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An experimental investigation on the mechanical behavior of MSW

M. Karimpour Fard[1], N. Shariatmadari[2,]*, M. Keramati[2], H. Jafari Kalarijani[2]

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Abstract

Due to the existence of fibrous materials such as plastic fragments, the strength anisotropy of Municipal Solid Waste (MSW) materials is the main source of differences between their mechanical response in direct shear and triaxial apparatus. As an extension of earlier research on the mechanical behavior of MSW using a large traixail apparatus, results presented in Shariatmadari et al. [1] and Karimpour-Fard et al. [2], the current study was programmed and executed. MSW samples were tested using a computer controlled large shear box apparatus with normal stress levels ranging between 20 to 200 kPa. The effect of fiber content, fiber orientation, aging and shearing rate on the response of MSW were addressed. The results showed that shear strength of MSW increases with normal stress, although, in spite of the presence of reinforcement elements in MSW and unlike the results from triaxial tests, no strain hardening could be observed in their mechanical response. An increase in the shear strength of MSW was observed with increasing the shearing rate. Increasing the shearing rate from 0.8 to 19 mm/min, enhanced the shear strength of samples from 16 to 27% depending on the shear displacement level. Although, the same trend was investigated in traixial tests, but lower rate-sensitivity in the mechanical response of MSW in direct shear tests were observed.

Unlike the results of triaxial tests with aging process, mobilized shear strength level of MSW samples tested under direct shearing decreased comparing fresh samples. It was also observed that altering the fiber content and their orientation could affect the mechanical response and shear strength of the MSW. Additionally, there is an optimum fiber angle in MSW which yields the highest level of shearing strength.

Keywords: *Direct shear test, Landfill, Municipal solid waste, Mechanical behavior.*

1. Introduction

Landfilling as a common and appropriate approach for disposing MSW materials has attracted the attention of many researchers in different related fields over the last decade.

From the geotechnical engineering point of view a landfill's design and construction, like other types of embankments, should be accompanied by sound and precise stability analysis. This is imperative for two main reasons: their failure will probably result in huge financial losses and secondly, environmental pollution and damage can be caused with devastating effects to local communities.

The main material that shapes the landfill body is MSW whose mechanical behavior governs both the overall and partial stability aspects of the landfill. However, due to the composite nature of this material and high variability of its components, the characterization of its shear strength is difficult.

As such, the evaluation of the mechanical behavior of MSW materials has been the subject of a large amount of research.

Landva and Clark [3, 4], Jessberger and Kockel[5], Gabr and Valero [6], Grisolia et al. [7], Grisolia and Napoleoni[8], Manassero et al. [9], Kavazanjian [10], Machado et al. [11, 12 and 13], Vilar and Carvalho[14], Zekkos[15], Reddy et al. [16, 17], Shariatmadari et al. [1], Bray et al., [18], Zekkos et al., [19], Karimpour-Fard et al [2] and many others are examples of research carried out into the mechanical behavior of MSW.

Between 1977 and 2005 at least six large-scale failures of municipal solid waste dumps and landfills were recorded of which two occurred in engineer-designed landfills, Dona Juana in Columbia and Bulbul landfill in South Africa [20]. This indicates that the mechanical behavior of MSW materials, in spite of all the valuable research, is still not completely known.

In landfill design, stability analyses are performed using the shear strength parameter of MSW materials in the form of the cohesion intercept and the internal friction angle achieved from direct shear and triaxial tests. As well as the difficulties related to the interpretation of shear tests on MSW materials, the difference between the mechanical response of MSW in direct shear and triaxial tests could

** Corresponding author: shariatmadari@iust.ac.ir*
1 Faculty of Engineering, The University of Guilan, Rasht, Iran
2 Dept. of Civil Engineering, Iran University of Science and Technology, Narmak, Teharn, Iran

cause a considerable difference between the related shear strength parameter.

This paper embraces the results of research carried out to evaluate the mechanical response of MSW using a computer controlled large shear box apparatus. It is an extension of earlier research performed on MSW using a large triaxial apparatus the results of which were published in Shariatmadari et al. [1] and Karimpour-Fard et al. [2]. This paper, firstly attempts to evaluate the effect of factors such as normal stress, shearing rate, aging, fiber content and fiber orientation on the mechanical response of MSW materials. Secondly, by comparing the observed mechanical response of MSW samples in direct shear test apparatus with those achieved from triaxial apparatus, the effect of the shearing mechanism on the mechanical behavior of MSW materials are discussed.

2. Materials, Equipment and Testing Program

2.1. Materials used

The MSW samples were collected from the Kahrizak Center Landfill (KCL) located around 40 Km from Tehran, capital of Iran. The daily input of MSW in this landfill is about 9000 tons, most of which comes from Tehran which has an estimated population of 10 million, makes it the biggest MSW disposal center in Iran.

Fig.1 shows that composition of the MSW in this landfill. As can be observed in this figure, paste or wet materials make up the main component of MSW in KCL with around 70%. If plastic fraction and textiles considered fiber elements, KCL's MSW exhibits fiber content of around 12%. It should be mentioned that because of the high moisture content of the MSW materials which leads to strength loss of papers and cardboards in this landfill, these materials are not counted as fiber elements in this research.

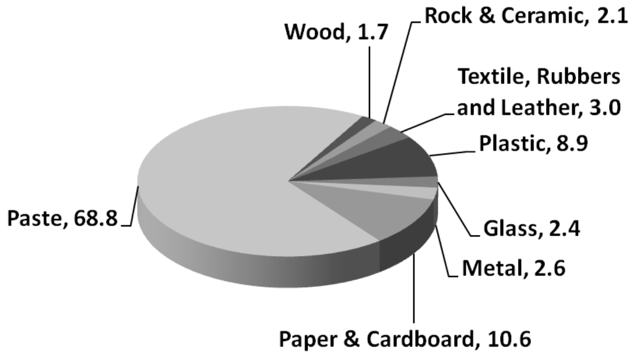


Fig. 1 MSW composition in the KCL

Fig. 2 depicts the average size distribution of the MSW materials in this landfill which is between the boundary limits suggested by Jessberger[21].

Fresh samples after preliminary processing. i.e. removing large particles (the maximum size of collected particles was 5cm), putting in plastic drums, were transported to laboratory. Measurements showed that the dry based water content and organic percentage of fresh samples on average were 70% and 65% respectively with an average plastic fraction of 5.6% by weight. To address the fiber content effect on the mechanical response of MSW, samples with different plastic content, 0%, 6% and 12% were tested. To prepare these samples, first all the plastic fraction and foil like materials inside the MSW were removed and then different percentages of plastic were added to the non-fibrous MSW.

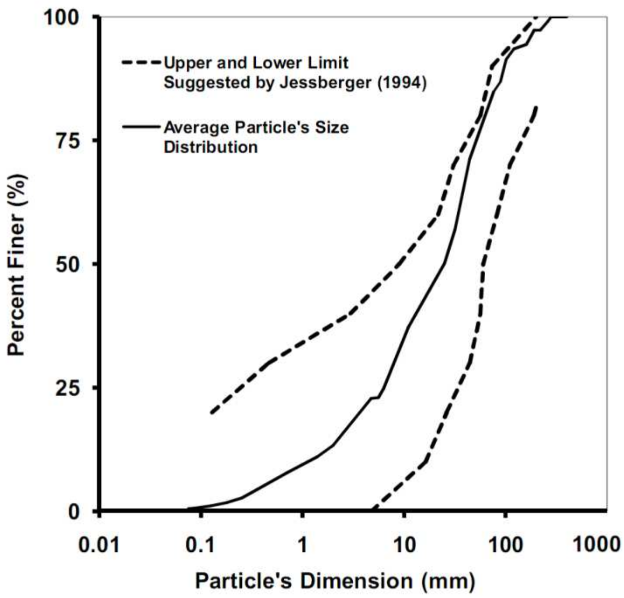


Fig. 2 MSW average size distribution

Generally in conventional landfilling techniques, MSW decomposed under anaerobic conditions after the aerobic phase which the oxygen entrained in the refuse at burial is consumed. To overcome problems due to low rate of stabilization in decomposition process, bioreactor landfills were developed which the major aspect of their operation is the recirculation of collected leachate back through the refuse mass to enhance refuse decomposition, gas production, and waste stabilization.

In the recent work also the techniques used in bioreactor landfill was employed. The samples to be tested in fresh conditions were placed in thick plastic bags and preserved in a fridge at a temperature of 5 degrees Celsius and the rest was kept in drums at environment temperature to be decomposed and prepared for testing as aged MSW samples. Drums containing the aged waste were equipped with a drainage valve to drain and recirculation of the produced lechate.

2.2. Direct shear test apparatus

A large computer controlled direct shear apparatus with a shear box with dimensions of 300 mm x 300 mm x 150 mm was used to perform the shear tests. The device has the capability of applying a shearing force of up to 100 kN and a maximum vertical load of 50 kN to produce normal stress up to 500 kPa. An electrical motor applied the horizontal displacement to produce shearing stress at a constant rate changing from 0.001 to 19 mm per minute.

The shear displacement and vertical deformation of the specimen was measured by two LVDT with a traveling course of 10 and 3 cm respectively. The shear load is measured by a proving ring, equipped with a digital dial gauge and connected to the shear box.

2.3. Specimen preparation and test schedule

Samples were compacted in four layers using a handy standard tamper, trying to fill the corners of shearing box to reach a nominal unit weight of 11 kN/m^3. It is comparable to the in-situ unit weight of MSW in KCL which is around 10 kN/m^3.

In the case of samples with non-horizontal fiber orientation (in each fiber contents 0, 6% and 12%, samples with fiber orientation of 0, 30, 60 and 90 degree were prepared and sheared), a split mold was made and used according to Zekkos[15]. Fig. 3 illustrates the sample preparation with different fiber orientations.

After this stage the samples were consolidated for at least 24 hours until they reached a negligible vertical deformation. It should be mentioned that in this research the samples were sheared at their natural water content without saturation.

Four levels of normal stress, 20, 50, 100 and 200 kPa were selected to perform tests in each set and a shearing rate of 0.8 mm/min was adopted as the base value. This rate is comparable with the shearing rates used by Zekkos[15] and Jones et al. [22].

Totally 57 tests were carried out in this research which could be observed with some brief details in Table 1.

Fig. 3 Preparation of samples with (a) vertical, (b) non-vertical fiber's orientation

Table 1 List of performed tests

No.	n (kPa)	F. C.* (%)	Orientation or compaction Angle (^{o})	Density (kN/m^3)		Shearing Rate (mm/min)	Age (month)
				Before consolidation	Before shearing		
1	20	5.6	0	11.12	11.83	0.8	0
2	50	5.6	0	11.15	13.05	0.8	0
3	100	5.6	0	11.05	13.67	0.8	0
4	20	5.6	0	11.2	11.75	8	0
5	50	5.6	0	11.14	13.21	8	0
6	100	5.6	0	11.3	13.72	8	0
7	20	5.6	0	11.11	11.85	19	0
8	50	5.6	0	11.23	13.07	19	0
9	100	5.6	0	11.07	13.71	19	0
10	20	5.8	0	11.18	11.96	0.8	3
11	50	5.8	0	11.23	13.11	0.8	3
12	100	5.8	0	11.31	13.14	0.8	3
13	20	5.7	0	11.34	11.72	0.8	6
14	50	5.7	0	11.21	13.32	0.8	6
15	100	5.7	0	11.24	13.87	0.8	6

16	200	5.7	0	11.07	14.12	0.8	6
17	20	7.2	0	10.92	12.5	0.8	18
18	50	7.2	0	10.97	12.75	0.8	18
19	100	7.2	0	11.05	13.15	0.8	18
20	20	0	0	12.06	12.78	0.8	0
21	50	0	0	12.07	13.12	0.8	0
22	100	0	0	12.11	13.24	0.8	0
23	200	0	0	12.06	14.69	0.8	0
24	200	0	30	11.53	13.45	0.8	0
25	200	0	60	11.64	13.7	0.8	0
26	200	0	90	11.35	13.85	0.8	0
27	200	6	0	11.32	11.75	0.8	0
28	50	6	0	11.21	12.79	0.8	0
29	100	6	0	11.26	13.1	0.8	0
30	200	6	0	11.19	13.61	0.8	0
31	20	12	0	10.34	11.1	0.8	0
32	50	12	0	10.28	11.57	0.8	0
33	100	12	0	10.12	11.68	0.8	0
34	200	12	0	10.23	12.23	0.8	0
35	20	100	0	7.53**	8.73	0.8	0
36	50	100	0	7.57**	9.14	0.8	0
37	100	100	0	7.82**	9.34	0.8	0
38	20	6	30	11.17	11.15	0.8	0
39	50	6	30	11.12	11.32	0.8	0
40	100	6	30	11.19	11.99	0.8	0
41	200	6	30	11.16	13.25	0.8	0
42	20	6	60	10.92	11.33	0.8	0
43	50	6	60	11.12	11.89	0.8	0
44	100	6	60	11.04	12.91	0.8	0
45	200	6	60	10.89	12.98	0.8	0
46	20	6	90	11.34	11.31	0.8	0
47	50	6	90	11.23	11.72	0.8	0
48	100	6	90	11.42	12.07	0.8	0
49	200	6	90	11.16	12.96	0.8	0
50	20	12	30	10.23	10.94	0.8	0
51	200	12	30	10.45	11.53	0.8	0
52	100	12	60	10.27	11.95	0.8	0
53	200	12	60	10.05	12.52	0.8	0
54	20	12	90	10.68	11.39	0.8	0
55	50	12	90	10.53	11.78	0.8	0
56	100	12	90	10.59	11.94	0.8	0
57	200	12	90	10.58	12.54	0.8	0

*: Fiber Content; **: dry density

3. Results and Discussion

3.1. Basic tests

To evaluate the effect of different target factors, a series of tests were performed on the fresh sample using a base initial state and loading condition.

The samples were sheared under normal stresses of 20, 50 and 100 kPa at a loading rate of 0.8 mm/min up to 4.5 cm of horizontal displacements.

According to Fig. 4, MSW samples exhibit a contractive behavior and their mechanical response demonstrates a downward curvature approaching an asymptote at high values of horizontal displacements [3, 4, 23, 24, 10, 18 and 19].

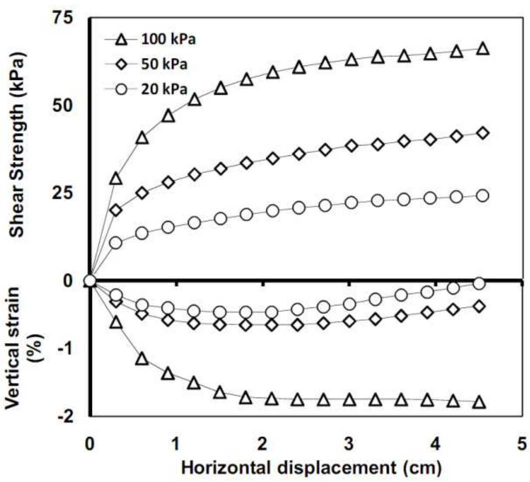


Fig. 4 The results of base tests

Kölsch[22] suggests the mechanical response of MSW involves four different stages (Fig. 5). According to this proposed mechanism with progress in shearing, the tensile forces in the fiber are activated, leading to a considerable enhancement in the overall shear resistance. Softening occurred in fibers and their tearing due to reaching their tensile strength or pulling out of surrounding materials resulting in a significant decrease in overall shear strength. Lastly, the residual shear resistance of the frictional components remains active as all the reinforcement effects have been eliminated.

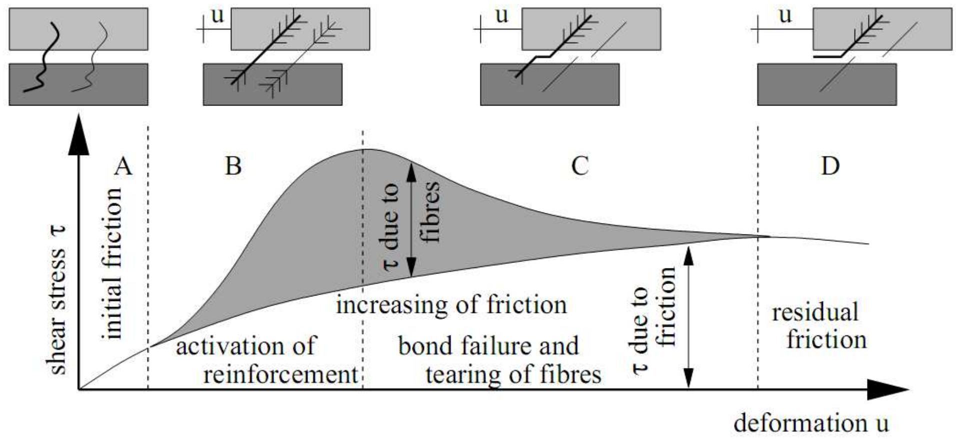


Fig. 5 Proposed mechanism for the mechanical behavior of MSW by Kölsch (1995)

A comparison between the proposed mechanism by Kölsch [22] and the results of the performed direct shear test (Fig. 4) indicates that the mechanical response of MSW samples in direct shearing do not include the reinforcement action of fibrous materials and as such samples behave rather like a frictional material.

According to Matasovic and Kavazanjian[24], although the waste material was not oriented preferentially when placed initially, the fibrous constituents of the waste tend to become aligned sub-horizontally as a result of compaction and the increasing vertical stress from placing additional waste on top of previously placed waste. The same trend was also observed in the direct shear tests.

In the direct shear tests, the fiber orientation is almost synchronized with the shear plane. As a result, shearing occurs parallel to the fibers and therefore no enhancement occurs in the shearing strength of the samples due to the lack of a reinforcement effect.

In the case of the triaxial apparatus in which MSW shows considerable strain hardening, even though during specimen preparation the fibers tend to orient themselves sub horizontally, as the shear plane has an orientation of $45+\theta/2$ to the horizontal direction, the shearing plane should pass and cut through the fibers which mobilize their reinforcement action during the shearing stage.

3.2. Effect of fiber content

It is commonly believed that the MSW fibrous components play a key role in the mechanical behavior of MSW [10, 25]. However, the number of papers that have systematically evaluated the effect of the fibrous waste components on the MSW mechanical response of MSW is limited.

Landva and Clark [4] during their research into MSW samples collected in different regions of Canada concluded that samples with higher plastic contents exhibit a lower level of shear strength.

Zekkos[15] performed several large triaxial tests on the MSW materials of varying compositions. He reported changing the composition from a completely soil like type waste to a sample with more foil-like material, amplifying strain hardening and increasing the shear strength level in high level of axial strain.

Fucale et al. [26] performed a series of direct shear tests on the MBT (mechanically and biologically treated waste) MSW materials with different fiber contents (0, 10 and 20%) and observed an optimum value (10%) which yielded the highest level of shear strength for MBT waste materials.

Fernando et al. [27] also reported the results of direct shear tests on MBT waste samples. Changing the amount of reinforcing elements from 2% to 6%, they observed an enhancement in both the peak and residual shear strength of samples.

Shariatmadari at al. [1] and Karimpour-Fard et al. [2] reported the results of large triaxial tests performed both in drained and undrained conditions on fresh MSW samples with 0, 6.25, 12.5 and 25% plastic contents. According to the research, by increasing the fiber content the shear strength level also increases.

Zekkos et al. [19] reported the results of direct shear tests on MSW samples. Based on their results, the effect of the fibrous content on the MSW samples shear strength is not pronounced, however, it seems that increasing the fibrous part slightly decreases the shear strength of the samples.

In Fig. 6 the results of the tests on samples with different plastic contents in different normal stress have been illustrated. Clearly it can be seen that with increasing fiber content, the shear strength of the samples reduces which is in agreement with the direct shear test results of Landva and Clarck [4] and Zekkos et al. [19].

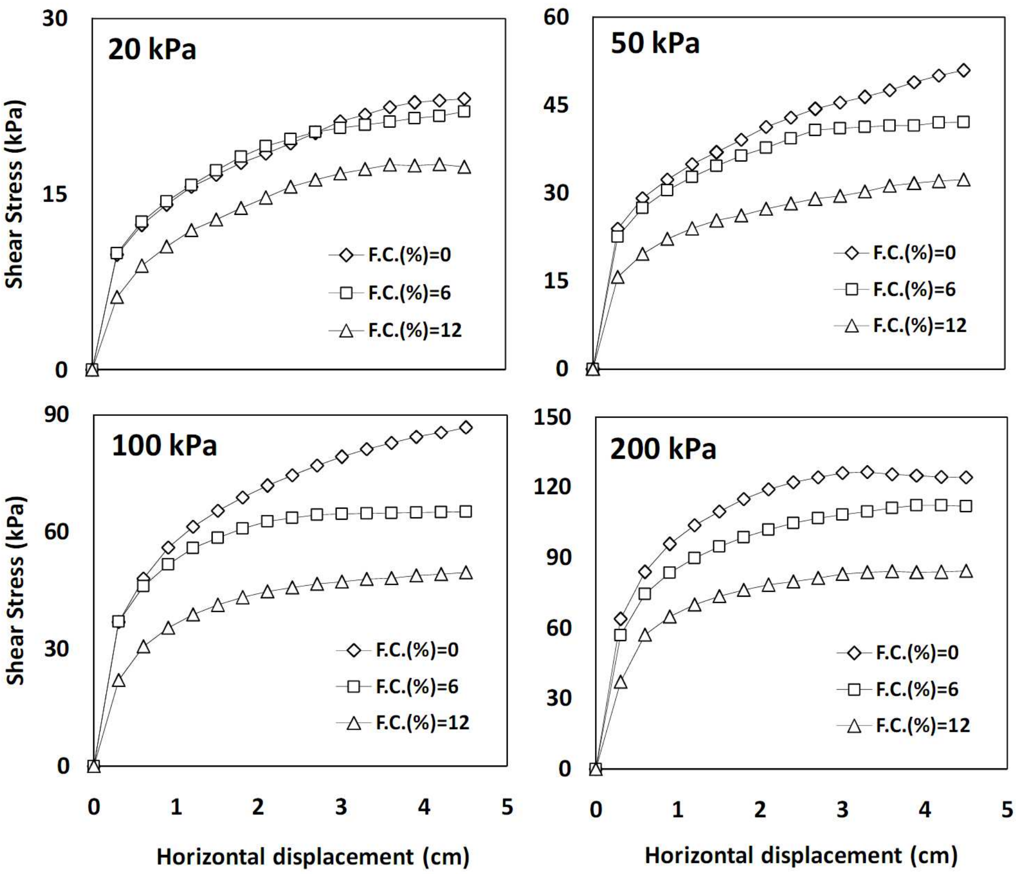


Fig. 6 Results of tests on samples with different plastic content at different normal stress

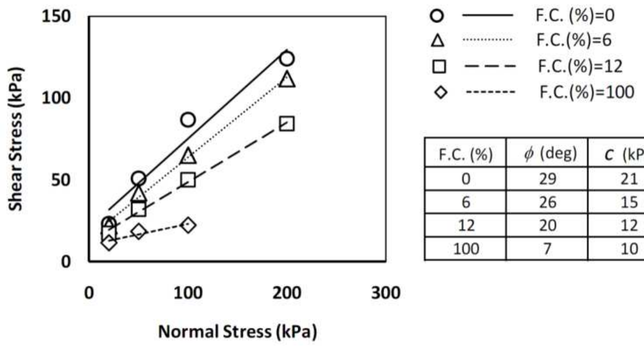
The observed trend is in contradiction with the triaxial test results of Zekkos (2005), Shariatmadari et al. [1] and Karimpour-Fard et al. [2] who reported that the shear strength of MSW increases with increasing plastic or fiber content.

The difference between observed trends in the variation in shear strength of MSW with increasing fiber or plastic content could be explained as follows.

In direct shear tests, as stated earlier, the direction of the shearing plane and the fibrous particles which tend to align themselves in a horizontal direction is the same. Therefore the presence of several sliding planes due to these horizontally oriented plastic fractions could affect the shear strength of the samples.

Fig. 7 presents the shear strength envelope of these tests along with the results of direct shear tests on the plastic fibers recycled from the fresh samples. As can be observed, both the internal friction angle and the cohesion intercept decreases with increasing fiber content.

According to Fig 7 a higher and lower limit for the shear strength of MSW samples based on their fiber content can be observed. In samples with no plastic fraction which exhibit the highest shear strength, the internal friction angle is caused by the paste to paste particle interaction whereas in plastic samples that have the lowest shear strength, this factor is due to friction among plastic sheets. In two other samples, the internal friction angle results from a composition of interactions between the paste to paste, plastic to plastic and paste to plastic components which lie between the two boundary limits.



F.C. (%)	ϕ (deg)	c (kPa)
0	29	21
6	26	15
12	20	12
100	7	10

Fig. 7 Shear strength parameter of samples with different fiber content

Indeed the source of the internal friction angle, in MSW samples sheared in direct shearing apparatus, with increasing the plastic content transform from paste to paste particle's interaction to friction created by interaction between plastic sheets. Therefore the higher the plastic content of MSW samples subjected to shear in direct shear box, the lower the shear strength of the MSW.

In the triaxial apparatus, the shearing plane with an orientation angle of 45+□/2 from a horizontal direction passes and cuts through the horizontally oriented plastic fraction. With increasing fiber content, this shear bond should cut and pass through more fibers and therefore the level of shear strength increases.

3.3. Effect of fiber orientation

The lower shear strength of MSW samples sheared in direct shear apparatus and the difference between its related mechanical response with those observed in a triaxial apparatus clearly indicate on the strength anisotropy of these materials.

Zekkos[15] reported the results of large scale compression and extension triaxial tests on fibrous MSW materials. According to Zekkos[15] the pattern of stress-strain response of MSW samples in extension condition is hyperbolic and similar to those observed in direct shear tests whereas the results of a compression test on the same material yields a pronounced strain hardening in the form of an upward concave.

Athanasopoulos et al. [25] performed several large direct shear tests on MSW. They observed the mechanical response of a MSW sample from a fully hyperbolic shape in the case of horizontally oriented fibers transforming to a curve with strain hardening in the case of non-horizontally oriented fibers.

Fig. 8 shows the results of tests on MSW samples with different fiber orientations for two normal stresses of 100 and 200 kPa.

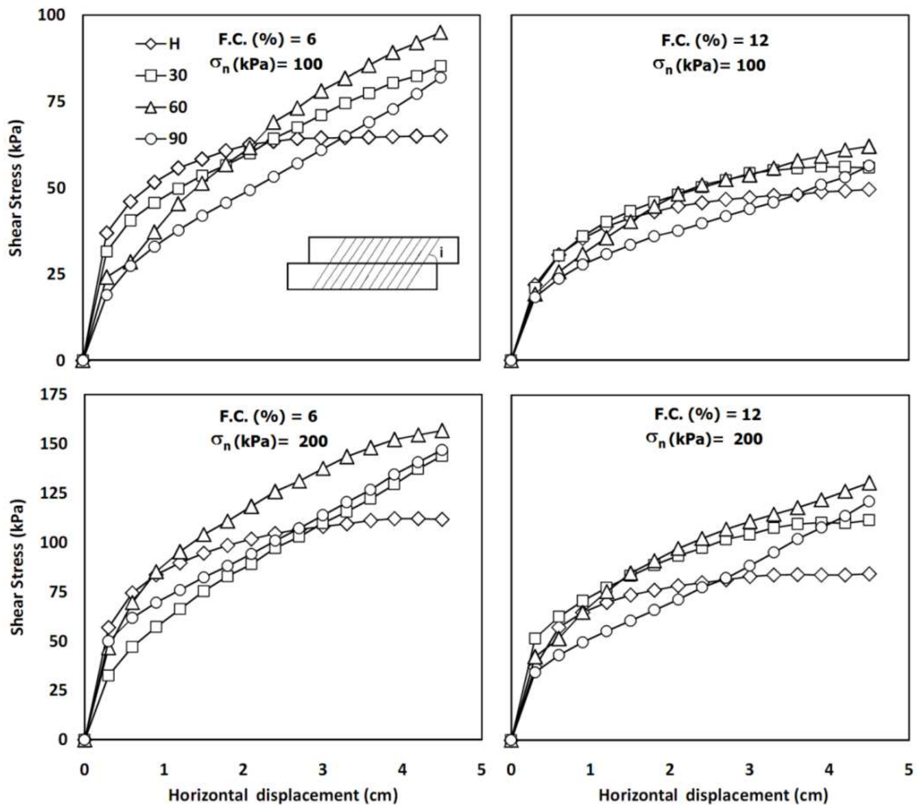


Fig. 8 Results of tests on MSW samples with different fiber orientation, for fiber contents of 6 and 12% and in two normal stresses of 100 and 200 kPa

As illustrated, altering the fiber orientation not only elevates the final shear strength level, but it also changes the shape of the stress-strain response. The mechanical response of samples with non-horizontal fiber includes a linear to an upward concave strain hardening without any peak, unlike the samples with horizontally oriented fibers.

Fig. 9 illustrates the variation in the internal friction angle achieved from each set of tests with the orientation angle of the fibers. According to this graph, samples with 6% fiber content show a higher shear strength, however, in both fiber contents the optimum orientation angle is the same and equal to 60 degrees which yields the highest internal friction angle. The achieved optimum orientation angle is in agreement with Athanasopoulos et al. [25] and Gray and Ohashi [28].

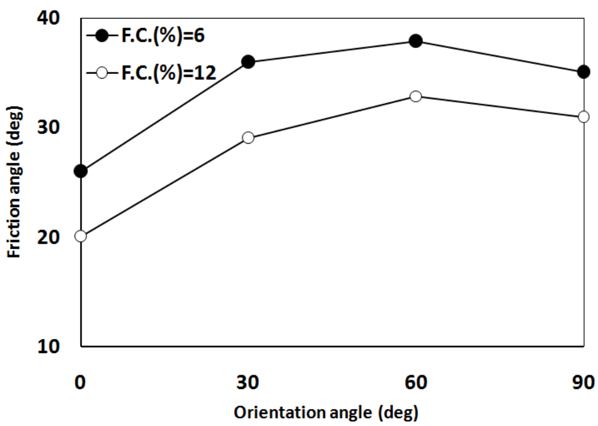


Fig. 9 Variation of internal friction angle of MSW with fiber orientation in fiber contents of 6% and 12%

In Fig. 10 the results of the tests on non-fibrous MSW samples compacted at different orientation angles can be observed. According to this figure, however, there were no fibers in the composition of the samples, but the compaction angle had a pronounced effect on the mechanical response of the MSW. It seems that the compressibility of the particles plays a key role in this respect. The bulky and relatively soft particles inside the MSW under pressure due to the compaction and the increasing vertical stress from placing additional waste on top of previously placed waste tend to re-shape in a rather planar shape. The new formation of these particles as well as interlocking resulting from the applied pressure might be the main source of the enhancement of the mechanical response of non-fibrous MSW samples.

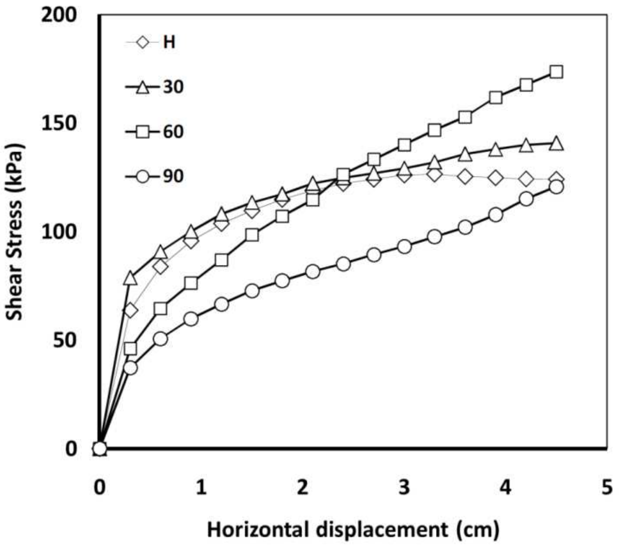


Fig. 10 Effect of compaction angle on the mechanical response of non-fibrous MSW

3.4. Time dependent behavior

The time effect on the stress-strain behavior of geomaterials consists of the two following components [29]:

- Aging effect; defined as time-dependent changes in the stress-strain properties including all mechanical properties of geomaterials, which can be described as a function of the time that has elapsed since a specifically defined origin.

- Loading rate effect; defined as the rate-dependency of stress-strain behavior due to the viscous properties, noted by creep deformation, stress-relaxation and strain rate effects on monotonic stress-strain behavior and so on.

Aging in MSW materials, including the impact of decomposition of degradable materials and change in the mechanical behavior of fibrous fraction is the most important aspect of time dependent behavior of these materials. However, the viscous behavior and the rate dependency of the strength of MSW mainly in regions with high seismic activity should also be evaluated.

In the following sections, both of these aspects will be discussed in more detail.

Aging effect

In MSW materials main part of the aging effect is due to the decomposition of degradable materials inside the MSW. According to Machado et al. [11], the mechanical behavior of MSW materials is a combination of the mechanical behavior of the paste and fiber part in which the shear resistance is shared between these two parts based on their volume ratio. As the age of the MSW increases, the mass loss due to decomposition also increases and the volume ratio of the paste part decreases. Therefore the fibrous part, which is considered as hard degradable materials, exhibits a more pronounced mechanical response. However, the strength and deformation properties of the fibers inside the MSW are also subject to alteration with time and this could have a paramount effect on the mechanical response of MSW in the long term. The plastic component, for example, tends to lose its ductility with time, causing failure in lower strain levels and with lower tensile strength [12].

Different trends in the shear strength evolution of MSW with time have been reported in the literature. From results of direct shear tests, Landva and Clark [3] and Gabr et al. [30] reported a reduction in the shear strength of MSW due to aging, however, Reddy et al. [16, 17] reported a different trend and an increase in the friction angle of MSW materials under decomposition for a period of 1.5 years.

From the results of triaxial tests, Machado et al. [12] and Zhan et al. [31] observed an increase in the shear strength of MSW materials with time.

Fig. 11 shows the results of direct shear tests on samples of varying ages. As can be observed the mechanical response of samples of ages up to 6 months is almost the same, and it seems that aging in this age range does not have a pronounced effect on the exhibited shear strength of samples. After this period and up to the age of 18 month a clear reduction in the final shear strength of MSW samples is observed. Variation of the shear strength parameter in the form of internal friction angle and cohesion intercept (Fig. 12) clearly shows that with increasing age, both of these parameters also decrease.

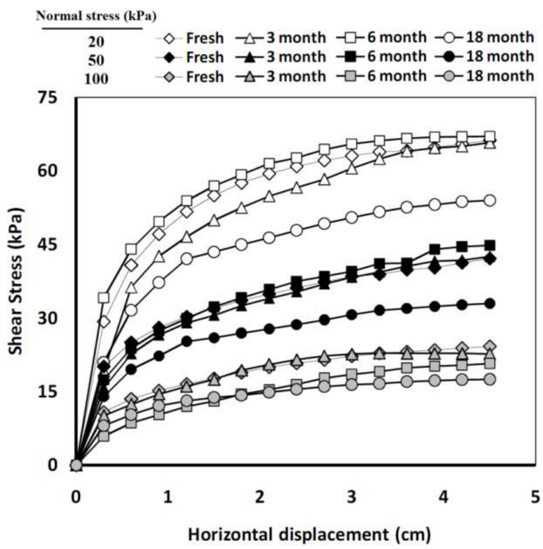


Fig. 11 Results of direct shear tests on MSW samples with different age

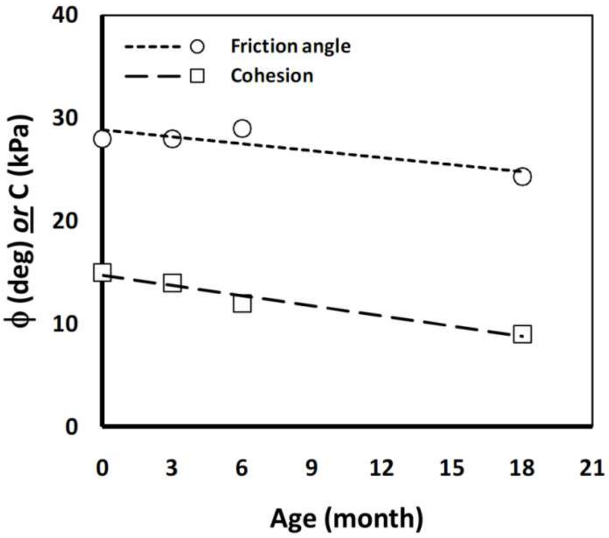


Fig. 12 Variation of MSW's shear strength parameter with age

As explained earlier, the decomposition process leads to a reduction in the volume and weight of the paste part which generally includes easily degradable materials and therefore this increases the fibrous part which is normally made up of hardly degradable materials.

Table 1 shows the plastic content of MSW samples of varying ages which was measured for samples with different ages. Based on measurements, a clear increase in the plastic percentage of the MSW (5.6% to 7.2%) with age can be observed.

As described earlier, in direct shear tests, with increasing fiber content, the shear strength of MSW samples also decreases. As the aging leads to increase in the fiber content of MSW, with increasing age of MSW samples a reduction in shear strength can be expected. This is compatible with the findings of Landva and Clark [3] and Gabr et al. [30].

In the case of triaxial tests, as the increase in fiber content increases the shear strength of MSW, therefore aging also leads to an increase in the shear strength of the MSW. However, it should be mentioned that as the tensile strength of fibers plays a key role in the exhibited shear strength of MSW in triaxial apparatus, impacts due to aging on the mechanical behavior of MSW could affect this increase.

It should also be mentioned that biodegradation and decomposition in MSW materials can continue for years and decades depending on the environmental conditions and therefore any evaluation of the aging impact on the shear strength and mechanical behavior of MSW materials needs to test MSW with a wide range of ages.

In current research however, the evolution of shear strength of MSW materials is monitored up to 18 months, but the high confidence levels regarding the same initial composition of samples is an advantage of the used method. Tracing the aging impact in MSW samples collected from different cells of landfills with different ages might address the wider range of ages, however, this always includes uncertainties regarding the initial composition of MSW which is necessary for comparative purposes.

Viscous behavior of MSW

Although the viscous behavior of MSW materials comprises aspects such as creep deformation, stress-relaxation and strain rate effects, in this paper only the last item is evaluated.

In regions prone to high seismic activity, stability issues during strong ground motions are a matter of concern. As such, the evaluation of the probable effect of loading rate on the mechanical response of MSW is imperative.

Augello et al. [32] analyzed the seismic performance of landfills during the 1994 Northridge earthquake and concluded that both the friction angle and cohesion intercept of MSW materials is higher in the case of dynamic loading. Also Zekkos[15] reported a 25% to 32% increase in shear strength of MSW materials sheared in triaxial apparatus for a 100-fold strain rate increase depending on the fiber content. Bray et al. [18] reported that as the shearing rate in direct shear test increases, the mobilized shear stress in the MSW also increases. Karimpour-Fard et al. [2] suggested changing the loading rate from 0.8 to 7.5 mm/min in undrained triaxial tests leads to an average increase in shear strength up to 15%.

To evaluate the loading rate effect on the stress-strain behavior of MSW, except the base shearing rate, 0.8 mm/min, two other shearing rates, 8 and 19 mm/min, were used.

In Fig. 13, the results of tests performed with different shearing rates are shown. Clearly, an increase in the shearing rate enhances the level of shear strength.

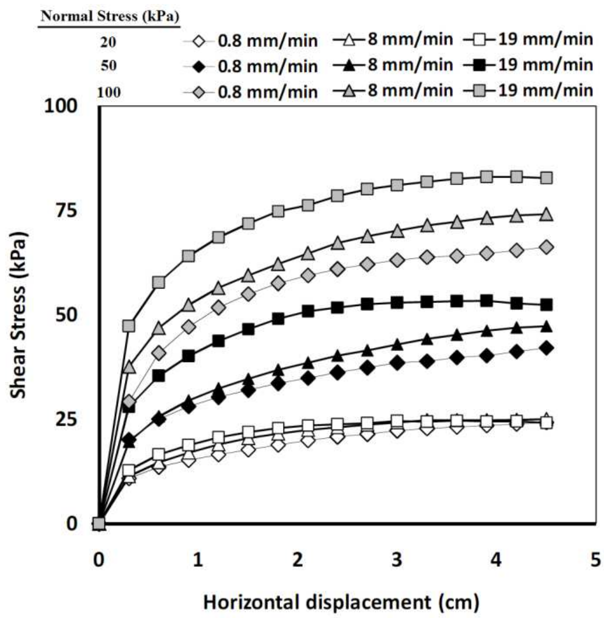


Fig. 13 Results of direct shear tests performed on MSW with different shearing rates

Fig. 14 shows the variation of shear strength ratio against shearing rate ratio for three horizontal displacements of 1.5 cm, 3 cm and 4.5 cm. The shearing rate ratio is the ratio of the used shearing rate to the base shearing rate and shear strength ratio is the ratio of the mobilized shear strength to the base shear strength.

probable higher rate-sensitivity comparing to paste part could elevate the rate-sensitivity of MSW as a whole.

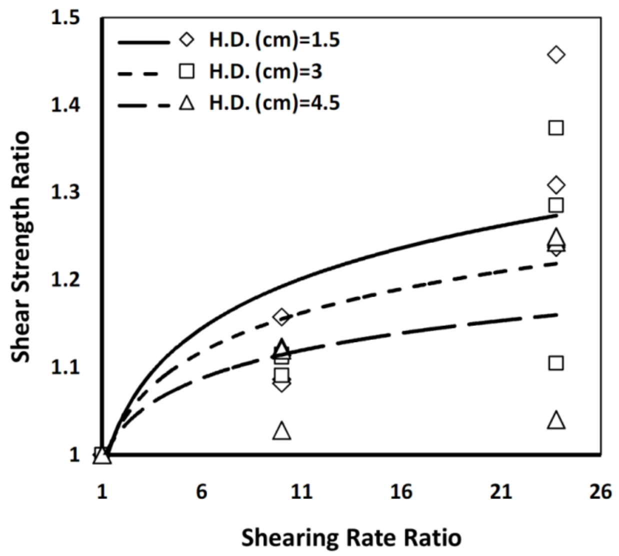


Fig. 14 Variation of shear strength ratio with shearing rate ratio

As can be seen, the lower the horizontal displacement, the higher the shear strength ratio. With an increase in the shearing rate from 0.8 mm/min to 19 mm/min, the shear strength of MSW increases up to 27%, 22% and 16% for horizontal displacements of 1.5 cm, 3 cm and 4.5 cm, respectively.

The results shows that although the cohesion intercept remains constant (14 kPa) with an increase in the shearing rate, the internal friction angle from the base value of 27 degrees changes to 31 degree for a shearing rate of 8 mm/min and 35 degree for a shearing rate of 19 mm/min.

Fig. 15 compares the rate sensitivity coefficient, β, achieved in this research with other results reported in literature. In this figure, the variation of this factor against deformation of samples normalized by the height of samples in the case of triaxial tests and length of samples in the case of direct shear tests is presented. The following equation, similar to that used by Tatsuoka[33], was used to estimate the rate-sensitivity coefficient (β) of the waste.

$$\beta = \frac{\Delta R / R_0}{\log\left(S_f / S_0\right)} \tag{1}$$

where R_0 is initial shear strength normalized with normal stress, ΔR, is the increment occurred in R_0 when the shearing rate is changed from initial shearing rate S_0 to the final value of shearing rate, S_f.

As can be observed the rate-sensitivity coefficient achieved in this research is higher than those calculated from direct shear test results reported by Bray et al. [18] and clearly lower than rate-sensitivity coefficients of MSW samples sheared in triaxial tests. The probable reason for this difference between the rate sensitivity coefficient of MSW materials sheared in direct shear and triaxial apparatus could be traced back to the viscous properties of the fibrous part of MSW. In triaxial tests unlike in direct shear tests, the fibers by mobilizing their reinforcement action have a considerable contribution in the mechanical response of samples. Therefore, their

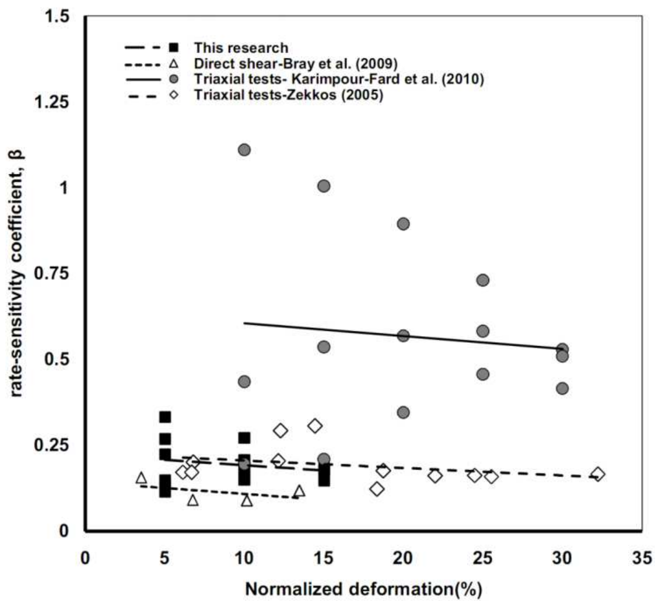


Fig. 15 Rate-sensitivity of different MSW materials sheared in different shearing devices

One aspect that must be mentioned is that test procedures used in this work are different from those used by Zekkos[15] and Bray et al. [18]. According to these authors, after starting the tests with the reference strain rate a change in the rate of strain was applied and changes in the mobilized shear strength were observed. In the case of the tests performed in this research, a constant rate of strain was adopted throughout the test and the values of ΔR and R_0 were calculated using the values of shear stress in a given value of axial strain for different strain rates. The method used in Karimpour-Fard et al. [2] is also similar to that used in this research.

4. Conclusion

A comprehensive testing program was performed to evaluate the mechanical behavior of MSW using the large scale direct shear test apparatus.

As opposed to the mechanical response of MSW materials in triaxial apparatus, which exhibit strain hardening in the form of upward concave, the mechanical behavior of MSW materials in direct shear tests follows a hyperbolic trend approaching a horizontal asymptote. Similar behavior has been reported by Landva and Clark [3, 4], Kölsch [22], Bray et al. [18], Zekkos et al. [19] and many others. The main reason for such a trend seems be due to the shearing mechanism in direct shear tests that creates a shearing plane parallel to the horizontally oriented fibers inside the MSW. As such, the reinforcement action of the foil like part could not be activated and as a result the mechanical response does not include strain hardening.

It was also concluded that increasing the fiber or plastic content in MSW materials subjected to shear in a direct shear box decreases the shear strength. This is because the source of internal friction angle, in MSW samples sheared in direct shearing apparatus, with increasing plastic content transforms from paste to paste particle interaction to friction created by interaction between plastic sheets which according to performed tests exhibits the lowest friction angle. The same explanation is valid for the decrease in shear strength of MSW materials with age, as the aged MSW samples contained a higher plastic content.

In the case of triaxial tests increasing fiber content or age may enhance the shear strength of samples because the shearing plane with orientation angle of $45+\emptyset/2$ from a horizontal direction passes and cuts through the horizontally oriented plastic fraction.

It was shown that altering the fiber orientation leads to strain hardening in the mechanical response of MSW samples. It was also observed that an orientation angle of 60 degree yields the highest level of shear strength which is in agreement with Athanasopoulos et al. (2008) and Gray and Ohashi[28].

According to the obtained results, it can be said that the mechanical response of MSW materials is rate dependent. The samples showed a higher shear strength when they were sheared at a higher shearing rate. Increasing the shearing rate from 0.8 mm/min to 19 mm/min resulted in an increase in the shear strength of the MSW up to 27%, 22% and 16% for horizontal displacements of 1.5 cm, 3 cm and 4.5 cm, respectively. It was also observed that the rate-sensitivity coefficient achieved in this research is higher than those calculated from direct shear test results reported by Bray et al. [18] and lower than rate-sensitivity coefficients of MSW samples sheared in triaxial tests by Zekkos et al. [19] and Karimpour-Fard et a. [2].

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