 cm), Pelkey et al. [12] reported cohesion and friction angle as zero and 26°–29°, respectively.

Caicedo et al. [1] conducted an experiment on fresh waste containing 48% organic materials, 45% paper, fabric and plastic, and 7% soil, metal and glass with unit weight of 10 kN/m^3. They utilized a direct in situ shearing device with 90 cm diameter. The cohesion and friction angle were 67 kPa and 23°, respectively.

Ali et al. [13] studied Pakistan municipal solid waste using a direct in situ shearing device (122 × 122 cm), with normal stresses of 6, 13 and 20 kPa using concrete blocks, at relative displacements of 2%, 3% and 4% strains. The samples were sheared stepwise to avoid the construction of new samples and to eliminate the effect of differences among samples. They called it "staged direct shear test" and found that the values of cohesion and friction angle wee 6.63 kPa and 25.077°, respectively.

Using a direct in situ shear device (30 × 50 cm), Miyamoto et al. [14] sheared each sample at a constant normal stress with 40 mm horizontal displacement, in two sites A and B in Japan and Laogang in China. The MSW physical analysis was also examined. Regarding the relationship between shear strength and fibrous elements, the researchers realized that as the percentage of fibrous elements increases, the shear strength is controlled by cohesion instead of internal friction. They demonstrated that the response and shear strength of different MSW can be evaluated, to some extent, by focusing on fiber components.

Falamaki et al. [3] studied the shear strength parameters of MSW materials of Barmshoor Landfill in Shiraz. They used a large direct shear test device (30 × 30 × 16.5 cm) and evaluated the variation of cohesion and friction angle of MSW with the temperature increase.

1.2 Effect of Aging

Age has a significant impact on the shear strength parameters of MSW; however, other factors such as composition, climate of the area, moisture content, landfill process procedures, permeability and daily cover can also significantly affect MSW degradation [15].

On the other hand, sometimes contradictory statements were reported about the effect of aging on shear strength parameters. For example, Landva and Clark [16] reported a decrease in both cohesion and friction angle as a result of decomposition over time, but Oweiss [17] reported an increase in shear strength with aging and density. According to Oweiss, the degradation of waste can also have a reverse effect by destroying and eliminating the reinforcement effect of fibers. Kavazanjian [18] noted that the drained shear strength of decomposed waste is similar to that of fresh waste. Caicedo et al. [1] observed a decrease in the friction angle and a slight change in cohesion, with aging of MSW.

Hossain [19] stated that degradation leads to an increase in the fiber content, and this leads to a decrease in the shear strength. Kolsch and Ziehmann [15] also noted that degraded MSW is weaker than fresh waste, although this trend has not been observed in all laboratory data. Machado et al. [20] indicated that shear strength increased with aging. Nascimento [21] noted that aging increased the density and, as a result, the shear strength of the MSW was increased.

Bareither et al. [22] reported an increase in the friction angle with degradation and noted no clear relationship between cohesion and degradation. Gomes et al. [23] reported an increase in the friction angle and a decrease in cohesion with aging of MSW. On the other hand, several researchers measured a decrease in the friction angle and an increase in cohesion with aging and degradation [24, 25]. Shariatmadari et al. [26] reported a reduction in the shear strength with increase in the fiber content. Moreover, they stated that non-isotropic strength and shearing mechanism play a crucial role in the MSW mechanical responses. Sadeghpour [27] stated that aging up to 5.5 years increases the shear strength, while it declines after that.

Some research was carried out on aging and its effect on various parameters including dynamic parameters and consolidation by Zekkos [28], Adil Haque [29], Ramaiah et al. [30] and Keramati et al. [31].

To determine the shear strength parameters, different techniques like the back analysis of failed or stable slopes, laboratory tests (direct shearing, simple and triangular shearing) and field tests such as direct shear and plate load can be utilized. It is impossible to obtain undisturbed samples due to the size of the particles and the nature of the MSW materials in laboratory studies, and the physical components of MSW can be changed during sample preparation for laboratory tests. In the current study, the large-scale in situ direct shear test was performed to improve the reliability of the results. Additionally, after literature review, variables such as waste composition and unit weight were also studied to obtain an appropriate understanding of the MSW mechanical responses in different conditions.

2 Materials and Method

In this study, the physical analysis, moisture content, organic content and in situ unit weight of MSW were investigated in Tabriz landfills for fresh, 5-year-old and 16-year-old MSW. Furthermore, the shear strength parameters of MSW were studied using a large-scale direct in situ shear test.

2.1 Tabriz Landfill Characterization

Tabriz is the largest city in the northwest of Iran with a population of about 1.5 million. At least 1100 tons of MSW is produced every day and transported to the Tabriz landfill (TL). Some of it is recovered and the majority is buried [32]. The landfill has two sections; an old one and a new one. The new sanitary section was built according to global standards. The coordinates of old and new TL are shown in Table 1. The 21-year-old landfill is located 20 km away from Tabriz International Airport and the new one is located near the old TL site. The location of TL in the city as well as the position of both old and new landfills is shown in Fig. 1, and in Fig. 2 a view of the old and new Tabriz landfills are presented.

2.1.1 Physical Properties of MSW

The physical properties of landfills play a fundamental role in the mechanical response of MSW. Parameters such as in situ unit weight, moisture and organic content of MSW in the TL investigated in this study are described as follows.

The MSW physical properties is affected by the consumption pattern, population and its economic activities. Increase in the age of landfills could change the components and proportions of the MSW considerably. This study investigated the physical properties of fresh, 5- and 16-year-old MSW of TL according to the proposed method by Tchobanoglous [33].

The process of mixing and separating and analyzing the MSW samples is illustrated in Fig. 3. The changes in physical composition of 5- and 16-year-old MSW with time are shown in Fig. 4.

The unit weight of MSW is one of the most important parameters for any engineering analysis on the landfill. The MSW unit weight is similar to that of the soil materials and is influenced by density, layer thickness, depth of landfill (e.g., overhead stress) and moisture content. However, the MSW unit weight is significantly different from the soil, due to a wide variety of MSW compositions (such as size

Table 1 Location of old and new TL

Landfills	Longitude	Latitude
Old	46° 15′28.0″ E	38° 11′27.1″ N
New	46° 15′51.3″ E	38° 11′55.9″ N

Fig. 1 Location of old and new TL

Fig. 2 A view of old (left) and new (right) pictures of the Tabriz landfill

Fig. 3 The process of mixing, separating and analyzing the MSW sample

and density), degradation and factors such as the thickness of the daily cover or its absence [34].

The low compaction effort of MSW has reasonably led to minimum unit weight in TL. Therefore, a test pit with dimensions of about 1 m × 1 m × 1 m was excavated and the volume of the ditch was determined by water replacement according to previous studies on various landfills [6].

In this study, the moisture and organic content of fresh and 5- and 16-year-old MSW in TL were investigated based on the proposed method by Zekkos [28]. For this purpose, samples were placed in separate ovens at a temperature of 55 °C until the difference between two consecutive readings was less than 1% for 12 h. Eventually,

Fig. 4 The appearance of 5-year-old (right) and 16-year-old (left) MSW

the moisture content was determined using the following relation:

$$W = (M_w/M_d) \times 100,$$

where M_d is the dry weight of the MSW and M_w is the water content removed at 55 °C in the oven.

Subsequently, the samples were heated to 105 °C. The sample's weight loss was negligible with the temperature increase from 55 to 105 °C. When samples' weight was stabilized in the oven, the MSW was prepared for the analysis of organic content according to the ASTM D2974 method [35]. The temperature of the samples increased to 440 °C in a muffle furnace and was kept constant until the samples reached a constant weight at this temperature. Finally, the organic content was determined according to the weight loss and the weight of the residue in the furnace.

2.2 Direct Shear Test, Specimen Preparation and Testing Program

The purpose of the present study was to investigate the shear strength parameters for understanding the mechanical behavior of TL with increase in the age of MSW. In the following sections, a large-scale in situ direct shear test device was used in this study, sample preparation and testing program.

2.2.1 In Situ Direct Shear Test Device Specifications

The mentioned device includes the shear and normal loading systems, force gauge, displacement gauge and frame. According to Richardson et al. [7], Houston et al. [8] and Ali et al. [13], dimensions larger than 1 m have been recommended for carrying out in situ experiments on MSW, so a metal box was constructed with internal dimensions of 122 × 122 cm. The box consists of an upper section to apply shear force and a lower section to support the upper part and control its movement while using shear force.

To distribute uniformly the jack shear force on the upper section, a push beam was placed in the lower quarter height region of the box. This will prevent the box from distorting and transfer all shear force on the sample to create the necessary interaction in the shear plate (Fig. 5). The schematic of the device is thoroughly illustrated in Fig. 6.

To measure the shear force, a ring force was utilized with maximum capacity of 3 tons consisting of a dial gauge with an accuracy of 0.01 mm. A 70 ton hydraulic jack was used to apply the shear force, and a dial gauge with an accuracy of 0.01 mm measured the horizontal displacement of the box as presented in Fig. 7. Some precast concrete blocks with a weight of 1 ton was used to apply the necessary normal stress.

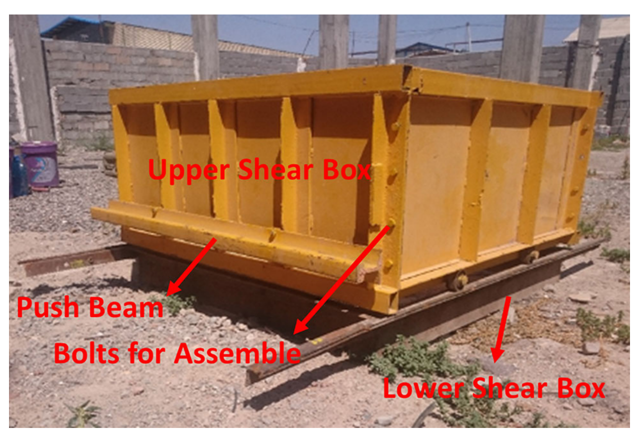


Fig. 5 The device's main parts

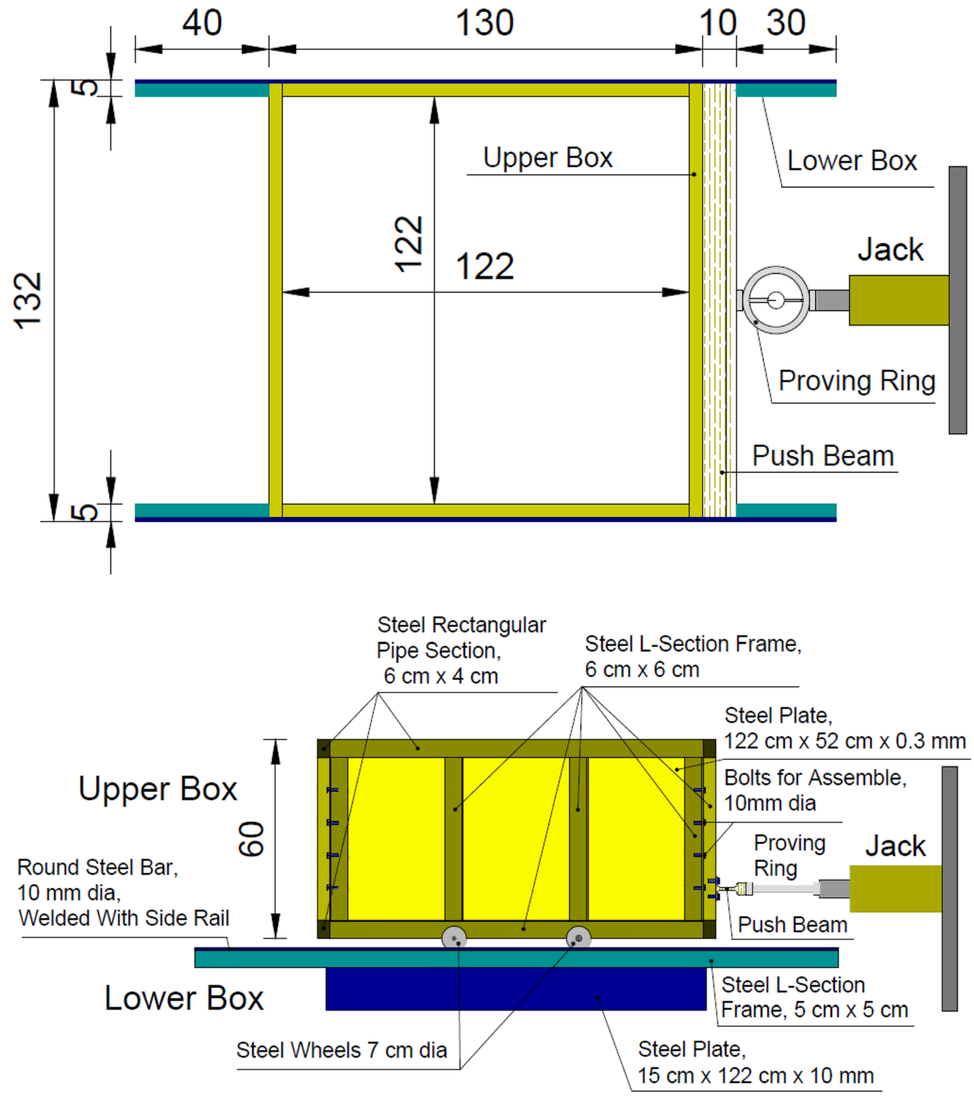


Fig. 6 Schematic view of the in situ direct shear box (**a** top view, **b** side view)

2.2.2 Specimen Preparation and Testing Program

In situ direct shear test specimens were prepared onsite to prevent minimum disturbance as well as each specimen was considered to have three steps of direct shear test with different vertical stress to eliminate the effect of variations among samples according to Ali et al. [13]. Normal stresses of 6.7, 14 and 22.2 kPa were applied stepwise, by placing precast concrete blocks on the specimens as normal stress. At each step, three strains of 2, 3 and 4% were considered for shear stress to determine the strain effect on the mechanical response of MSW. The test was performed at a shearing rate of 4 mm/min, as shown in Fig. 8.

As shown in Fig. 8, samples were prepared in six steps; first, 20 cm coating soil from the top of the landfill was removed and the in situ intact specimen with a size of 122 × 122 × 75 cm were excavated. To avoid emission of toxic gases, a coating of clayey soil with a thickness of about 10 cm was spread over the excavated MSW. At this stage, the lower box was placed around the specimen at the lowest possible depth so that the shear plate can be prepared with minimum disturbance. Subsequently, the lubricated upper box was set around the sample and few empty areas in the box were filled with MSW. Afterward, a concrete block was placed for the support of the shear force hydraulic jack that was loaded with the truck weight over the block. After preparing each sample, the jack and displacement gauge were fitted next to the box and the experiment was carried out.

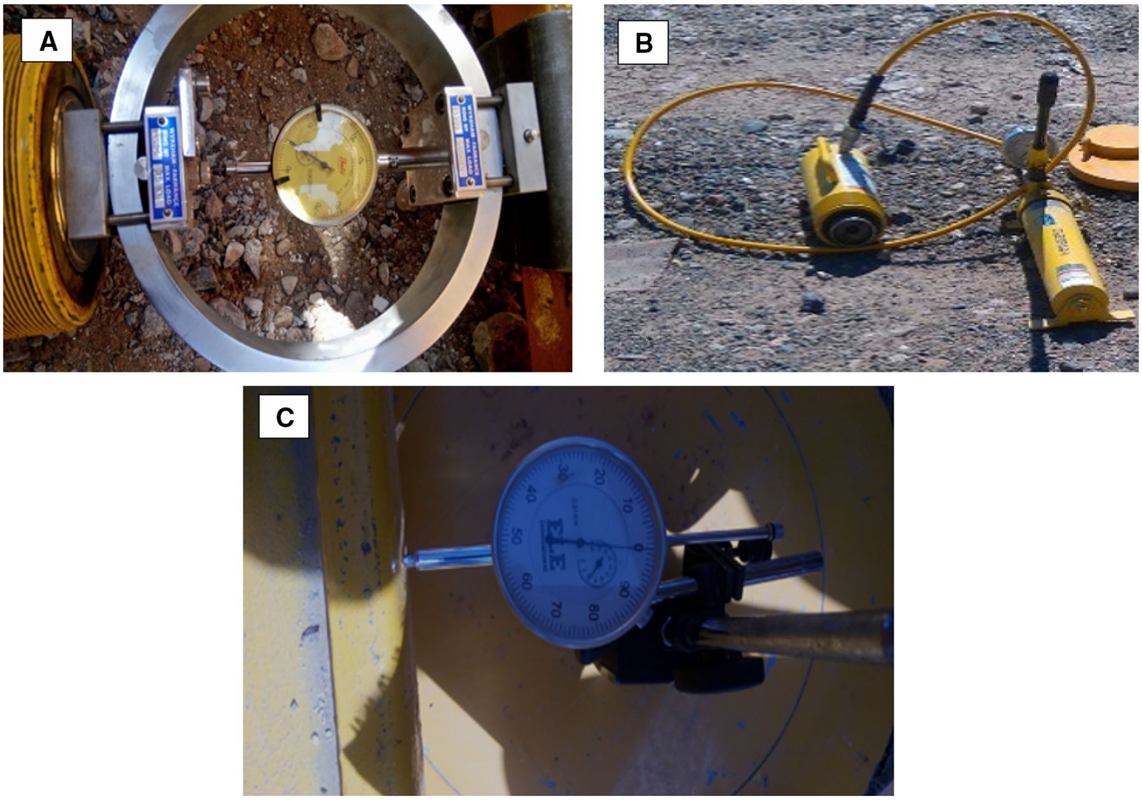


Fig. 7 Equipment used for large-scale in situ direct shear test (**a** load ring, **b** hydraulic pump, **c** dial displacement gauge)

3 Results and Discussion

3.1 Physical Properties of Municipal Solid Wastes

The MSW unit weights at different ages are presented in Fig. 9; this figure shows a higher increasing trend in the beginning until 5-year-old and then lower. This trend could be explained by the MSW composition, the method of landfilling, compression effort, as well as the decomposition rate of organic elements, which increase the waste density over the time.

The MSW unit weight of different landfills in the world is shown in Fig. 10. It is observed that the in situ unit weight of the Tabriz landfill is in the range of other landfills. By comparing the MSW components of TL and Okhla and Ghazipour landfills in India presented by Ramaiah et al. [6], it was observed that the percentage of plastic materials in TL MSW materials was higher than that of the mentioned landfills. Considering their low weight, big volume and low compressibility, a high percentage of the plastic materials can be the reason for the relatively low in situ unit weight of TL. On the other hand, Tabriz and Tehran are Iran's two metropolitan cities with similar consumption pattern. However, Tabriz landfill MSW has a more moderate density and lower unit weight compared to Tehran Kahrizak landfill MSW [36]. This can be explained by the burial conditions in Tabriz landfill.

Table 2 presents the physical analysis, unit weight, moisture and organic content of TL at fresh and 5- and 16-year-old MSW. According to the results, with aging, moisture and organic element content decreased, which confirms the reported results by Shariatmadari et al. [36] and Keramati et al. [31]. As shown in this table, the percentage of plastics in TL increased with the age of MSW, which could affect the shear strength significantly.

Figure 11 compares the moisture content of TL with the data reported in other studies. According to this comparison, Tabriz MSW's moisture content is higher than the average, with the exception of Tehran's Kahrizak landfill [36]. Also, the organic content of Tabriz's MSW is higher than that of other landfills as presented in Fig. 12, which can be interpreted due to differences in consumption pattern, components, landfilling and weather conditions.

Figure 13 shows that the percentage of the pasty portion of fresh MSW reduced from 73 to 53% in the years 2005–2017. However, the percentages of plastics and papers increased significantly in these 12 years. This is interpreted as a consequence of changes in the consumption pattern in accordance with the city development. Indeed, such intensive changes in fresh MSW components have affected the mechanical responses of MSW over time.

Fig. 8 Large-scale in situ direct shear experiment steps (**a** removing the coating, **b** preparing a sample with approximate dimensions of 122 × 122 cm, **c** placing the lowest part of the box, **d** placing the upper box around the sample, **e** placing support, **f** fitting the box to a jack and displacement gauge and applying normal stress)

On comparing of fresh (in the year 2012) and 5-year MSW components, it is obvious that the plastic material was increased more than 200% and the pasty materials decreased about 30% because of the degradation and aging process.

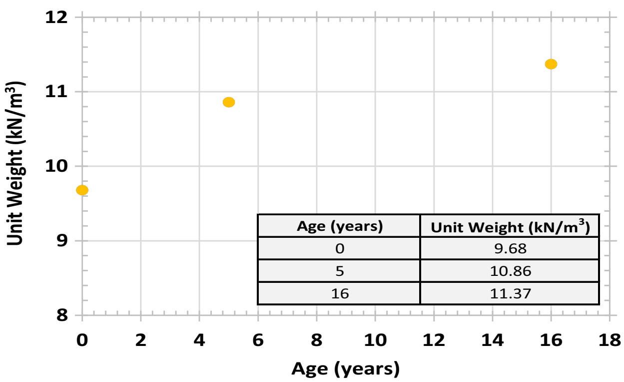


Fig. 9 Results of the unit weight TL MSW with increase in the age

3.2 Shear Strength Parameters

In Figs. 14 and 15, the shear stress of 5-and 16-year-old MSW is presented against normal stress and horizontal displacement. Results showed that the cohesion and friction angle for 5- and 16-year-old MSW were evaluated as 1.17 kPa and 31.51° and 2.215 kPa and 21.51°, respectively.

The estimated MSW's friction angle and cohesion at the two mentioned ages for different strains are summarized in Table 3. The results show that there are different shear strength values between 5- and 16-year-old MSW, and the 16-year-old has lower shear strength than 5-year-old MSW. Indeed, the MSW shear strength was mainly due to the friction angle with a negligible effect of cohesion. For 5-year-old MSW, as the shear strain increased, the angle of friction decreased, while for 16-year-old MSW the friction angle increased with increase in the shear strain up to 3%, and afterward it slowly decreased. On the other hand, in both 5- and 16-year-old MSW, cohesion increased with increase in the shear strain.

According to Kolsch [51], the presence of fibrous materials causes the reinforcement and increases the shear strength of MSW at a certain strain. Therefore, considering the MSW components at the ages of 5- and 16-year MSW, increasing the plastic content as fibrous materials increased the effect of reinforcement. The rising trend of cohesion can be attributed to the aging and rise of plastic content.

L laboratory tests, *I* in situ tests, *D* circular box, *PS* peak stress, *PD* peak displacement, *NR* not reported

As presented in Fig. 16, the cohesion and friction angle of this study were compared to the other related published data on the landfills using in situ and laboratory direct shear test. Table 4 presents some information of these studies in

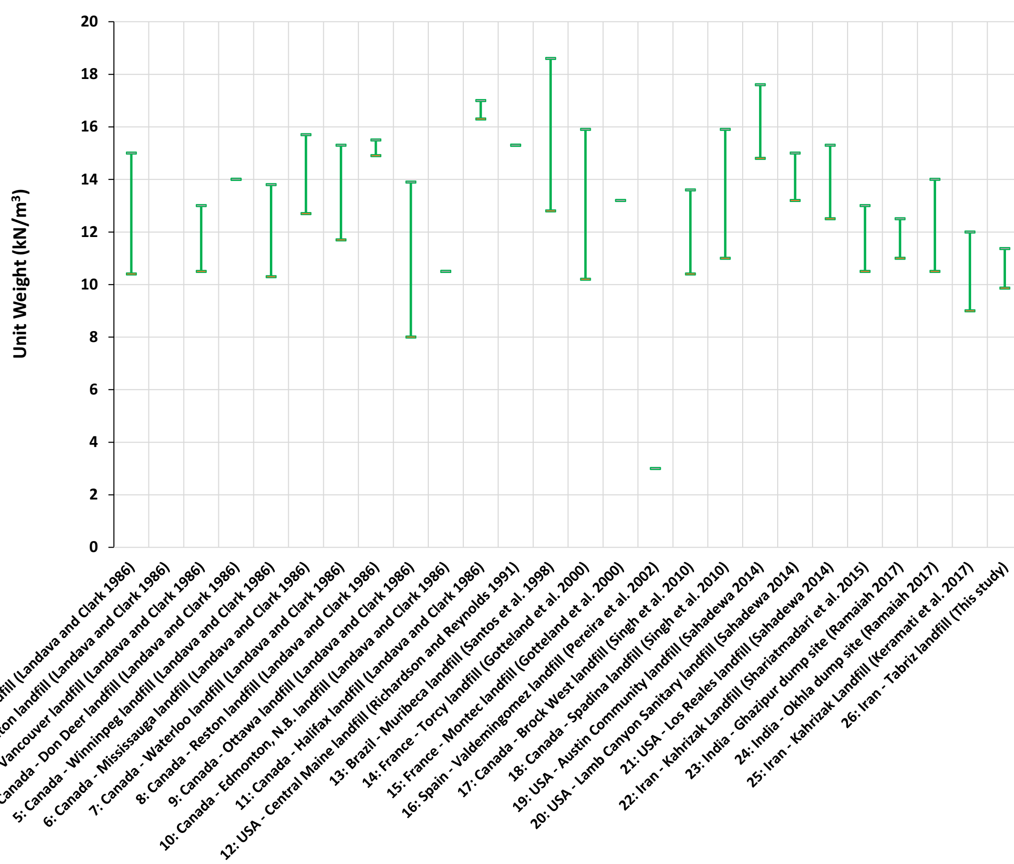


Fig. 10 Comparing the in situ near surface MSW unit weight of the current study with some MSW landfills in the world [6, 7, 36–42]

Table 2 Physical analysis and properties of TL at different ages of MSW

Age (years)	Composition (percentage by dry weight)								In situ unit weight (kN/m^3)	Moisture content (%)	Organic content (%)
	Paste	Metal	Soil and rock	Wood	Plastic	Paper and cardboard	Textile and rubber	Glass			
Fresh	52.6	0.96	8.29	5	14.08	9.1	7.97	2	9.68	145	64.8
5	47.4	1.6	9.4	2.4	21.2	9.4	4.8	3.8	10.86	83	40.5
16	51.7	0.8	9.8	3.4	27.4	1.8	3.1	2	11.37	51	22.3

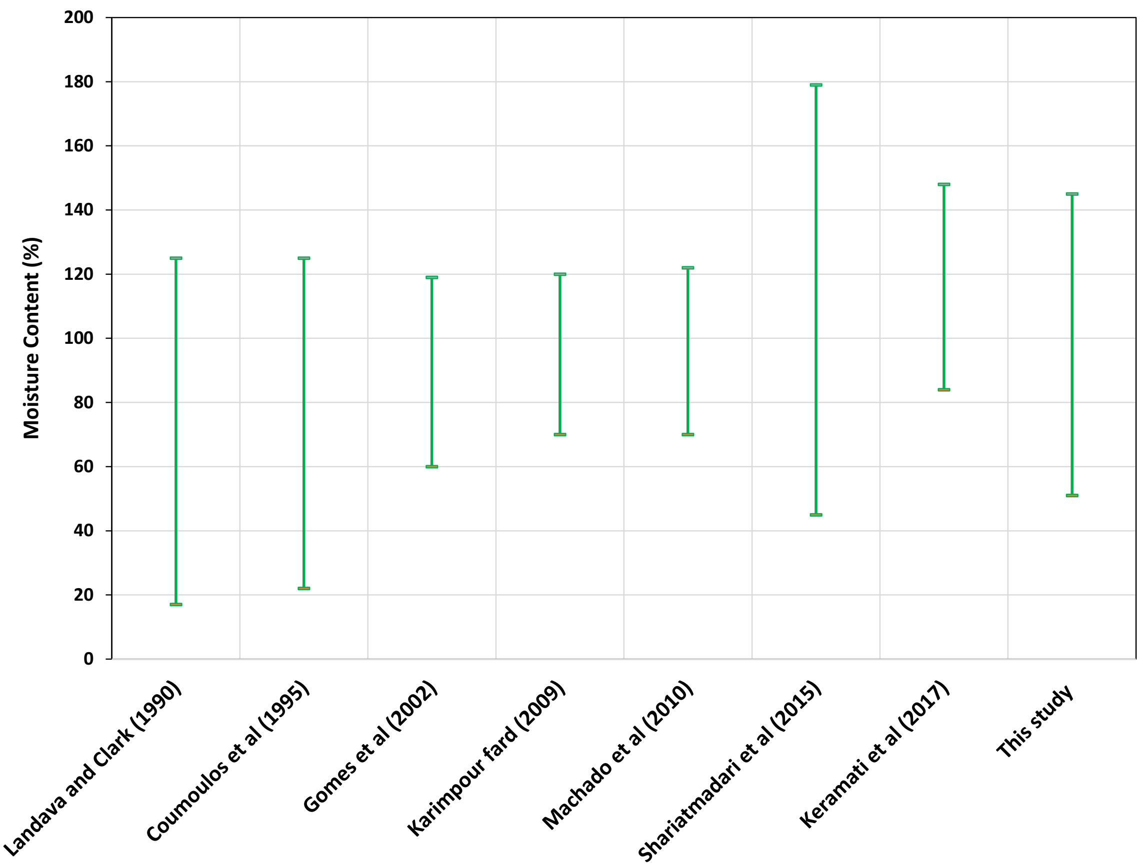


Fig. 11 MSW moisture content reported in different studies in comparison to the TL [16, 31, 36, 43–46]

which the width of the shear box varies between 6.35 cm and 150 cm.

3.3 Shear Strength Parameters in Different Unit Weights and Ages of MSW

According to Table 3, the results show that with increase in the age of MSW, the friction angle decreases and cohesion increases. Also, the significant increase in the plastic percentage of MSW because of the degradation process has led to greater reduction of the frictional strength. Similar findings were reported by Thomas et al. [11], Hossain [19], and Gabr et al. [24].

According to Zekkos et al. [5], both MSW composition and unit weight affect the shear strength response of MSW, but they could not demonstrate the mechanical behavior of MSW independently. However, in the landfills, MSW components change significantly over time that can affect the unit weight and shear strength parameters.

Ramaiah et al. [6] reported different results about the two landfills in India. They showed an increase in friction angle and a reduction in cohesion with aging. According to their results, the mechanical response of MSW materials was independent of age and related to the displacement rate, although this is not observed in the TL MSW. This contradiction could be related to the different MSW

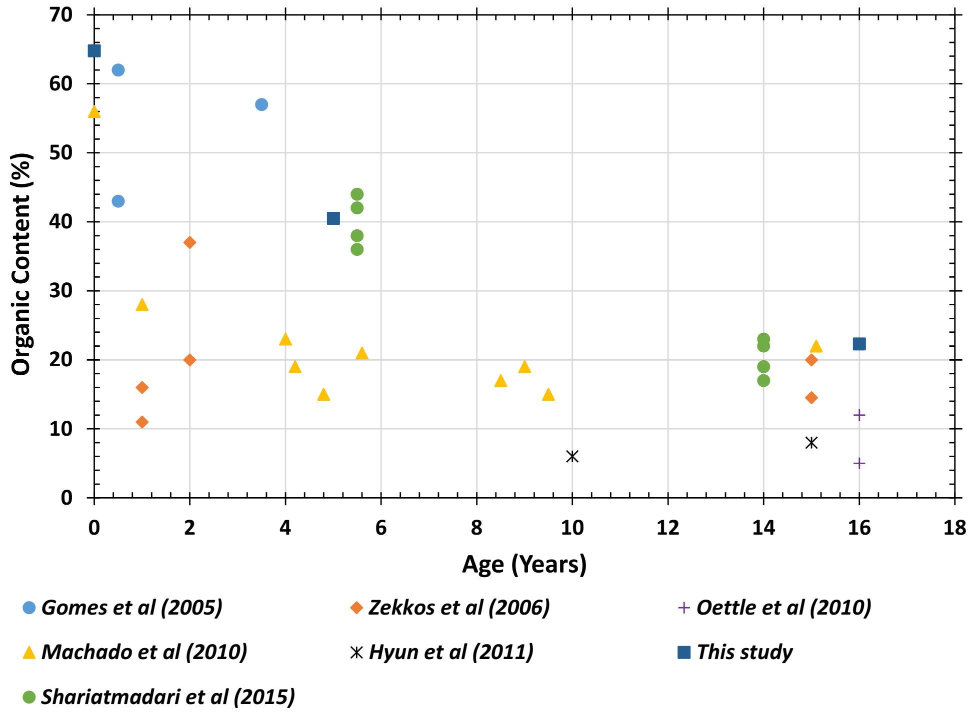
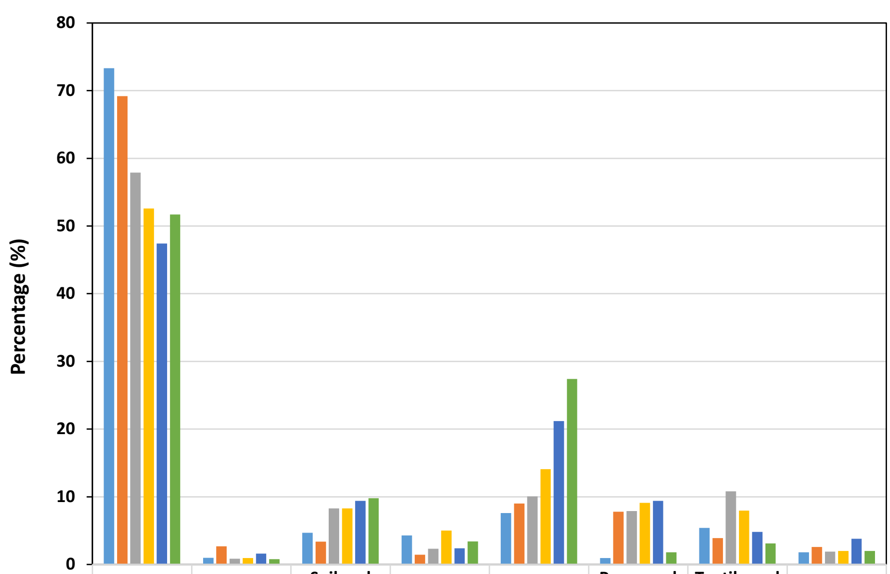


Fig. 12 MSW organic content reported in different studies in comparison to the TL [36, 46–50]



	Paste	Metal	Soil and Rock	Wood	Plastic	Paper and Cardboard	Textile and Rubber	Glass
Fresh MSW 2005	73.3	1	4.7	4.3	7.6	0.95	5.4	1.8
Fresh MSW 2012	69.2	2.68	3.36	1.44	9.01	7.81	3.91	2.59
Fresh MSW 2016	57.88	0.85	8.28	2.34	10.06	7.88	10.8	1.91
Fresh MSW 2017	52.6	0.96	8.29	5	14.08	9.1	7.97	2
Old MSW 5-year	47.4	1.6	9.4	2.4	21.2	9.4	4.8	3.8
Old MSW 16-year	51.7	0.8	9.8	3.4	27.4	1.8	3.1	2

Fig. 13 Tabriz MSW components at different ages [32]

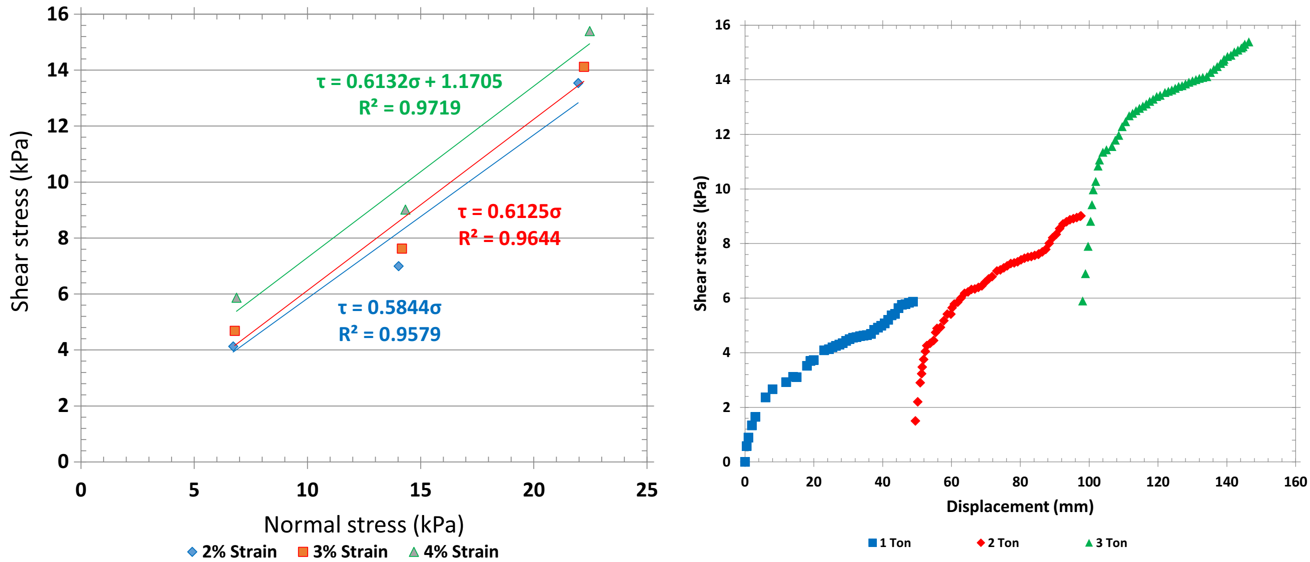


Fig. 14 Results of large-scale in situ direct shear test on 5-year-old MSW, Tabriz

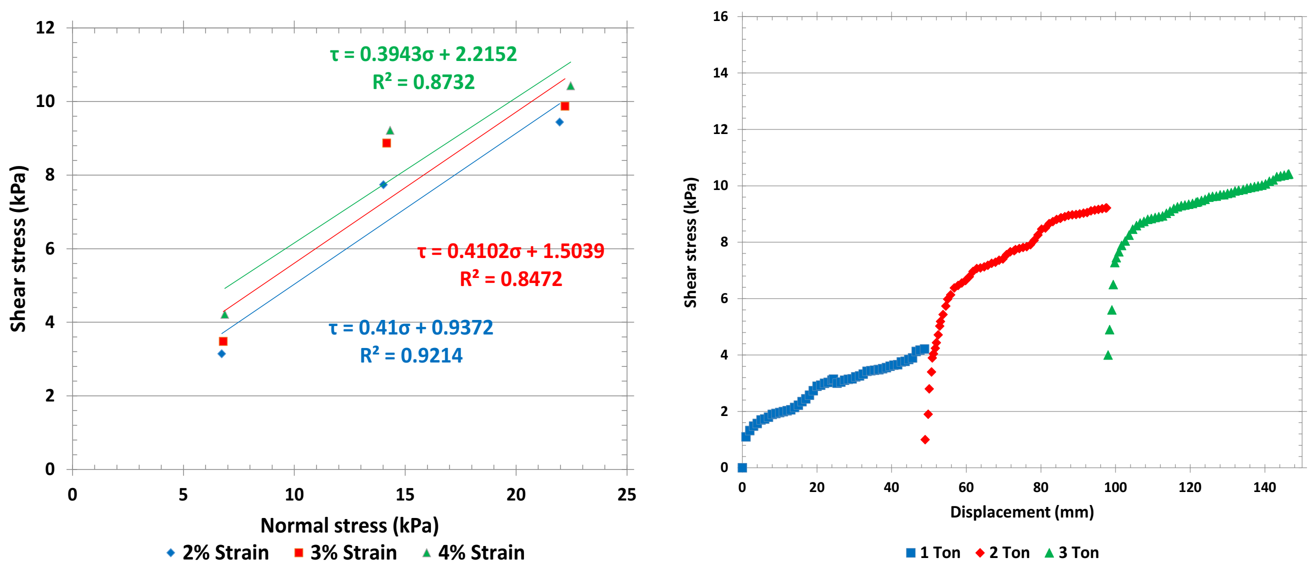


Fig. 15 Results of large-scale in situ direct shear test on 16-year-old MSW, Tabriz

Table 3 Shear strength parameters of 5- and 16-year-old MSW in different horizontal strains

Age	Strain (%)	Friction angle (°)	Cohesion (kPa)
5-year-old MSW	2	30.30	0
	3	31.48	0
	4	31.51	1.17
16-year-old MSW	2	22.29	0.937
	3	22.30	1.503
	4	21.51	2.215

compositions in TL and India's landfills. The main differences are in the percentage of textile materials, plastics and organic content (Table 2). As shown in Figs. 14 and 15, the slope of shear strength envelope changes for both 5- and 16-year-old MSW with increase in the normal stress also with different trends. When the normal stress reached more than 15 kPa, the shear strength envelope of 5-year-old MSW increased while for the 16-year-old MSW decreased. The reason for such differences is the changes in the composition and percentage of plastic and pasty MSW materials over time.

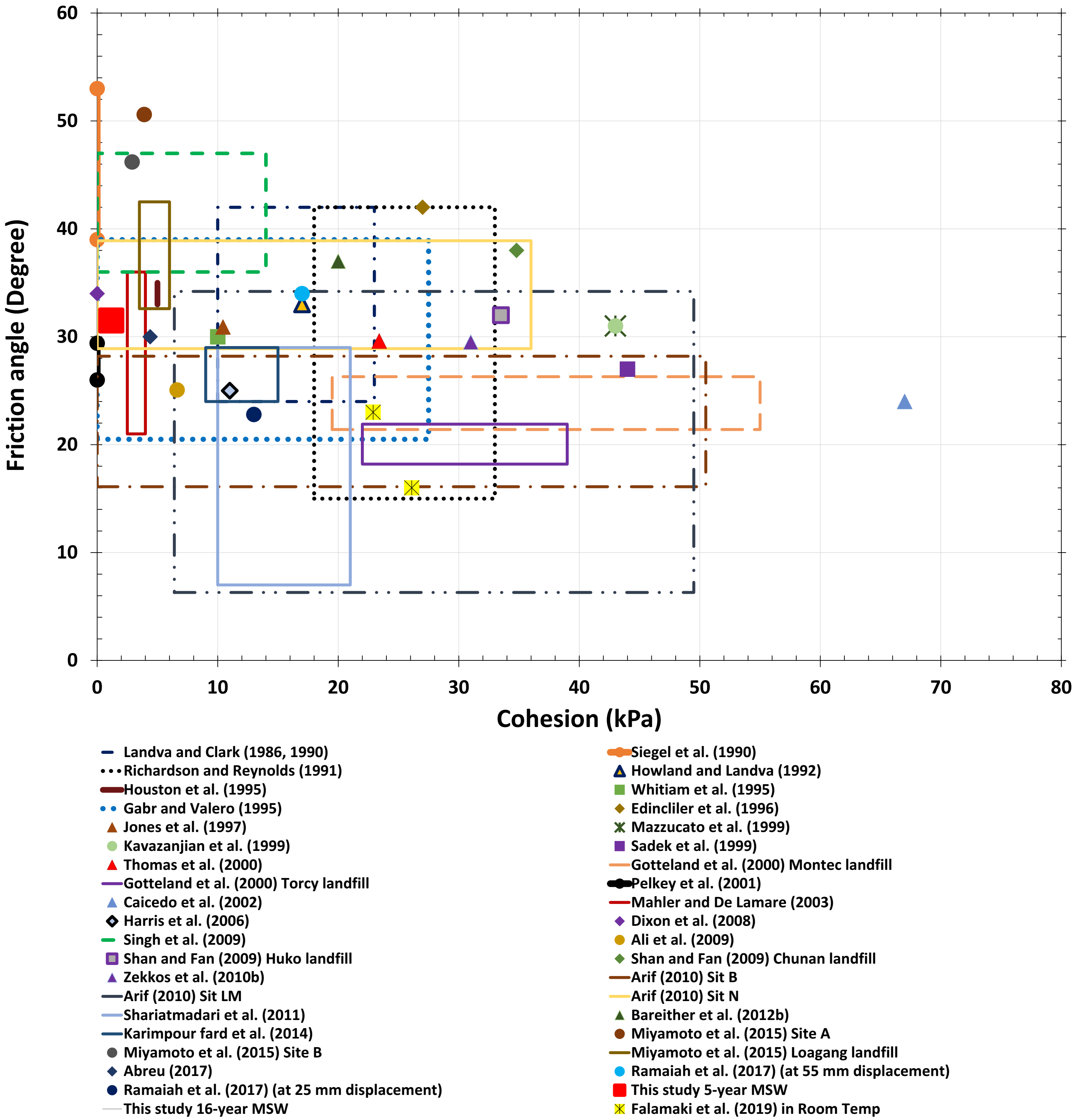


Fig. 16 Comparison of TL shear strength parameters with other landfills

4 Conclusion

In this study, the physical properties, moisture and organic content, unit weight and the shear strength parameters of the MSW of the TL at the ages of fresh and 5- and 16-year-old MSW were investigated; for this objective, a large-scale in situ direct shear test device was used.

According to the results, the shear strength of 5- and 16-year-old MSW is mainly controlled by the friction angle which seems due to the MSW composition as a function of the consumption pattern. Because of the degradation process, the percentages of plastics and fibrous materials were increased, so that the 5- and 16-year-old MSW indicated low cohesion values of 1.17 kPa and 2.22 kPa, respectively. Also this high plastic content of MSW caused the reduction of friction angle from 31.51° to 21.51° over time for 5- to 16-year-old MSW.

Table 4 Data on the shear strength of MSW using a direct shear test (laboratory and in situ) from various studies for statistical analysis

Reference	Sample location	Testing method, sample size (cm) and no. of tests	Displacement or strain at the shearing resistance considered and normal stress (kPa)
Landva and Clark [16, 37]	Four landfills in Canada	L, 43 × 29, 23	PS, 30.3–565
Siegel et al. [52]	OII landfill in the USA	L, 13 (D)	PD (10% strain), 90–570
Richardson and Reynolds [7]	Central Maine landfill in the USA	I, 122 × 122, 17	NR, 15–40
Howland and Landva [53]	USA	L, 43 × 29, 6	PS, 30.3–565
Houston et al. [8]	North West Regional landfill in the USA	I, 122 × 122, 6	PS, 15.3–44.5
Whitiam et al. [9]	Decorte Park landfill in the USA	I, 150 × 150, 5	PS, 0–21
Gabr and Valero [54]	Pioneer Crosing landfill in the USA	L, 6.35 (D)	PD (5% and 10% strain)
Edincliler et al. [55]	A landfill in Wisconsin in the USA	L, 30 (D), 18	PD (60 mm), 13.8–138
Jones et al. [56]	A landfill in Durham in the UK	L, 30 × 30, 32	PD (30 mm), 50–400
Mazzucato et al. (1999) [10]	A landfill in Verona in Italy	I & L, 80 (D)	PS, 50–220
Kavazanjian et al. [57]	OII landfill in the USA	L, 46 (D), 9	NR, 137.5–1730
Sadek et al. (1999) [58]	Normandy landfill in Lenanon	L, 60 × 60, 5	PD (48 mm), 49.1–245.3
Thomas et al. [11]	Torcy landfill in France	I, 100 × 100	PD (180 mm), 50–125
Gotteland et al. [39]	Montec landfill in France	I, 100 × 100, 10	PD (100 mm), 50–125
Gotteland et al. [39]	Torcy landfill in France	I, 100 × 100, 10	PD (100 mm), 50–125
Pelkey et al. [12]	Three landfills in Canada	L, 45 × 30	PS
Caicedo et al. [1]	Dona Juana landfill in Columbia	L, 90 (D), 6	PS or PD, 2.2–117
Mahler and De Lamare [59]	Two landfills cities in Brazil	L, 40 × 25	PS, 25–100
Harris et al. [60]	Outer Loop landfill in the USA	I, 30 × 30, 3	PD (30 mm), 172–690
Dixon et al. [61]	Narborough landfill in the UK	L, 100 × 100, 9	PD (240–260 mm), 25–100
Singh et al. [62]	Brock West landfill in Canada	L, 100 × 100, 3	PD (250–300 mm), 60–150
Ali et al. [13]	A landfill in Pakistan	I, 122 × 122, 3	4% strain (48.8 mm), 6–20
Shan and Fan [63]	Huko landfill in Taiwan	I, 80 × 80, 4	PS, 64–226
Shan and Fan [63]	Chunan landfill in Taiwan	I, 80 × 80, 4	PS, 52–229
Zekkos et al. [5]	Tri-Cities landfill in the USA	L, 30 × 30, 11	PS or PD (55 mm), 1.8–700
Arif (2010) [64]	Landfill Site B in France	L, 30 × 30, 3	PD (33 mm), 50–200
Arif [64]	Landfill Site LM in France	L, 30 × 30, 21	PD (33 mm), 50–200
Arif [64]	Landfill Site N in France	L, 30 × 30, 6	PD (33 mm), 50–200
Shariatmadari et al. [26]	Kahrizak in Iran	L, 30 × 30, 15	PD, 20–200
Bareither et al. [22]	Deer Track Park landfill in the USA	L, 28 (D), 22	PD (56 mm), 12–90
Karimpour fard et al. [65]	Kahrizak in Iran	L, 30 × 30, 57	PD, 20–100
Miyamoto et al. [14]	Landfill Site A in Japan	L, 30 × 50, 6	PD (35 mm), 8.2–19.1
Miyamoto et al. [14]	Landfill Site B in Japan	I, 30 × 50, 6	PD (35 mm), 8.2–19.1
Miyamoto et al. [14]	Loagang landfill in China	I, 30 × 50, 6	PD (35 mm), 7.5–22.3
Abreu [66]	Sao Carlos sanitary landfill in Brazil	L, 50 × 50, 18	PD (100 mm), 50–250
Ramaiah et al. [6]	Ghazipur dump site in India	I, 30 × 30, 15	PD (55 mm), 7–400
Ramaiah et al. [6]	Okhla dump site in India	L, 30 × 30, 6	PD (55 mm), 7–400
Falamaki et al. [3]	Barmshoor landfill in Iran	L, 30 × 30, 8 series	PS in different Tempreture
This study 5-year-old MSW	Tabriz landfill in Iran	I, 122 × 122, 3	4% strain (48.8 mm), 6.7–22.2
This study 16-year-old MSW	Tabriz landfill in Iran	I, 122 × 122, 3	4% strain (48.8 mm), 6.7–22.2

L laboratory tests, *I* in-situ tests, *D* circular box, *PS* peak stress, *PD* peak displacement, *NR* not reported

The physical analysis of fresh MSW from 2005 to 2017 showed an increase in the fiber content including plastics and textiles. Moreover, studies on MSW mechanical responses over time revealed a decrease in the shear strength because of the increase in the fiber and plastic content.

Also, the following results were obtained from the present study:

- The MSW shear strength was mainly due to the friction angle.
- The MSW shear strength decreased with aging because of the degradation of organic materials and increased with higher shear displacement.
- Aging and degradation cause the organic materials to change into soil-like materials and this leads to more MSW compression and higher in situ unit weight.
- The moisture and organic content decreased over time because of the degradation process.
- Higher plastic content of the MSW over time reduced the friction angle and increased cohesion slightly.
- Although the in situ unit weight showed a clear increase over time, its effect on shear strength was not notable.

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