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RESEARCH PAPER

Laboratory Shear Strength Measurements of Municipal Solid Waste at Room and Simulated In Situ Landfill Temperature, Barmshoor Landfill, Iran

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Abstract

This study was aimed to determine the influence of temperature within the landfill on the shear strength of the MSW samples through the shearing procedure. Different waste samples, i.e., the fresh (C1), 2 years old (C1-2Y) and lab oratory prepared (C2) MSW samples, were heated up, prepared, and placed in the shearing box with the designated temperatures of about 25, 45, and 65 °C (i.e., the range of an anaerobic landfill). The Mohr–Coulomb strength parameters for the warmed-up and room-temperature specimens were separately calculated and compared. The temperature decreases the friction angle from 21 to 17° for $T > 45$ °C. The cohesion was also decreased by temperature from 19.9 to 13.1 kPa. In addition, two nonlinear envelopes were developed for the specimens tested at room and simulated temperature within the landfill. The test results show a reduction of about 20% for friction angle and shear strength at the temperatures between 45 and 65 °C. Although the warmed-up specimens of fresh MSW were denser under certain normal stress, heating the MSW specimens to temperatures of 45 and 65 °C resulted in loss of the shear strength. Results further indicated that the temperature of the wastes plays an important role when the shear stress is conducted on the MSW specimens. It can be then concluded that temperature of the landfill should be considered as a factor influencing the shear strength of MSW. Considering temperature for site investigation of the shear strength and the correlation of the results with the laboratory tests is important, too.

Keywords Landfill temperature · Shear strength · Municipal solid waste · Direct shear test, warmed-up waste

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1 Introduction

Municipal solid waste (MSW) generation is accelerating due to growing population levels, rapid urbanization, and the rise in community living standards [1–3]. Economic problems cause the last functional element of waste management, i.e., disposing of MSW, to be accomplished by burying of waste in a landfill [4]. Therefore, designing a safe and manageable landfill is a major concern in geo-environmental engineering. Landfill slope failure, excessive settlement, leakage of leachate into the environment [5], and the safety of landfill operator and its worker are some of these concerns. Feng et al. [6] emphasized that geotechnical problems in landfills have arisen due to the complex properties of MSW. Hence, considering the properties of MSW is important to overcome such problems. The shear strength has been taken into consideration as an essential parameter for landfill design by several researchers [7–13]. Feng et al. [6] suggested studying shear strength parameters of MSW (the friction angle and cohesion calculated from Mohr–Coulomb envelope) for different regions, because the reported values by researchers widely varied due to distinct waste compositions, climate conditions, operation styles, and testing methods. These variations enforced the researchers to investigate the various factors that could influence the strength behaviour of MSW, i.e., test method, test device and data interpretation, age, composition and decomposition, unit weight, the rate of shearing, and confining pressure and stress path (e.g., [14–21]).

In addition to leachate and gas generation, heat is the primary by-product in the MSW landfill process [20]. Therefore, temperature is a key factor in designing and operating of a landfill. Some researchers explained that the in situ temperature of anaerobic MSW landfills ranges from 30 to 65 °C [22, 23]. The process is considered as the aerobic degradation in the first (early) stage of the anaerobic landfills [24]; however, the degradation process is anaerobic in the next stages. Townsend et al. [23] declared temperature often reaches up to 60 °C, while, in the aerobic systems, temperature of more than 70 °C is reported. Jafari et al. [22] studied the temperature status of a landfill and explained that oxygen for aerobic conditioning increases waste temperatures up to 85 °C. They described that, in the anaerobic systems, this temperature becomes self-regulating to avoid limiting the activity of the anaerobic organisms.

Landfill temperature affects decomposition and degradation of the waste mass. The biodegradation of MSW increases with temperature [20, 25]. The magnitude and extent of temperature governs the type of chemical and biological processes as well as the rate of decomposition. The older wastes experience the landfill temperature variation; hence, the decomposition of the wastes varies with time. Abreu and Vilar [26] based on a literature review of previous studies reported significant variation in their results due to composition and age of MSW. However, they believe that the age of MSW does not cause further degradation, since there are different factors, which limit the decomposition of biodegradable components in a landfill such as moisture, pH, temperature, and operating conditions. Therefore, this type of the heat effect on the waste variation could be considered as a time-dependent procedure.

Temperature also affects the mechanical properties of materials. The effective temperature to change the mechanical properties (the stress–strain behaviour) of different materials is variable. MSW is a heterogeneous mixture, consisting of various soft/hard and fibrous/non fibrous materials. Stiffness and mechanical behaviours of these fibers may be considered sensitive to the variation of temperature. Another part of MSW like leftover foods and wood-like materials (branches and grass, weeds and leaves) has the potential of burning when exposed to the landfill heat. Consequently, determining the influence of temperature on shearing of the waste could be considerable. When the slopes of a landfill are constructed, shear stress is mobilized through the waste materials with temperature ranging from 30 to more than 100 °C, depending on the type and operational procedure of landfill. The previous studies of stress–strain behaviour of MSW by others have been performed at room temperature in the laboratory. In addition, some researchers compared the mechanical behaviour of the MSW using laboratory and in situ testing; therefore, knowing the in situ temperature of the waste is important. This means that the shear (or failure) plane passes through a colder waste in laboratory relative to the in situ condition. As of today, shearing of MSW specimens at an in situ temperature of landfill has not been studied. The objective of this study is, therefore, to characterize the influence of temperature on the stress–strain behaviours of MSW specimens tested in the laboratory at some temperatures corresponding to in situ temperature within the landfill.

2 Materials and Methods

2.1 Sample Collection

Bulk samples of MSW were taken from Barmshoor landfill which is located at approximately 20 km west of Shiraz city, Fars province, Iran. This landfill receives more than 1000 tons of MSW daily out of which 70% is disposed (buried). There is no aeration or leachate recirculation system and the highest temperature observed in this landfill is about 60 °C. Back on 2013, there was a slope failure within this landfill which had seven fatalities. Two bulk samples of MSW were taken: one from the waste delivered to the landfill C1 (fresh sample) and the second sample (C1-2Y) from an area of landfill which the MSW has been buried for 2 years. The samples were hand-sorted to assess composition.

The main constituent of this landfill is wet and organic waste which corresponds to about 68% of the waste. To further investigate the combined effect of temperature and composition of specimen on the shearing of MSW, a third sample (C2) was mixed/made in the laboratory from the fresh waste and fiber like materials (plastic pieces). Moisture content tests were performed on the samples C1, C1-2Y, and C2 in the laboratory. The average moisture contents of these samples, i.e., C1, C1-2Y, and C2, were obtained to be 57.6%, 43.1%, and 37.4%, respectively. Karimpour-Fard et al. [28] recommended that papers and cardboard should not be considered as fiber in the MSW with high moisture content. The composition of C1 fresh waste within Barmshoor landfill, C2 laboratory made waste, and C1-2Y waste obtained from the landfill are given Table 1. The measured composition of C1 waste in this study is in accordance with that reported by Norouzian et al. [29]. The high content of organic materials in municipal solid waste of Shiraz has been already reported by Norouzian et al. [29] and it is the same as for MSW of many landfills in Iran. Waste separation at source does not performed and the waste is, therefore, a mixture of dry and wet wastes. This is the main reason of high moisture content of the waste. Using ASTM D 2974-87 method, the organic matter (OM) of the wet waste (excluding metals, textile, glass, and plastic) for C1 waste was measured equal to 29.7 and 54.5% at 450 and 700 °C, respectively, using a muffle furnace. The composition of C2 waste was selected near to the waste of the other countries with more fiber content and lower organic waste (Table 1). The OM for C2 waste is considered as C1, since it is assembled by the constituents of C1 waste. Recognizing of the wet waste and soil for C1-2Y waste was quite difficult. For an aged waste, it is hard to specify the material types. The constituents of this waste with further plastic waste are also shown in Table 1.

2.2 Specimen Preparation and Direct Shear (DS) Testing Program

In this study, a computer controlled direct shear device having a relatively large shear box with dimensions of 300 × 300 × 165 mm was used. The maximum shearing force of the device was up to 200 kN, maximum normal stress up to 500 kPa, and a motorized constant rate of horizontal displacement from 0.1 to 200 mm/min. Some researchers [30, 31] used the rates higher than 1 mm/min in shearing of MSW. For this study, a displacement rate of 2 mm/min was selected to minimize the loss of MSW specimen temperature during the shearing.

Fresh C1 waste was disassembled in the constituents. Hard materials like stone were separated, and the large sheet-like materials such as textiles, paper, and plastic were shredded to 100 × 50 mm dimension. The size of more

Table 1 Main constituents of C1, C2, and C1-2Y compositions used in this study

Constituent (%)	Comparison of Shiraz waste constituents		Comparison of laboratory made waste (C2) and other countries, reported by Zhang et al. [27]				2-year-old waste (C1-2Y) from (Barmshoor) landfill used in this study	
	C1	Norouzian et al. [29]	C2	Netherlands	Japan	Portugal	Constituent (%)	C1-2Y
Wet and organic waste	68.6	66.17	35	35	34	34	Wet waste and soil	67.5
Plastic	8.8	10.3	17	19	13	11	Plastic	16.6
Paper/cardboard	5.9	5.38	24	26	33	21	Paper/cardboard	5.4
Glass	2.5	2.4	3	4	5	7	Glass	2.4
Wood	2.9	–	9	–	–	–	Wood	2
Textile and leather	2.5	–	3.5	–	–	–	Textile and leather	2.4
Metals	2	2.09	3.5	4	3	4	Metals	3.8
Soil	4.9	–	5	–	–	–		
Miscellaneous	2	13.63	–	12	12	21		
Water content (%)	57.6	–	34.7				Water content (%)	43.1
TOC at 450 °C (%)	29.7	–	29.7					
TOC at 700 °C (%)	54.5	–	54.5					

than 70% of the waste was less than 50 mm. The constituents were mixed together in Plexiglas container to prepare C1 or C2 composition according to Table 1. Therefore, for a certain composition, all the specimens have the same fiber content (the fibrous contents of C1, C2, and C1-2Y were about 11%, 20%, and 19%, respectively). The same procedure was used for C1-2Y composition. A total eight series tests were conducted at different temperatures and normal stresses as presented in Table 2. A plastic bag was placed within the shear box mold for handling and ease of extruding and keeping the molded specimen together after the molding. To avoid formation of the oriented fibers in the samples, the MSW was placed in the shear box mold in layers and tried to place the fibers horizontally. A combination of compactive effort and pressing utilizing a surcharge was used to mold the specimens, i.e., one-third of the waste was placed in the shear box with fibers in a nearly horizontal orientation and compressed with 200 kPa pressure. The second and third layers were placed and compressed with the same pressure. Dixon et al. [30] in their experiment were also placed the waste in layers in shear box while statically loaded each layer. After the molding, specimens were extruded and placed in some more plastic bags to avoid any change in the moisture content. Then, some of them were kept at room temperature and some were placed in the oven at a desired temperature without any surcharge (for 24 h before the testing/shearing). The weight of each packed specimen was determined after molding and before shearing to obtain the weight loss of the specimen due to curing for 24 h (especially for warmed-up samples). The weight loss percent of samples before shearing are given in Table 2. The weight losses of the specimens were negligible (with the maximum weight loss of 1.19%) which is negligible. After

Table 2 The testing scheme for this study

No.	Test symbol	Ave. T (°C)	Waste composition	Normal stress (kPa)	Loss of weight (%)	Specimen height (cm)	Unit weight prior to shearing (kg/m^3)	Shear strength (kPa)
1	C1, σ = 50 kPa	Room	Fresh C1	50	< 0.1	15.6	713.6	43.1
	C1, σ = 100 kPa	Room	Fresh C1	100	< 0.1	15.4	722.0	51.3
	C1, σ = 200 kPa	Room	Fresh C1	200	< 0.1	15.0	739.8	85.3
2	C2, σ = 50 kPa	Room	Fresh C2	50	< 0.1	15.6	541.3	42.0
	C2, σ = 50 kPa, duplicated	Room.	Fresh C2	50	< 0 .1	15.5	545.9	44.0
	C2, σ = 100 kPa	Room	Fresh C2	100	< 0.1	15.4	549.8	63.7
	C2, σ = 200 kPa	Room	Fresh C2	200	< 0.1	11.3	750.0	105.9
3	C1, σ = 50 kPa, T = 45 °C	46	Fresh C1	50	0.48	15.1	737.3	39.2
	C1, σ = 100 kPa, T = 45 °C	45	Fresh C1	100	0.59	14.6	745.2	44.1
	C1, σ = 50 kPa, T = 45 °C, duplicated	46	Fresh C1	50	–	14.9	760.0	33.3
4	C1, σ = 50 kPa, T = 65 °C	66	Fresh C1	50	0.74	14.7	756.9	13.4
	C1, σ = 100 kPa, T = 65 °C	65	Fresh C1	100	0.38	12.3	903.3	45.1
	C1, σ = 100 kPa, T = 65 °C, duplicated	66	Fresh C1	100	0.42	13.3	835.4	43.5
	C1, σ = 200 kPa, T = 65 °C	64	Fresh C1	200	–	9.0	1234.6	–
5	C2, σ = 50 kPa, T = 45 °C	45	Fresh C2	50	0.49	14.5	580.8	35.5
	C2, σ = 100 kPa, T = 45 °C	44	Fresh C2	100	0.75	13.7	616.4	48.5
	C2, σ = 200 kPa, T = 45 °C	46	Fresh C2	200	1.14	13.5	625.5	76.5
6	C2, σ = 50 kPa, T = 65 °C	66	Fresh C2	50	–	14.7	576.0	23.9
	C2, σ = 100 kPa, T = 65 °C	66	Fresh C2	100	0.3	13.6	620.9	46.1
	C2, σ = 100 kPa, T = 65 °C, duplicated	65	Fresh C2	100	1.19	–	–	39.2
	C2, σ = 200 kPa, T = 65 °C	67	Fresh C2	200	0.59	10	844.4	–
7	C1- 2Y, σ = 50 kPa	Room	C1-2Y	50	< 10	15.3	726.2	26.5
	C1-2Y, σ = 100 kPa	Room	C1-2Y	100	< 10	14.2	782.5	57.5
8	C1-2Y, σ = 50 kPa, T = 65 °C	64	C1-2Y	50	0.69	15.0	740.7	21.9
	C1-2Y, σ = 100 kPa, T = 65 °C	67	C1-2Y	100	1.03	12.7	874.9	42.5
	C1 = waste composition 1							
	C2 = waste composition 2							
	C1-2Y = 2 years old waste							

24-h period, the specimen would be placed in the shear box, the plastic bag would be perforated (for draining during the shear test) and cut horizontally along the shear box halves, so that it could not affect the MSW strength. Then, the desired normal stress was applied and the vertical displacement/settlement for each sample was measured before shearing. In this study, the specimens were tested at room temperature (22–25 °C) as well as at the desired simulated temperatures (50 and 70 °C) within the landfill. The temperatures of up to 65 °C were observed within the Barmshoor landfill. For warmed-up specimens, temperatures of the specimens were checked before and after shearing (Table 2). By inserting a thermometer in the core of the sample before and after the shearing, the average temperature of the waste is calculated and presented in Table 2. The time duration for placing the specimen in the setup and shearing, was less than 30 min. In most cases, the temperature loss of the core of sample where the shear surface occurs was less than 5 °C after the test. Therefore, the temperatures of tested specimens at the end of the test were near the temperatures at the beginning of the test. In addition, all the specimens were tested at or close to the in situ moisture content.

Test series 1 and 2 are performed on specimens from samples C1 and C2 at room temperatures and different normal stresses. The comparison of the test results from these two series showed the effect of fiber content and composition of MSW on its strength properties. To find out the effect of temperature on the mechanical properties of MSW test, series 3–6 were performed and compared with the previous series. The specimens for these series (3–6) were kept in the ovens at 50 °C and 70 °C, respectively, for 24 h, and were sheared/tested at temperatures of 45 °C and 65 °C. To determine the effect of temperature on the aged MSW, series 7 and 8 were performed on the specimens molded from C1-2Y samples. These specimens were tested at room temperature and at 65 °C. Figure 1 shows the sample preparation and setup used in this study. The decomposed 2-year-old sample was darker with less moisture content relative to fresh sample (Fig. 1a). The packed compressed warmed-up samples are presented in Fig. 1b. To check the repeatability of the obtained results, some of these tests were duplicated.

3 Results and Discussion

3.1 Initial Tests on Fresh Waste: Effect of Composition

Based on the data presented in Table 2, initial DS tests were conducted to evaluate and compare the shear strength of different compositions (series 1 and 2). For both compositions, three tests with the normal stresses equal to 50, 100, and 200 kPa were conducted. The results of the shear stress-horizontal displacements of these tests are presented in Fig. 2. It is obvious that, for a certain type of waste, reducing the normal stress causes a reduction in the shear strength. In addition, comparing the tests with the same normal stress, but with different composition shows that composition affects the shear strength to some extent.

It is well known that the strength of MSW is affected by the composition or fibrous materials such as plastics, textiles, and wood [9, 16, 31–34]. Considering the plastic and textile fractions as the fibrous content, a significant difference was observed in the fibrous content of C1 and C2. The fibrous contents of C1 and C2 are about 11 and 20%, respectively. The fibrous content plays a key role in the shear strength, and different observations have been reported in this respect. Landva and Clark, Zekkos et al. and Karimpour-Fard et al. [17, 28, 35] reported reduction of the shear strength with increasing the fiber content.

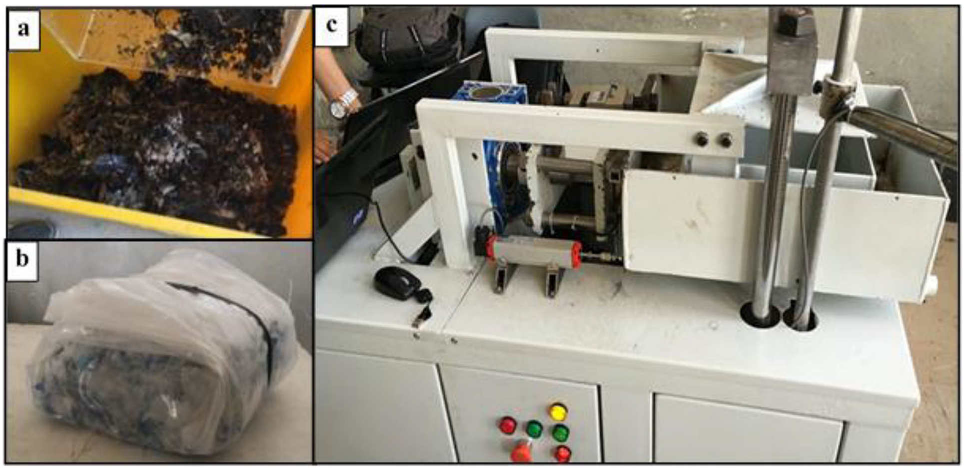

Fig. 1 Sample preparation and testing setup; **a** 2-year-old waste, **b** compressed warmed-up waste before shearing, and **c** DS setup

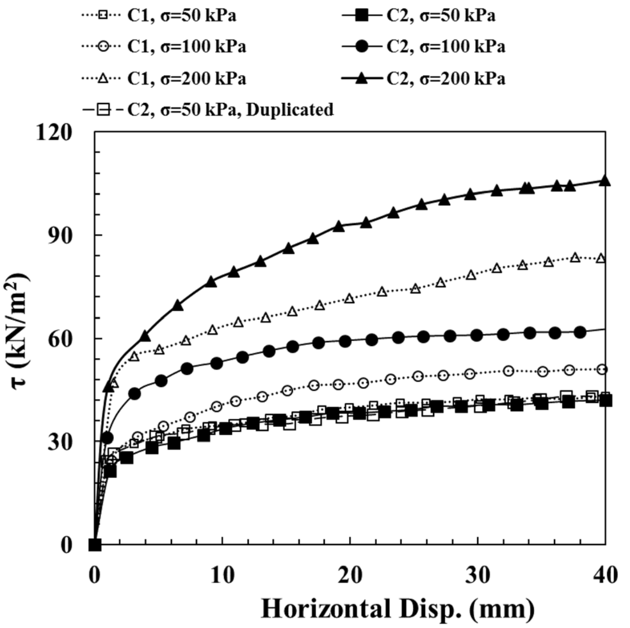

Fig. 2 Effect of composition of MSW on shear stress-horizontal displacement curve

However, our results are in line with studies of Zekkos et al. [36] who reported an increase in the shear strength with increasing the fiber content of the waste.

To calculate the MSW shear resistance parameters, i.e., the cohesion (*c*) and angle of internal friction (ϕ), Mohr–Coulomb envelope was used. The related results are presented in Table 3. Parameters *c* and ϕ for 25 mm as well as for the peak strength are calculated and presented in this table [13, 37]. The C1 with fewer fiber content and higher moisture content and wet and organic matter has smaller friction angle and larger intercept cohesion relative to C2. The strain level is effective on the friction angle of C1 and increasing of the strain level changes the friction angle from 14° to 16°. However, it did not change the friction angle of C2. Babu et al. [38] concluded that increasing the axial strain in triaxial test or deformation in DS test increased the shear strength of MSW, and in DS test, more deformation increased the cohesion and friction angle. Although Bray et al., Zekkos et al., Babu et al., and Gomes et al. [9, 36, 38, 39] reported an upward curvature of the stress–displacement curve due to shearing of oriented fibers of MSW, this was not observed in this study. Bray et al. [9] reported that the specimen with horizontal fiber orientation does not exhibit an upward curvature in DS test; however, an increasing shear stress with horizontal displacement was observed. Bareither et al. [40] also reported downward curvature with increasing strength in DS tests. The stress–strain response depicted in Fig. 2 shows a downward curvature with increase in the strength. Results confirm that placing of the waste in the shear box has been accomplished with nearly horizontal fibers. Therefore, any change in strength in warmed-up specimens in the next section is more attributed to temperature (not randomly fiber orientation).

Table 3 The Mohr–Coulomb envelope for MSW by DS test at room temperature

Composition	25 mm displacement		Peak strength	
	C (kPa)	ϕ (°)	*C* (kPa)	ϕ (°)
C1	26.3	14	26.1	16
C2	19.6	23	22.9	23

3.2 Influence of Temperature on Vertical Compression Before Conducting Shear Force

After placing a specimen in the shear box and exerting the desired normal stress, the initial settlement was measured by vertical ruler to determine the exact volume and total unit weight before shearing. This settlement was measured from the top of the shear box. Table 2 illustrates the height of each sample. Figure 3 represents the measured settlement before shearing at the normal stresses between 50 and 200 kPa and the related temperatures. Depending on the normal stress at the room temperature, the settlements of C1 and C2 were restricted to the range of about 9–15 mm. As the temperature of both wastes increased the settlement of the waste increased, too. The settlements due to 200 kPa stresses for the warmed-up samples were measured to be more than 65 mm. This was too high to perform shearing procedure, since the shearing zone is limited by the upper plate of the DS setup.

Cerato and Lutenegger [41] discussed the specimen scale effects of DS test and demonstrated that it is

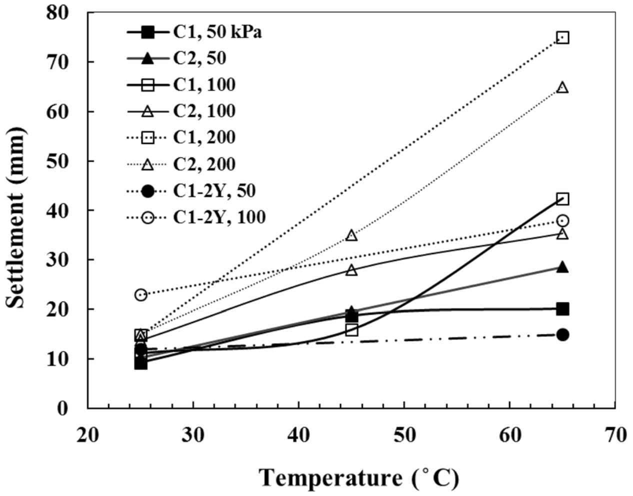

Fig. 3 Settlement due to normal stress before shearing vs waste temperature

important to take the aspect ratio into account (height relative to the width) when conducting direct shear test and understand that this parameter affects the results. Moreover, the effect of the temperature on the compression results began some challenging affairs in the sample preparation, and increased the unit weight of the warmed-up samples. For composition C1-2Y, the same results were obtained, but with less magnitude.

3.3 Influence of Temperature in Shearing on MSW

Test series 3–6 in Table 2 were considered to deliver and prove the main objective of this research. In these series, both compositions of the fresh waste were warmed-up at 50 °C and 70 °C and sheared immediately at about 45 and 65 °C. During the performing of the tests, it was obvious that the waste had been changed, dramatically. The plastic fraction of both compositions was clearly more compressible in high temperatures. Figure 4 compares the DS test results conducted on C1 at 25, 45, and 65 °C temperatures in shearing for 50 and 100 kPa normal stresses. It is worth mentioning that the warmed-up C1 sample under 200 kPa compressed more than 70 mm vertically; therefore, shearing of the warmed-up samples under this stress was impossible. Figure 4 shows that warming up and shearing the samples cause the shear strength to be decreased.

The same results for the composition C2 are illustrated in Fig. 5 where the results of the DS tests are compared at different temperatures for normal stresses equal to 50, 100, and 200 kPa. Due to high initial vertical displacement (> 60 mm), testing/shearing of specimen with a normal stress of 200 kPa and temperature of 65 °C was impossible. For all the normal stresses, warming up the specimen to 45 and 65 °C causes a reduction of the strength. In both figures, the duplicated tests coincide to each other and demonstrate good agreement. Although the strength of the warmed-up samples was decreased, according to Table 2, the initial unit weight of these samples, especially at 65 °C, was more than the tests of series 1 and 2. This can be attributed to the greater settlement as discussed in the previous section. MSW consists of heterogeneous materials with different stress–strain behaviour and response to heat changes. The shear strength of warmed-up MSW may be affected by different factors and mechanisms. Defining and understanding of these factors and mechanisms are beyond the aim of this study.

The C1 and C2 compositions are fresh wastes with different fiber and organic contents. To explore whether the foregoing results from Figs. 4 and 5 are reliable for an aged waste, the tests series 7 and 8 (Table 2) were performed and the related results are presented in Fig. 6. It is obvious that the temperature in shearing does reduce the strength. It is worth nothing that, contrary to fresh wastes C1 and C2, the C1-2Y has probably experienced in situ temperature. Waste specification (such as composition, fiber content, and age) may affect the response of the MSW stress–strain when it is loaded at simulated landfill temperature. More investigations are needed to find out how the waste specification affects the response of warmed-up MSW.

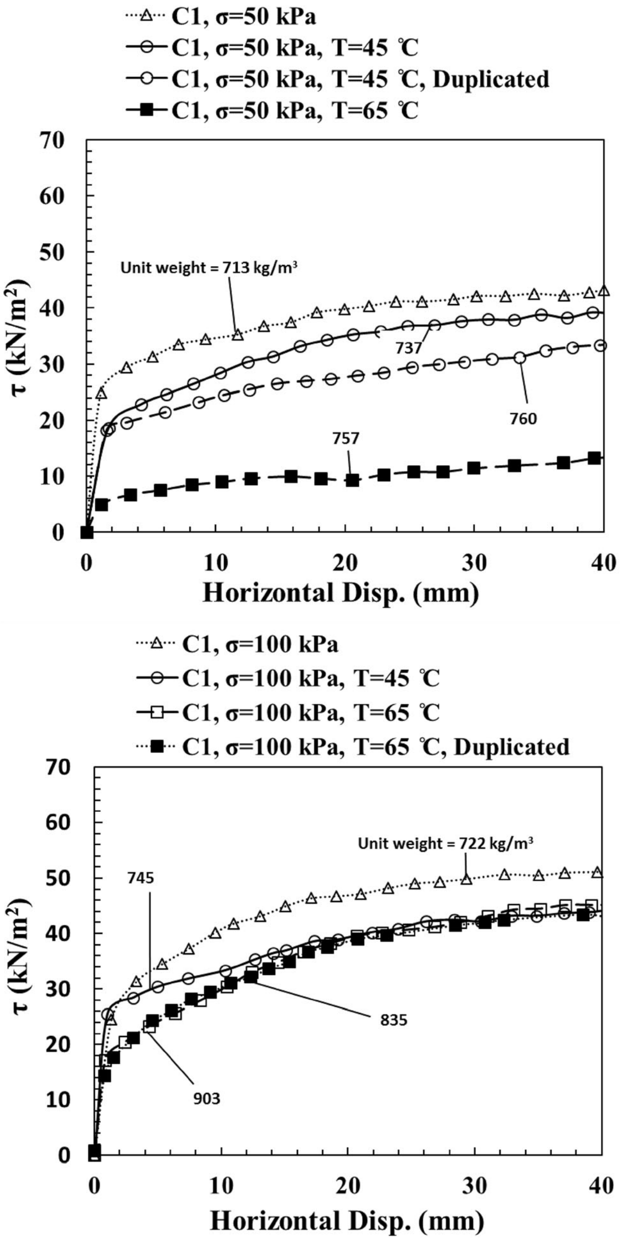

Fig. 4 Shearing behaviour of waste C1 under different temperatures

The compressibility of the warmed-up specimens under a certain load was more than that of the room-temperature specimens, as discussed previously. Figure 7 demonstrates the total unit weight of the specimens after normal loading phase and prior to the shearing phase. For a certain

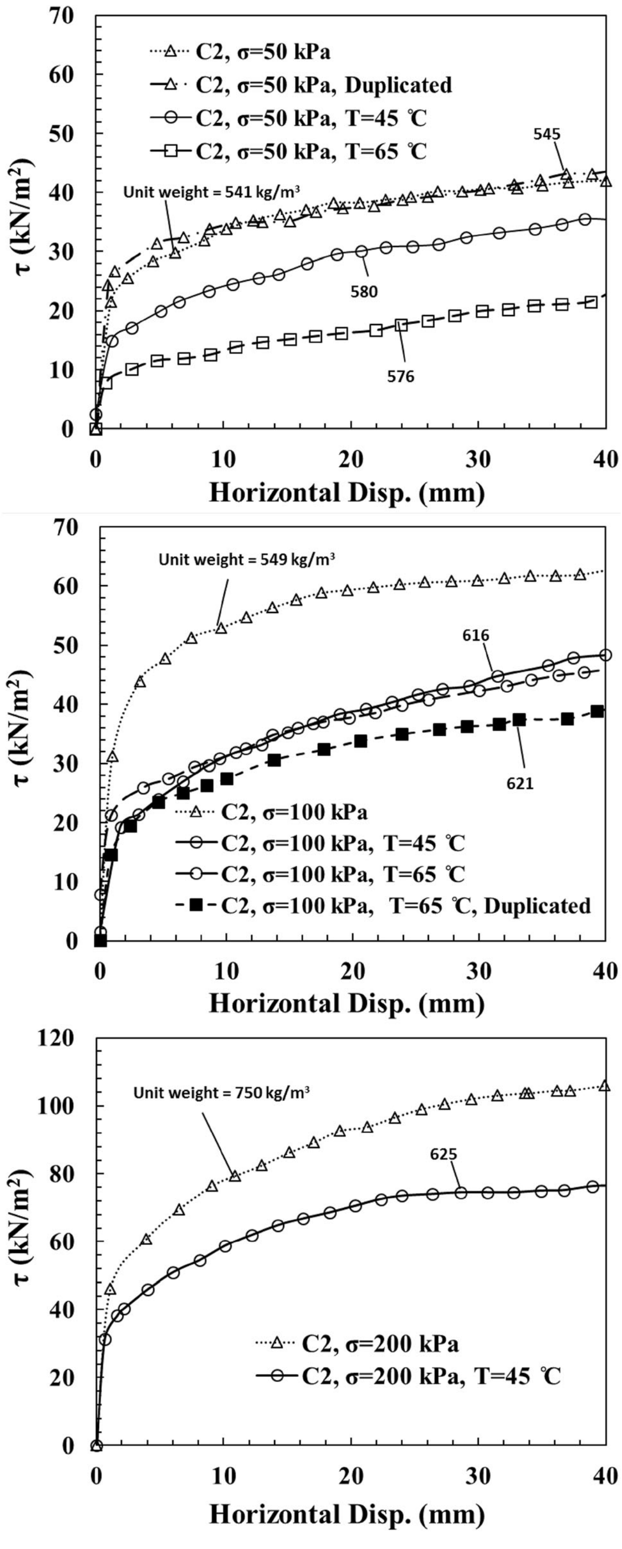

Fig. 5 Shearing behaviour of waste C2 at different temperatures

composition (C1 or C2), the unit weights of the warmed-up specimens are further and more dependent on normal stress relative to the room-temperature specimens.

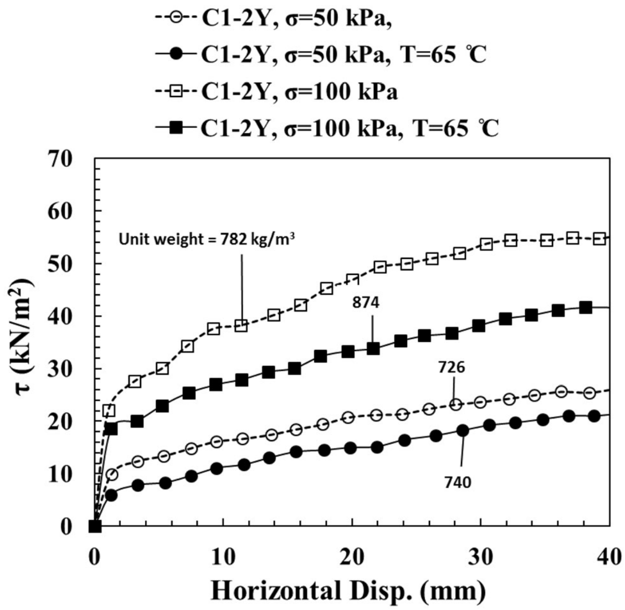

Fig. 6 Shearing results of 2-year-old waste at room and 65 °C temperatures

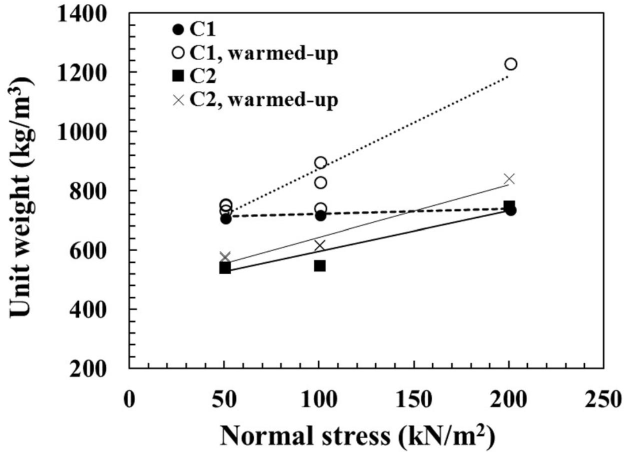

Fig. 7 Total unit weight of specimens prior to shearing phase vs normal stress

Some researchers concluded that unit weight was an important factor in shear strength of MSW [6, 9, 36, 38]. They concluded that the shear strength increases with increasing the unit weight of MSW. Zekkos and Fei [42] reported that the shear strength parameters of compacted MSW specimens are higher than uncompacted specimens. Although the unit weight of the warmed-up specimens has increased (relative to the room-temperature specimens), the shear strength for a certain normal stress has decreased according to Figs. 4 and 6. The peak shear strength of each specimen is given in Table 2. Figure 8 also demonstrates the normalized shear strength vs temperature by normalizing the warmed-up shear strength ($\tau_{T\ ^{\circ}C}$) to the room-

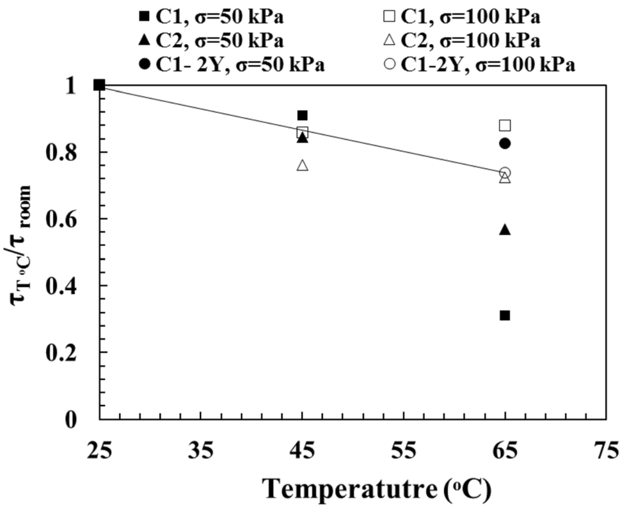

Fig. 8 The relation between normalized shear strength and temperature

temperature shear strength (τ_{room}) at the same applied normal stress. For a certain normal stress, all the samples with room temperature show more shear strength. These results are the same for C1-2Y composition (i.e., strength reduction of the warmed-up specimen with more unit weight relative to room-temperature specimen as depicted in Fig. 6). Consequently, it can be concluded that, for warmed-up specimens, between the reduction of strength by temperature and increase of the strength by unit weight, the former governs.

Temperature may change the organic part of the waste in a short time, especially in the fresh waste. This may decrease the stiffness and make this part softer and more ductile, thus, causing lesser strength. MSW is a mixture of this wet and organic waste and a significant fraction of plastic. It is well known that the temperature affects the mechanical behaviour and elastic modulus of the polymers. Different polymers depend on their molecular structure, which experience from glass-like brittle behaviour at low temperatures to a rubber-like behaviour at high temperatures [43]. Consequently, the temperature makes the plastic more flexible, causing the waste more compressible under a certain pressure. On the other hand, further temperature decreases the plastic modulus and tensile strength and may decrease the fibrous role of the plastic fiber. The temperature in shearing of MSW C1 and C2 decreased the strength and this reduction may be due to the softening of waste.

Testing method, apparatus, and sample preparation may also affect the results of the warmed-up samples. For example, Bray et al., Zekkos et al., Karimpour-Fard et al., and Abreu and Vilar [9, 17, 26, 28] reported significant differences and difficulties between direct shear (DS) and triaxial test on MSW. They stated that, with the DS test, the main reinforcing components are parallel to the shearing plane, therefore; the reinforcing elements are not mobilized. Moreover, shearing by a triaxial test may result in another behaviour, since the tensile strengths of the fibers are temperature-dependent. Therefore, conducting tests with temperature-controlled device (triaxial) is recommended. Such devices may also be used to investigate the pore water pressure variation for warmed-up specimen.

3.4 Influence of Temperature in Shearing on Mohr–Coulomb Strength Parameters

For this study, the Mohr–Coulomb strength parameters for the warmed-up and room temperature specimens, i.e., the cohesion and friction angle, are separately calculated and presented in Fig. 9. It is concluded that temperature decreases both cohesion and friction angle.

According to this figure, the temperature decreases the friction angle from 21° to 17° for $T > 45$ °C. The cohesion was also decreased by temperature from 19.9 to 13.1 kPa. In this regard, it is worth noting to Fig. 7, where the variation of the unit weight with the temperature for different waste compositions is shown. Although the unit weight of warmed-up specimen has increased, but reduction of these parameters is governed by the heat effect.

For a better interpretation of the results, it is necessary to consider the secant friction angle; ϕ_s, to define a nonlinear envelope. Bray et al., Zekkos et al., and Ramaiah et al. [9, 13, 17, 36] used the secant friction angle in the analysis of their results obtained by DS setup. Stark et al. [37] emphasized that, due to the importance of the stress dependent nature of MSW and nonlinearity of the strength envelope, the shear strength can be evaluated in the terms of mobilized secant friction angle. Secant friction angles

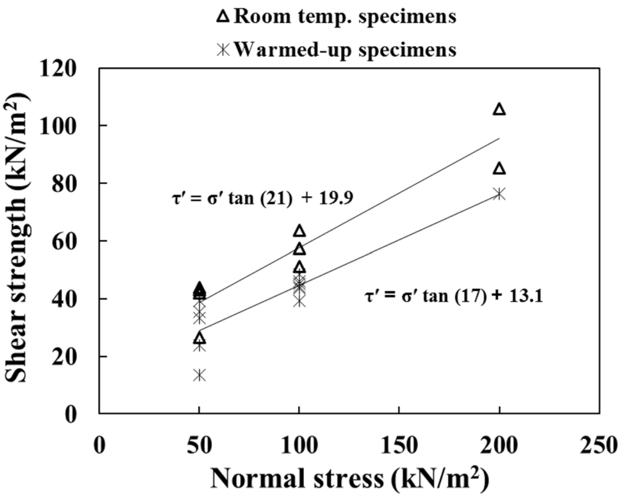

Fig. 9 The Mohr–Coulomb strength parameters for warmed-up and room-temperature specimens

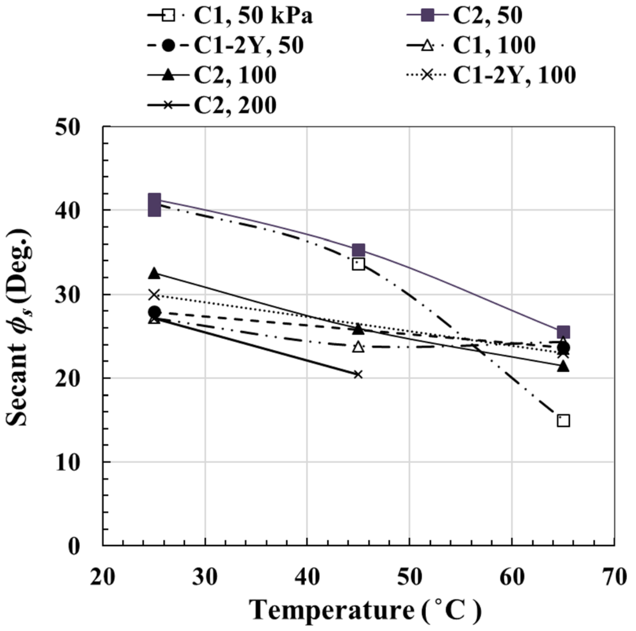

Fig. 10 Variation of secant friction angle with shearing temperature (for c = 0)

(for c = 0) were calculated for each normal stress and plotted versus the temperature in Fig. 10. For all compositions and normal stresses, ϕ_s decreases with increasing the shearing temperature.

In this study, to compare the changes of strength parameters, we determined the envelopes for the sheared waste at room and landfill temperatures. Bray et al. and then Ramaiah et al. [9, 13] used a nonlinear envelope defined as follows:

$$\tau = c + \sigma_n \cdot \tan(\phi_\sigma) \quad (1)$$

$$\phi_\sigma = \phi_0 - \Delta\phi \cdot \log(\sigma_n/p_a), \quad (2)$$

where τ is shear strength, c is cohesion intercept, σ_n is normal stress, ϕ_σ is normal stress dependent friction angle, ϕ_0 is friction angle measured at a normal stress of 1 atm, $\Delta\phi$ is change of the friction angle over one log-cycle change of normal stress, and p_a is atmospheric pressure.

A linear best curve fitting was applied for the variation of secant friction angle with σ_n for both categories of ϕ_s (i.e., at the room and landfill temperatures) at different intercepts c. Then, R^2 for each intercept is calculated as in Table 4.

According to Table 4, the highest R^2 for the warmed-up waste was obtained at c = 10 kPa. To compare the difference between ϕ_σ for both cases, c = 10 kPa was selected. To calculate ϕ_σ, the variation of ϕ_s with log (σ_n/p_a) is plotted in Fig. 11. By selecting c = 10 kPa and combining with the proposed equations in this figure, we can compare the drop of the strength due to the temperature effects in shearing. Table 5 compares the proposed envelopes by different researchers with the envelopes in this study. Bray et al. [9] developed an envelope by mobilized shear strength data form the Tri-Cities landfill, and then presented the second one based on a database of 109 large-size direct shear tests. Ramaiah et al. [9, 13] also used more data to develop a new nonlinear envelop; however, they finally proposed a linear strength envelope.

Table 4 R^2 for linear fitting on secant friction angle vs. σ_n

Intercept c (kPa)	ϕ_s Room temp	ϕ_s Warmed-up
0	0.71	0.70
5	0.79	0.78
10	0.85	0.81
15	0.88	0.80

Regarding Table 5, it is obvious that the shear strength envelopes of this study underlie the other ones. It may be due to the lower threshold displacement (where strength is defined), the higher moisture content, and wet waste and lower unit weight of the waste compositions relative to the other references. The envelope for $T \geq 45$ °C underlies the

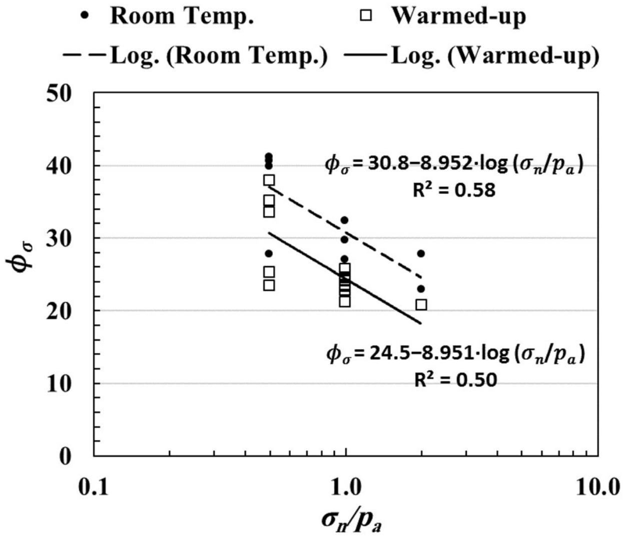

Fig. 11 Linear fitting to determine ϕ_σ equation

Table 5 Proposed nonlinear envelopes ($\tau = c + \sigma_n \tan \phi_\sigma$)

Reference	C (kPa)	σ_n (ϕ_σ/a)
Bray et al. [1]	15	σ_n = 41–12 × log
Bray et al. [2]	15	σ_n= 36–5 × log
Ramaiah et al. [13][a]	0	σ_n= 39.7–16.9 × log
This study, T = 25 °C	10	σ_n= 30.8–8.9 × log
This study, $T \geq 45$ °C	10	σ_n= 24.5–8.9 × log

[a] A linear model proposed because of better fitting

Table 6 Reduction of friction angle and shear strength due to temperature

σ_n (kPa)	ϕ_σ (°)		ϕ_σ Reduction	τ (kPa)		τ Reduction
	T = 25 °C	$T \geq 45$ °C	(%)	T = 25 °C	$T \geq 45$ °C	(%)
50	34	27	19	43.2	35.7	17
100	31	25	21	69.8	55.6	20
200	28	22	23	117.1	90.0	23

one for T = 25 °C, which means that the strength of the waste reduces when the temperature of the waste is high in shearing.

To quantify the reduction of the strength caused by the temperature in shearing, ϕ_σ and τ were considered for both thermal conditions, and then, the percent of relative reduction is calculated in Table 6. These calculations show, with normal stress of $50 \leq \sigma_n$ (kPa) ≤ 200 and MSW compositions of this research, the friction angle and shear strength reduce near 20%. It is worth noting that the waste used in this study was fresh, or less than 2 years old with the shearing temperatures of 45 and 65 °C.

4 Conclusions

In the recent decades, researchers neglected the effect of temperature within the landfill in shearing when assessing the mechanical behaviour of MSW, particularly during the testing in the laboratory. In addition, the outcome and conclusions by other researchers in correlating in situ measurements of the shear strength of a landfill with laboratory test data are controversial because of eliminating/neglecting the landfill temperature in the laboratory during the preparation and testing of MSW. This study focused on a series of the laboratory tests on MSW by the direct shear box, while the temperature of waste specimens was the same as an anaerobic landfill (less than 70 °C). Drained condition was considered and possible effects of the temperature on the excess pore pressure on the waste mass were not investigated. The main conclusions are as follows:

- Vertical compression of the samples in the box at a normal stress is temperature-dependent and was measured in the range of 9–15 mm at 25 °C; however, it increased to 30–75 mm at 65 °C. The settlements due to 200 kPa normal stress for the warmed-up samples were too high to perform shearing procedure. Therefore, temperature increases the compressibility and unit weight of the warmed-up samples under a certain normal stress.
- Although the warmed-up specimens are denser under a certain normal stress, warming up to 45 and 65 °C causes reduction of the shear strength of the fresh waste. It seems that, among two different mechanisms, i.e., strength reduction by the temperature and increasing of the strength by higher unit weight, the former governs on the fresh MSW.
- For both C1 and C2 (the fresh wastes) compositions, warming up the waste for a short period of time (about one day) even at a low temperature (≥ 45 °C) will cause the reduction of strength.
- Temperature decreases the friction angle from 21 to 17° for $T > 45$ °C. The cohesion was also decreased by temperature from 19.9 to 13.1 kPa. Although the unit weight of warmed-up specimen has increased, but reduction of these parameters is governed by the heat effect.
- Using a statistical analysis and developing two nonlinear envelopes (used by Bray et al. 2009) for testing/shearing the waste at room and landfill temperatures, shearing MSW compositions of this research with normal stresses of between 50 and 200 kPa, and shearing temperature between 45 and 65 °C the friction angle and shear strength reduces about 20%.
- Landfill temperature should be considered as a factor that affects the shear strength of MSW in addition to other factors such as composition, rate of loading, age of the waste, confining pressure, and strain level.

Defining and understanding the effective factors and mechanisms which cause the reduction of the strength of the warmed-up specimens relative to cold specimens are beyond the aim of this study. However, softening of the waste materials (especially organics) seems to be an important factor. Waste specification and testing method may be effective, too. As a result, considering temperature for site investigation of the shear strength and the correlation of the results with the laboratory tests is important. Knowing the in situ temperature of the waste is important in comparing the mechanical behaviour of the MSW using laboratory and in situ testing.

Finally, there are some aspects of the temperature effects in shearing of MSW that were not addressed throughout this study. Limitation of the DS device in activating fibers is a major concern, since the tensile strength and modulus of plastic waste are temperature-dependent. The composition and unit weight used in this research was considered the same as a case study with low compacting effort and high moisture content and food waste. Moreover, the temperature used in this study was in the range of an anaerobic landfill, which is common in the developing countries, and the tests were mostly conducted on the fresh waste.

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