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# Effects of aging on shear strength behavior of municipal solid waste

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***Abstract***

*In this research, the effect of aging on the behavior of municipal solid waste (MSW) was studied in Kahrizak landfill, the biggest landfill in Iran. The sample used for this study was taken from the fresh as well as aged MSW. The aged samples were obtained from older burial locations aging 5.5, 14, and 21 years using mechanical excavation. Analyzing the variation in MSW components demonstrated that, in the aged MSW, paste fraction decreased, while the amount of fibers showed a rising trend in comparison with fresh ones. Also, the moisture content and organic content of MSW decreased by more than 50% of the initial values, while degree of decomposition (DOD) increased by up to 60% (for 14-year samples). The shear strength of the MSW samples was analyzed by CU tests using large-scale triaxial apparatus (D=150mm, H=300mm). The results of stress-strain curves depicted that stress increased with the increase of strain level without reaching a peak point. Fresh samples represented the lowest value of shear strength followed by 21, 14, and 5.5 year-old ones, respectively. The results also revealed that the increase in fiber content of MSW led to increase in shear strength. Aged MSW samples experienced higher values of internal friction angle. In contrast, cohesion showed an inverse trend and its value decreased in the aged samples compared to their fresh counterparts. Regarding the effect of burying condition and preliminary composition of aged MSW, DOD seemed to show more appropriate results than age for analyzing the long-term behavior of MSW.*

**Keywords:** *Municipal solid waste, Aging, Shear strength, Large-scale triaxial test, Kahrizak landfill.*

## 1. Introduction

Although modern techniques such as incineration and composting are available nowadays, landfilling is still one of the most common ways which is utilized for municipal solid waste (MSW) management in many countries. Numerous reports have considered the damage and failures of different landfills around the world (Blight and Fourie [1]; Merry et al. [2]); however, there is lack of enough information about the behavior of MSW. Therefore, comprehensive information is required about the mechanical behavior of MSW, especially in a long term and for a given specific condition. Also, most landfills are adjacent to the cities and residential areas; thus, these kinds of damage have resulted in problems such as homelessness, death of hundreds of people living around these areas, and intensive financial and environmental damage.

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Therefore, further studies are needed to analyze the detailed characteristics of MSW and specify its behavior in long term periods.

The issues related to MSW such as the variation in its content in different regions, its heterogeneity, variable size of its components, and its time-variant nature have added to the complexity of MSW. The mechanical and geotechnical characteristics of MSW have been explored by many researchers (Landva and Clark [3]; Grisolia and Napoleoni [4]; Kavazanjian [5]; Zekkos [6]; Reddy et al. [7]; Bray et al. [8]; Karimpour-fard et al. [9]). There is a limited number of studies though considered the changing trends of MSW components based on its decomposition over time (Pelkey et al. [10]; Hossain [11]; Machado et al. [12]; Zhan et al. [13]; Bareither et al. [14]).

In summary, in spite of its importance, the effect of aging on shear strength of MSW has been scarcely studied and there is not adequate consensus among the researchers. Some results have implied increase in shear strength through ages (Van Impe [15]; Harris et al. [16]), while others (Landva et al. [17]; Hossain and Haque [18]; Gabr et al. [19]) have illustrated a decrease in such a parameter. Also, another group of authors (Landva and Clark [3]; Kavazanjian [5]) have declared that the decomposition of MSW does not influence shear strength and suggested the same strength parameters for fresh and aged MSW. In addition, some others (Zhan et al. [13]; Reddy et al. [20]) have separately evaluated the variation trend of internal friction angle (Φ) and cohesion (C) of MSW in their recent studies. Obviously, the influence of different parameters and test methods on the behavior of MSW has caused such different results.

Regarding mechanical behavior and aging effect, analyzing the details of previous studies has demonstrated that most of them have been performed on the MSW of industrialized and developed countries. Their MSW samples are significantly different from the samples of this study in some aspects such as initial components, moisture content, and burying conditions. In addition, most of the previous studies have been carried out using direct shear test and/or small-scale triaxial test (5-7 cm in diameter), unsaturated samples, drained condition, and in general conditions which are different from those of Kahrizak MSW. Therefore, the results of this study may be different from those of other previous works.

The main objective of this investigation was to find out the trend of changes in the mechanical behavior of waste mass due to the aging process in this landfill. According to the site restriction and continuance of burying, 60 meter high trenches of MSW in the landfill are still rising. Hence, their stability analysis and failure probability are necessary. The age of MSW layers increases from up to down in trenches. Therefore, for stability analyses, it is necessary to use the physical and mechanical parameters relating to each layer.

In this research, results of the field studies and experimental works on the fresh and aged buried MSW in Kahrizak landfill were presented. Field studies consisted of sampling from fresh MSW, excavating test pits to take MSW samples, along with performing grain size distribution (for oversize parts) and in-situ unit weight tests. The prepared samples were carried to the laboratory to determine MSW composition alongside grain size distribution, moisture content, organic content, degree of decomposition, and shear strength parameters. After the sample remolding, shear strength parameters were determined by large-scale triaxial test and finally effects of aging and degree of decomposition on the shear strength parameters were evaluated.

## 2. Landfill Description and Sampling

Kahrizak landfill is the largest waste disposal facility in Iran, in which Tehran MSW has been buried for about 40 years. It is located 25 km to south of the city and has an area of 1200 ha. Nowadays, the entire MSW produced in Tehran, which is about 7500 ton per day, is transported to this landfill.

In the past, MSW was buried in different locations; either natural craters or artificial trenches; however, due to lack of appropriate locations, burying has recently been concentrated in some parallel layers with 2 or 3 m thickness on one section of the landfill. Today, this section of the landfill has reached the height of almost 60 m and the waste has been covered by layers of soil and construction debris followed by partial leveling and traffic compaction.

According to Karimpour-Fard et al. [9], if there is no efficient leachate collection system and/or the final cover fails to work properly, the MSW may become saturated and the level of leachate inside the landfill may increase. Therefore, most of the MSW in this landfill can be considered saturated due to the lack of leachate collection system. Some of the leachate produced from the waste is gravitationally directed toward a low-land adjacent to this region. Since the ground contains clayey layers with negligible permeability, a leachate lake has been formed beside the burying location.

According to the information obtained from the official documents in Kahrizak landfill facility, MSW of three different time spans (from June to August 2006, 1998, and 1991) was attainable in three different positions of the landfill. The MSW related to 1991 was buried in the low-lands which were adjacent to the leachate lake, while other aged MSW sites were at higher levels and up to 2 km away from the leachate lake. However, the MSW related to other years was not attainable due to the changes in the landfill or there was not sufficient information about the ages. Thus, the samples aging 5.5, 14, and 21 years old were taken for the purpose of studying the effect of aging on MSW behavior. The age of samples was confirmed by the readable dates of newspapers and magazines as well as dates written on the food packs and cans. Besides, information showed that the maximum thickness of aged MSW was limited to approximately 10 m in most cases. Therefore, three test pits with maximum depth of 5 m which were excavated by a mechanical excavator were used for sampling. Then, all the samples were prepared at depth of 2-4 m. Fresh MSW samples were taken from the entrance station, where MSW trucks dumped their load. In Fig. 1, aerial image of Kahrizak landfill and the locations of MSW sampling are presented. Excavating operation on the test pit for obtaining 14 year-old MSW is shown in Fig. 2.


**Fig. 1** Aerial photograph of Kahrizak Landfill and the locations of sampling

**Fig. 2** Excavating the test pit in aged MSW location

Fresh MSW sampling was done in four times during one year. Each time, 10 fresh samples with weight of 30 to 40 kg were prepared. Regarding the aged MSW, 4 samples with approximate weight of 35 to 45 kg were obtained from each test pit. Overall, 40 samples of fresh MSW besides 36 aged MSW samples (12 from each age) were prepared and were immediately placed in plastic and gunny sacks in order to preserve moisture prior to their carrying to the laboratory and maintenance in the refrigerator at 5°C. Fresh, 5.5, 14, and 21 year-old MSW samples are abbreviated to Sf, S5, S14, and S21 in the presented tables and Figs, respectively.

Regarding the physical properties of aged MSW, three samples were selected from each of the test pits. Also, for the fresh MSW, two samples were collected from each period of sampling. Finally, the average value was calculated and reported for each age. For triaxial tests of aged MSW, two samples were collected from one of the test pits relating to one particular age and then were mixed in order to obtain a much more homogeneous sample for the tests. Triaxial tests for the fresh MSW were performed on the mixture of the samples collected in the second sampling attempt, as their physical properties were almost closer to the average of the long-term results.

## 3. Physical Characterization of MSW

Physical analysis was carried out in order to assess MSW components. The MSW components were separated visually and based on the weight of each group according to the common methods used in the previous works (Zekkos [6] and Oettle et al. [21]). Table 1 presents the components of fresh and aged MSW. In Machado et al. [22], the paste group of MSW was defined to include three types of organic materials, namely, quickly decomposable (e.g. food scraps), fairly decomposable (e.g. leaves of plants), and hardly identifiable. Due to the gradual variation in consumption habit, fresh MSW components have changed in the last two decades. Paste fraction has decreased by almost 20%, while other parts have increased by the same amount. Also, maximum increase has been related to the plastics and paper/cardboard.

**Table 1** Fresh and aged MSW composition of Kahrizak landfill

| Component | Average percentage | | | |
|---|---|---|---|---|
| | **Sf** | **S5** | **S14** | **S21** |
| Metals | 1.8 | 1.6 | 0.8 | 0.1 |
| glass | 2.4 | 3.8 | 2 | 3.6 |
| Stone/ceramic | 0.9 | 9.4 | 9.8 | 2.6 |
| Paper/cardboard | 14.6 | 9.4 | 8 | 7 |
| plastic | 11.5 | 27.4 | 21.2 | 26.8 |
| wood | 0.6 | 2.4 | 3.4 | 4 |
| textile | 5.6 | 4.8 | 3.1 | 4 |
| paste | 62.6 | 41.2 | 51.7 | 51.9 |
| total | 100 | 100 | 100 | 100 |

**Sf**=Fresh sample **S5**=5.5 Year-old sample **S14**=14 Year-old sample **S21**=21 Year-old sample

Fig. 3 depicts the results of particle size distribution for the samples at different ages. As can be observed, by an increase in the age, the size of the particles became smaller and the diagram of particle size distribution approached the region of finer particles, which could be probably due to the biodegradation and chemical change processes occurring over time. The average moisture contents for Sf, S5, S14, and S21 were mea

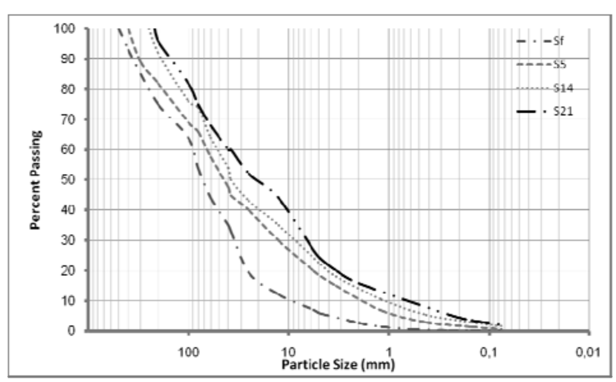


**Fig. 3** Particle size distribution for MSW samples

sured to be 153%, 88%, 52%, and 70%, respectively.

In order to determine organic content (OC), the MSW samples were kept at 440°C inside the furnace until reaching stable weight at this temperature. The organic content was determined according to the percentage of the weight difference between the sample before and after being placed in the furnace to the remaining weight of the burnt sample.

Degree of decomposition (DOD) is a parameter which can be used to estimate the amount of decomposition of the aged MSW including effects of burying conditions in the landfill. This parameter was defined by Andersland et al. [23] as follows:

$$DOD = \left(1 - \frac{X_{fi}}{X_{fo}}\right)\frac{1}{\left(1 - X_{fi}\right)} \times 100 \qquad (1)$$

where $X_{fo}$ is the initial organic fraction and $X_{fi}$ is the organic fraction after partial decomposition.

Fig. 4 shows the measurement results of the organic content (OC) and degree of decomposition (DOD) in the MSW samples at different ages. This Figure indicates that an increase in the age of the samples up to 14 years leads to a fall in the organic content and also a rise in the degree of decomposition. The depicted increase in the organic content as well as decrease in DOD of S21 was considered to be the result of the location of these samples in the environmental conditions which were different from those of S5 and S14. Furthermore, the heterogeneity of their initial fresh samples can be accounted a reason for these variations in behavior trend.

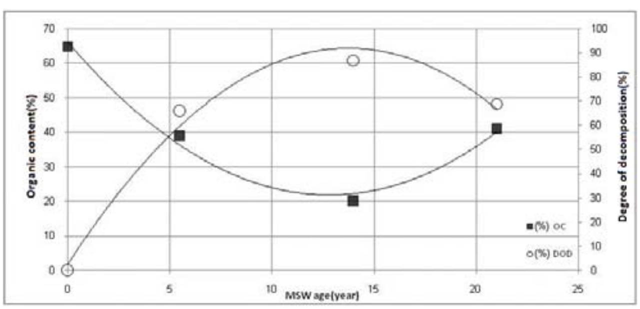


**Fig. 4** DOD and OC variation curves over the time

## 4. Specimen Preparation and Testing Program

According to the dimension limitation on triaxial test (15 cm in diameter and 30cm in height), large parts of the samples were cut up into smaller pieces with the maximum dimension limited to 30mm. Moreover, for preparing a similar condition to compare the behavior of the samples, all the samples were remolded in the laboratory with the unit weight of 11kN/m$^3$ (wet density) based on the measured values obtained from in-situ unit weight tests for aged MSW. In order to prevent moisture effect, remolding was set to an almost equal value prior to the preparing of the specimens. This value, according to the unit weight envelope presented by Zekkos et al. [24], stands in the range of medium to high for surface unit weight of landfills. According to the volume of the specimen, specific weight of the fragmented MSW was used for remolding.

Specific cylindrical metal mold was used to remold the specimen. For this purpose, the definite amounts of the fragmented MSW were separated at first; then, they were put in the mold in five equal layers and, after initial compressing which was separately done for each layer, the whole specimen was put under the compression force by means of a special hydraulic disk to obtain the intended unit weight and shape stability at the end of the remolding process. According to swelling potential (especially, in fresh samples) which is mainly due to plastic parts, the specimens were remained under compression for about 2 hours.

Reddy et al. [7] quoted Holtz and Kovacs 1981 that, in geotechnical engineering, CU strengths are typically used for stability problems, in which soils are at equilibrium after being fully consolidated and then fail with insufficient drainage which occurs when additional stresses are quickly applied. According to their opinion based on geotechnical characteristics of MSW, similar situations in a bioreactor landfill can be expected. Hence, results of CU strength may be considered suitable for analyzing the stability of a bioreactor landfill. Also, Karimpour-Fard et al. [9] stated that the undrained behavior of MSW played a key role in the instability of the slopes studied in the technical literature. Therefore, the undrained behavior of the MSW was analyzed in this study in terms of the aging effect on the mechanical behavior of the MSW.

All the tests were performed on saturated specimens in CU conditions. For this purpose, the upward water flow in the specimen and back-pressure technique were used while the effective confining pressure was set at 10kPa. The minimum value of B for all the specimens was considered to be 0.9; thus, the flow lasted for about 1.5 to 3 h. After saturation, the specimens were put in consolidation stage for at least 15 h in order to observe the negligible rate of volume change.

Loading was conducted using strain control method at the strain rate of 0.6 mm/min. This rate was determined based on the suggested equation by Head [25]. Loading stage lasted until obtaining the minimum strain of 30%. Fig. 5 illustrates a typical specimen before and after the test.

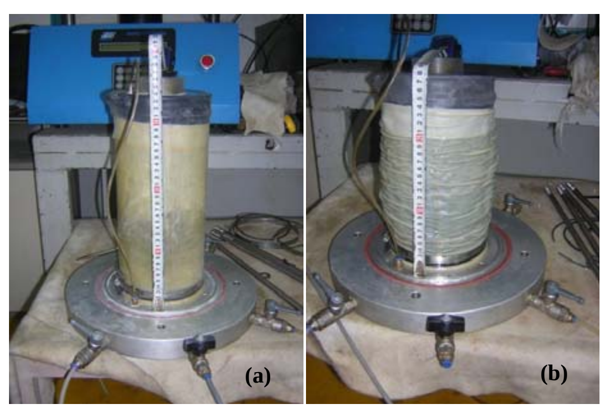


**Fig. 5** Remolded specimen in triaxial test (a) before and (b) after shearing

Large-scale triaxial test was performed for each of the four samples with confining pressures of 50, 150, and 300kPa and also an equal unit weight. Moreover, two tests were repeated for each of the fresh and aged samples in order to check repeatability. To find out the effect of the paste fraction of MSW, after separating the paste from each of the four samples, the tests were performed with the confining pressure of 150kPa. For each of the mentioned tests (effect of unit weight, paste fraction), at least one test was repeated to control their repeatability.

## 5. Results and Discussion

*5.1. Mechanical behavior of MSW*

Fig. 6 presents the obtained results of the reference tests for fresh and aged MSW samples. According to the stress-strain curves for Sf, from the beginning of shearing stage to the strain of almost 2-3%, stress had a sharp rise, which was followed by a steadily slow increase until the end of the test. Similarly, the pore water pressure had a sharper rising rate prior to the strain level of 10%, although its rising trend continued to the end of the test and finally the maximum value of pore pressure reached over 90% of the effective confining pressure. In stress-strain curves for S5 in Fig. 6, stress increased more sharply after the strain level of 15-20% so that strain-hardening can be exhibited.

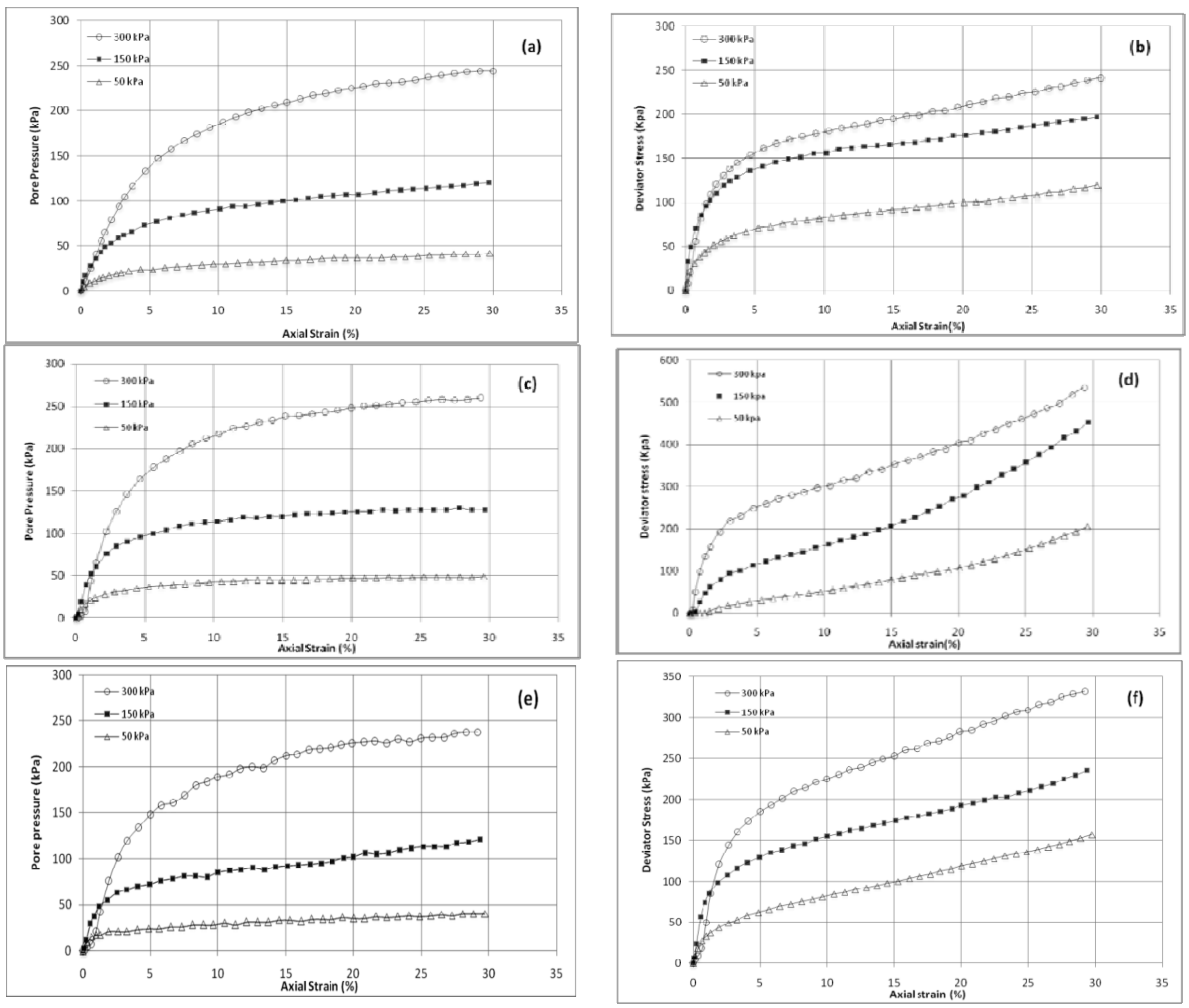


**Fig. 6** Stress-strain and pore pressure curves. (a, b): Sf; (c, d): S5; (e, f): S21

The similar point in the general stress-strain behavior was that the stress value increased as long as strain increased and continued with no specific peak point. Therefore, shear strength is a function of strain level. The fact that stress increases with an increase in the relative deformation without producing any peak point in the stress-strain curve of MSW samples has been reported by numerous researchers (Gomes et al. [26]; Shariatmadari et al. [27], Nascimento [28]).

*5.2. Aging effect*

Effect of decomposition, due to aging process, on MSW behavior has been studied by different researchers, who have utilized various factors in order to find degree of decomposition.

Hossain and Haque [18], Reddy et al. [20], and Bareither et al. [14] have used factors such as volatile solids (VS) or organic content (OC) in order to assess changes of shear strength or behavior parameters in aging process. [C+H]/L ratio (cellulose [C], hemicelluloses [H], and lignin [L]) has been utilized by Gabr et al. [19], Hossain [11], and Harris et al. [16], Bareither et al. [14] to evaluate the effect of decomposition level on MSW behavior. Another group of researchers (Reddy et al. [20], Mc Dougall and Pyrah [30]) have used the degree of decomposition (DOD) factor to understand MSW changes regarding decomposition process. A general evaluation exhibits that the various factors used for assessing effect of aging have shown variation in the changeable and flammable components of the MSW material in a period of time and, accordingly, some specific relations can be established between them. Nevertheless, in this paper, the DOD factor was utilized to realize the effect of aging on MSW.

Fig. 7 shows the stress-strain curves for MSW samples. Comparing these stress-strain curves for fresh and aged samples demonstrates that all the samples (Sf, S5, S14, and S21) had a similar, general curve shape and, as long as strain increased up to 30%, stress value had its rising trend. In addition, it can be observed that, for confining pressures of 50 and 150kPa up to the strain level of 10% or 12%, stress-strain curves converged and, afterwards, they were separated. However, for the confining pressure of 300kPa, these curves were separated from each other after the strain level of about 2% and their inter-space gradually increased.

As can be seen in Fig. 7, points scattered as long as the level of strain increased. Although, at the strain level of 10% and confining pressures of 50 kPa and 150 kPa, deviator stresses were approximately congruent, they showed more than 80% of variation at the strain level of 30%. For the confining pressure of 300 kPa, the difference in deviator stress for the strain level of 30% between the fresh and aged samples was more than 100%. In conclusion, it seems that difference increased between the behavior of samples at higher confining pressures and higher levels of strain and, in a similar condition, S5 samples represented the highest shear strength, while Sf samples had the minimum.

The present authors believe that this mechanical response can be attributed to the existence of plastics and fibers which are not in tension at low confining pressures (50, 150 kPa) and low strain levels. As a result, the general behavior of waste mass can be related to other parts, especially paste fraction in this state. Therefore, MSW behaviors were almost similar in the initial regions of the curves. At higher strain levels (more than 12%) and also higher confining pressures (300 kPa), because of the existence of plastics in waste mass, general behavior was influenced by this fraction of MSW and, as a consequence, the spaces between the curves increased according to the proportion of plastic fraction as well as its behavior. Towhata et al. [31] studied the results of triaxial test on ordinary MSW samples and also MSW without plastic sheets. Their results illustrated that deviator stresses in the MSW specimens containing plastic sheets at strain level of 15% increased up to 200% in comparison with the specimens without plastics. They also stated the effects of plastic sheets as a reason for variation in principle stresses.

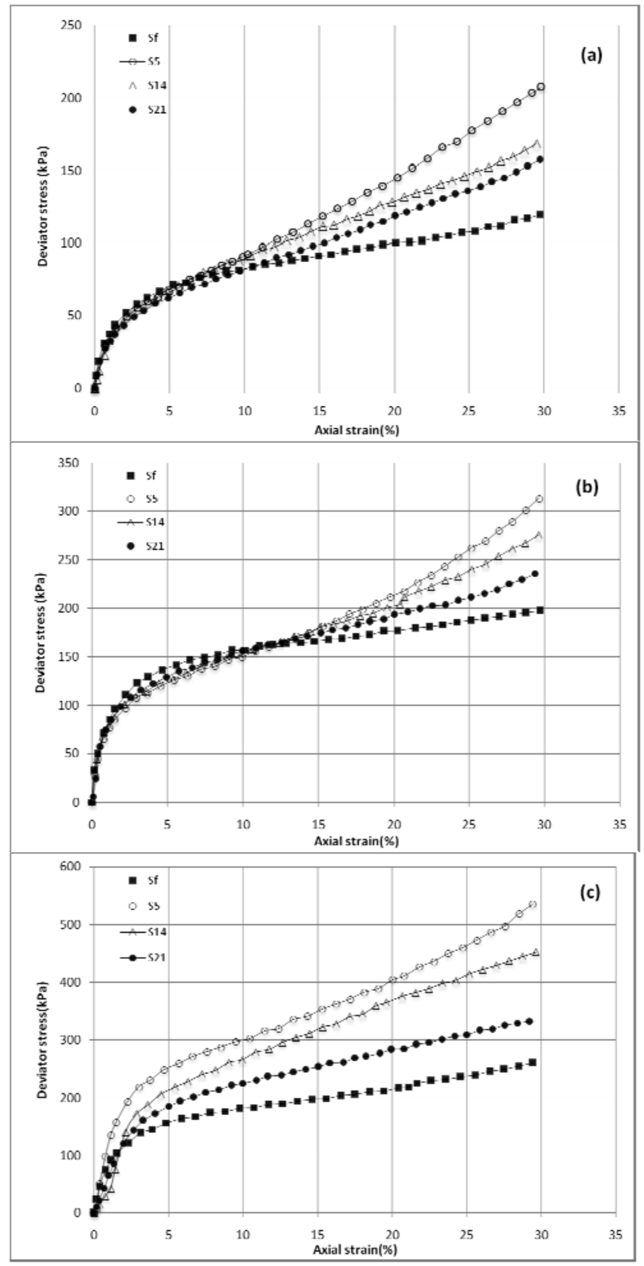


**Fig. 7** Stress-strain curves under confining pressure of (a) 50kPa, (b) 150kPa and (c) 300kPa for Sf, S5, S14 and S21

Machado et al. [12] performed experiments on the tension strength of the plastic samples obtained from fresh and 4 year-old MSW, as exhibited in Fig. 8. As can be observed, stress had a sharp rise until the strain level of almost 10%; afterward, stress had a slow rise in fresh specimens, while it decreased in 4 year-old ones. They reported that average of Young's modulus decreased from

82 MPa for fresh samples to 62 MPa for 4 year-old ones and almost 9% drop was observed at the ultimate tension stress. According to this investigation, it can be deducted that the ultimate tension stress of plastic fibers decreased over time and they lost their elasticity to some extent due to decomposition process. Therefore, they showed different tension effects from the fresh ones.

Fig. 7 illustrates stress-strain curves of the specimens. At all the confining pressures, the curves relating to Sf, S21, S14, and S5 were arranged from down to upper regions, respectively. Thus, Sf represented the lowest level of stress, while S5 had the highest level. S5 had the highest amounts of fibers and, accordingly, they represented the highest level of stress in similar conditions. Afterwards, S21 and S14 had more fibers along with more shear strength. Finally, Sf had the minimum amount of fibers and, consequently, showed the minimum level of stress. It seems that 7 years old difference between S21 and S14 which led to a noticeable decrease in tension stress caused stress level of S21 to be less than S14 in spite of being consisted of more fibers (about 6.5%).

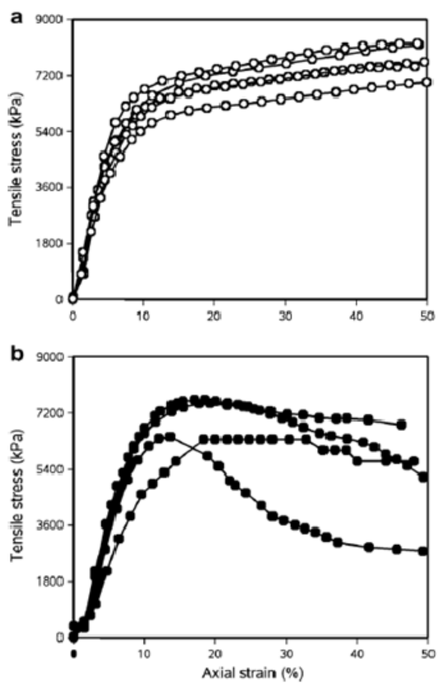


**Fig. 8** Stress-strain curves obtained from plastic materials: (a) new samples; (b) 4 year old samples (Machado et al. [12])

### *5.3. Shear strength assessment*

According to the stress rise even at high strain levels near 30% and in the absence of any peak points in the stress-strain curves, the stress which was related to strain level of 15% was considered the failure stress, as is usual in geotechnical studies. Also, because of soil cover on top of the landfill which touches waste layer, a deformation more than 15% leads to crack and failure as well as lack of efficiency for the cover layer. Therefore, the strain level of 15% was considered the critical point. Furthermore, many researchers (Reddy et al. [7], Reddy et al. [20]; Caicedo et al. [32]) have used strain level of 15% in their investigations for shear strength behavior in order to determine relevant parameters, although higher and lower levels of strain are also utilized. Overall, in this paper, shear strength parameters were calculated and presented based on the strain level of 15%.

Fig. 9 shows the calculated shear strength parameters obtained from triaxial tests. Total stress and effective stress were separately calculated since pore pressure was measured.

Fig. 10 illustrates the variation in internal friction angle (Φ) in comparison with cohesion (C) for MSW samples. As can be seen, internal friction angle had a noticeable increase in S5 in comparison with Sf whether for total stress or effective stress. Afterwards, it showed a slight fall until S21 and it was noticed that internal friction angle of aged samples was always larger than that of the fresh ones. For the cohesion intercept, the curves for total and effective stress displayed a general reduction in this parameter over years and the cohesion factor of aged samples evidently decreased in comparison with the fresh ones, except in one case.

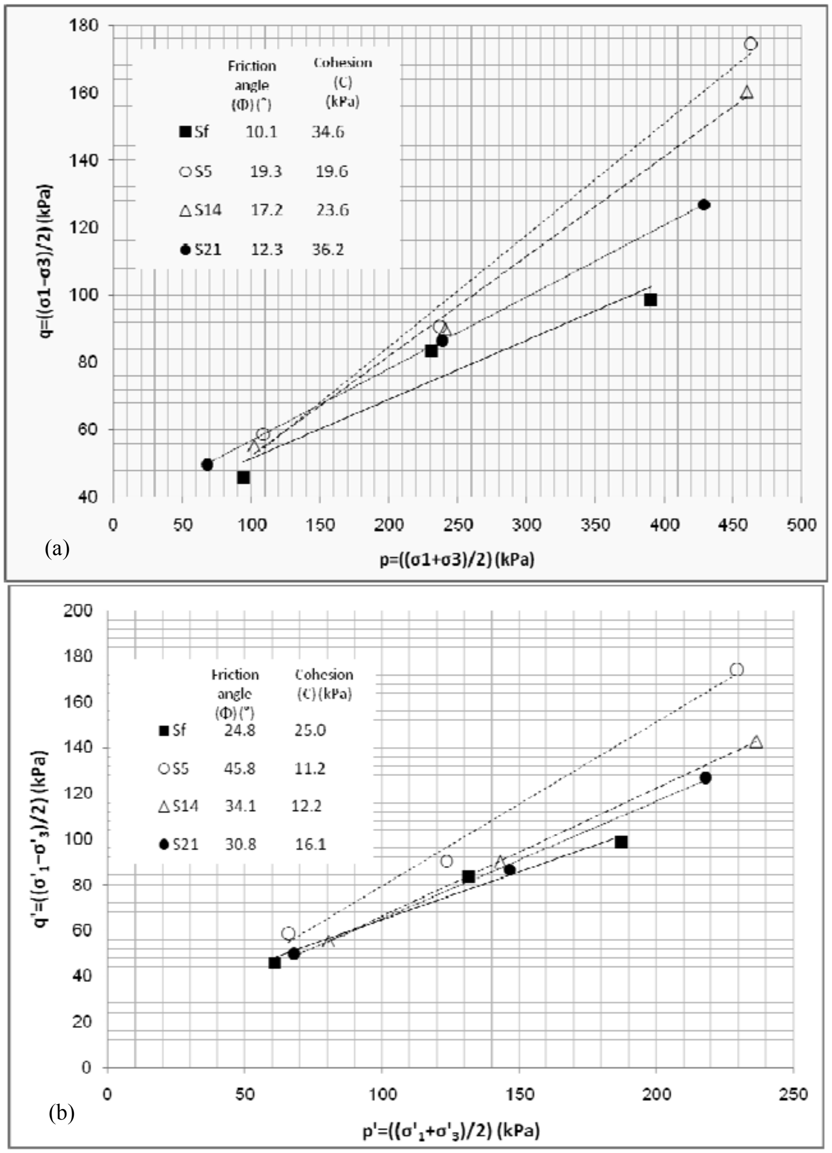


**Fig. 9** Assessment of shear strength parameters for MSW samples based on (a) total stress and (b) effective stress

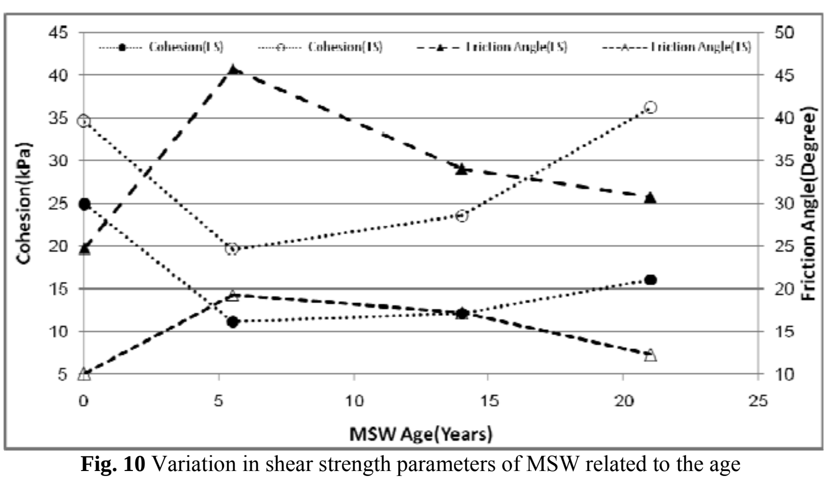


**Fig. 10** Variation in shear strength parameters of MSW related to the age

All in all, variation in shear strength parameters did not show any constant trend. According to the equal remolding condition and performance of the experiment for different specimens, it seems that the main reason for these variations can be related to their content or variation in the components of MSW. Based on the results obtained from Table 1, the highest variance in MSW components was related to paste, plastic, and rock/ceramics, which was 21%, 16%, and 9% respectively. In addition to the aging process, variation in MSW components depends on two main factors; i.e. initial composition of MSW samples and variation in the burying condition of the landfill. Thus, according to the dependence of sample behaviors on their composition and extreme effects of initial component on the results besides burying conditions, it seems that variation in the results of the literature is owing to these two main factors.

DOD factor increases as long as time passes and also depends on the condition of burying and initial composition. The variation trend of strength parameters in comparison with DOD factor is illustrated in Fig. 11. Although cohesion factor decreased with a rise in DOD either in total stress or effective stress, internal friction angle in both cases showed an increasing trend. According to the scattering results obtained from age factor or DOD factor, the authors believe that DOD is a more appropriate parameter than age factor in order to realize the variation trend of MSW due to aging process. Results of studies in Zhan et al. [13] which were done on 1.7 and 11 year-old MSW samples from Suzhou landfill also showed that internal friction angle increased with an increase in age, while cohesion factor decreased.

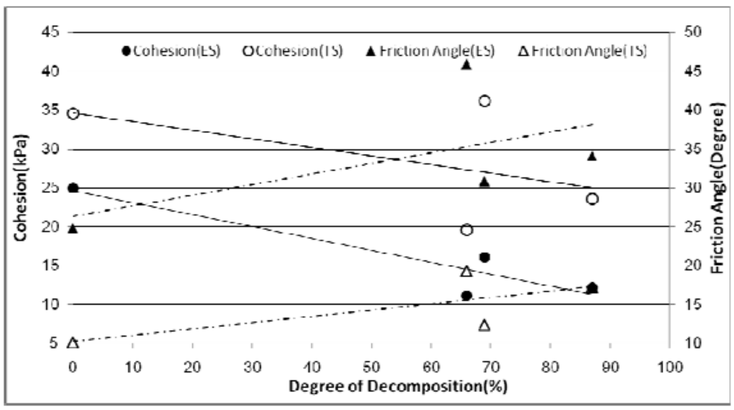


**Fig. 11** Variation in shear strength parameters of MSW related to DOD

*5.4. Paste effect assessment*

Based on Machado et al. [33], the long-term mechanical behavior of MSW is a combination of mechanical response of the paste and fibrous fraction, which varies over time.

According to Table 1, paste fraction represents more than 40% to 60% of the sample weight and it is actually the main part of MSW and acts as a link among other parts. In other words, fibrous fractions including plastic, fiber, and leather as well as other components such as wood, metal, rock/ceramics and paper/cardboard are linked by paste fraction and this part acts as a cohesive matrix for others. Thus, paste material performance can have a significant role in the general behavior of waste mass.

Moisture content and organic content of paste fraction are illustrated in Fig. 12. As can be observed, the moisture content of paste fraction decreased with an increase of age up to 14 years, from 181% for Sf to 35% for S14. Also, organic content had a direct relationship with moisture content and decreased from 85% for Sf to 15% for S14. Reduction in the organic content of MSW caused other parts such as rock/ceramics and other inflammable or unchangeable parts to increase. As mentioned before, moisture and organic contents of S21 increased due to burying region and conditions besides the probable difference in their initial composition.

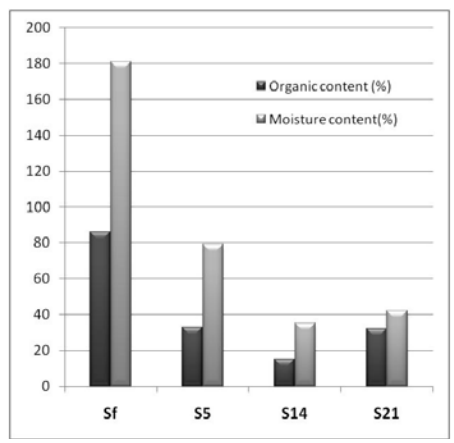


**Fig. 12** Moisture content and organic content of the paste fraction

In order to compare paste fraction behavior, CU triaxial tests were performed with confining pressure of 150 kPa and other similar conditions on the paste fraction of MSW samples. Stress-strain curves of the studied specimens besides their paste fraction are exhibited in Fig. 13. Sfp, S5p, S14p, and S21p were related to the paste fraction of Sf, S5, S14, and S21, respectively.

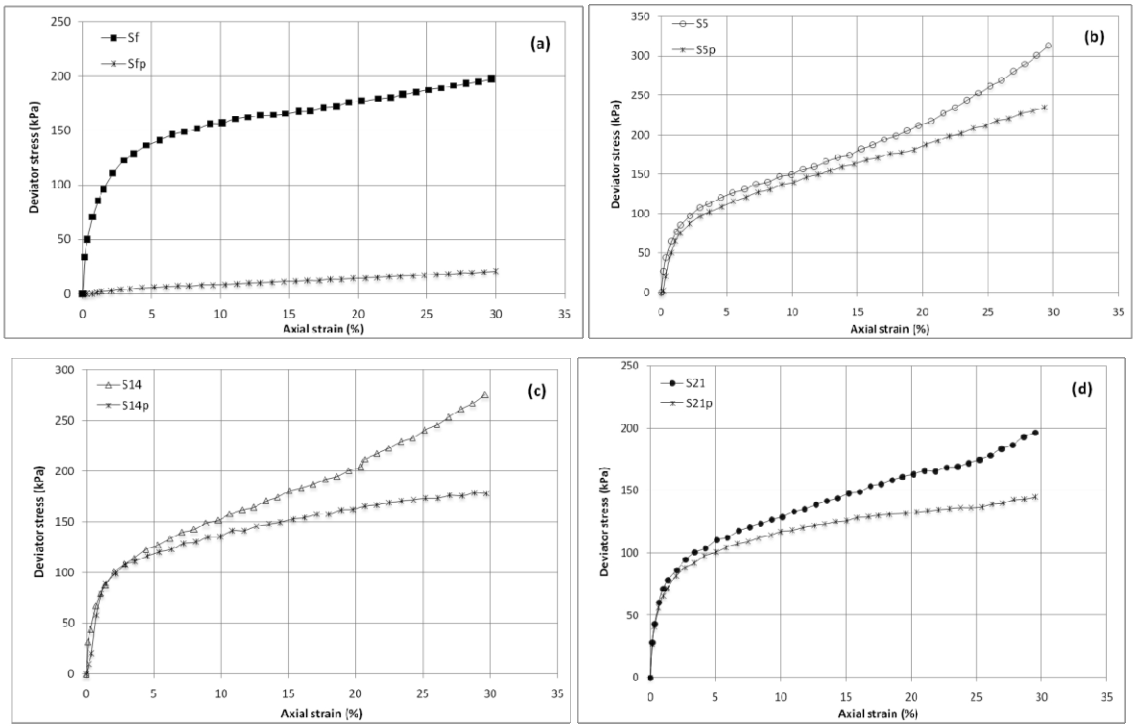


**Fig. 13** Stress-strain curves of MSW in comparison with the paste fraction (a) fresh sample; (b) S5; (c) S14; (d) S21

As can be seen, the general shape of the paste behavior curves were significantly similar to the stress-strain curves of MSW specimens and continued up to the strain level of 30% without any peak points. Also, in all of the aged samples, the paste curves stood below their relevant sample curves in such a way that the shear strength of paste fraction at strain level of 15% represented 0.85 to 0.9 shear strength of the relevant sample. However, in fresh samples, this proportion was almost less than 10%. Extreme difference in the stress-strain curves for Sf specimens described the slight shear strength of paste fraction in the fresh samples in comparison to the significant contribution of other components. Additionally, stress-strain curves at low strain levels (3%) were congruent, except in Sf specimens, and their difference increased with a strain increase.

Fig. 14(a) shows the stress-strain curves of paste fraction in the studied samples which were obtained from triaxial tests. As can be observed, stress-strain curve of Sfp was extremely distant below others, whose curves were completely separated over the strain level of 10% and showed a similar trend to their relevant sample behaviors, as illustrated in Fig. 7(b). Variation in pore water pressure is also exhibited in Fig. 14(b). Rising trend in the pore water pressure of Sfp was noticeably different from others, which was seemingly owing to different organic contents that could finally lead to a drastic decrease in shear strength.

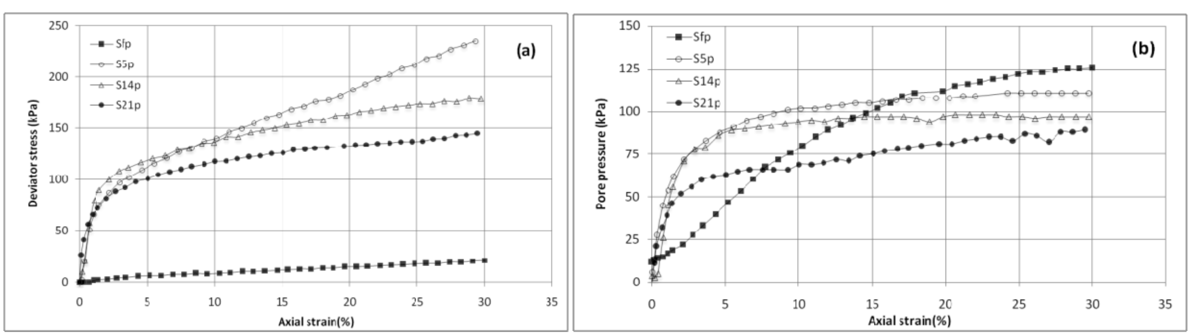


**Fig. 14** MSW paste fraction behavior (a) stress-strain, (b) pore pressure

Overall, the results exhibit that, first, the general behavior of paste fraction was similar to the stress-strain behavior of their relevant samples without any peak points and, second, the difference in their behavior became significant over the strain level of 10%. Also, similar to their original samples, Sfp, S21p, S14p, and S5p represented more shear strength, respectively. Furthermore, the paste fraction of aged MSW represented 85% to 90% shear strength of the whole sample, although this proportion was less than 10% in fresh samples.

## 6. Conclusions

This research was conducted to explore the effect of aging on physical characteristics and shear strength of the MSW samples obtained from Kahrizak landfill. For this purpose, aged MSW (5.5, 14, and 21 years old) were collected by means of mechanical excavators in the burial site and compared with the fresh ones. The characteristics of MSW including particle size distribution, moisture content, organic content, degree of decomposition (DOD), in-situ unit weight, and sample components were determined. Shear strength was evaluated using large-scale triaxial apparatus in CU condition through which all the specimens were remolded in a similar condition. The following results could be obtained from the field study as well as the experimental work:

- The highest proportion of the fresh MSW was the paste fraction. In the aged MSW, the paste fraction was less and the plastic and fiber parts were more than that of the fresh one.
- The initial value of moisture content, which was 153% for fresh MSW, decreased to below its half for the aged samples. The aging process influenced the particle size as well; the particle size distribution curve was prolonged and the amount of finer particles increased.
- Organic content of the samples was reduced from 65% for fresh MSW to 20% for the aged one. Also, DOD of MSW reached 85% after 14 years. Regarding 21 year-old MSW samples, irregular variation in DOD factor and organic content was due to its different burial conditions, soil cover, and initial components.
- Stress-strain curve of both fresh and aged MSW samples showed an increasing trend to the strain level of 30% and no peak point was approached. Also, the pore water pressure of CU tests increased up to approximately 80% of the confining pressure.
- The shear strength of the specimen was influenced by their age as well as the amount of fibers. The fresh and 5.5 year-old MSW sample, which had the lowest and highest fiber contents, respectively, showed minimum and maximum shear strength among the MSW samples. The shear strength of 21 year-old samples demonstrated lower value than the 14 year-old ones, which might be attributed to aging process that reduced the tension strength of the fibers, even though the amount of fibers was higher for 21 year-old samples than the 14 year-old ones.
- In the aged MSW compared to the fresh one, the internal friction angle (Φ) increased, while cohesion (C) decreased; however, no constant trend related to the age was observed. The extremum values for the C and Φ curves, which were 5.5 year-old samples, can be attributed to the significant increase in the fiber content of these samples compared to that of others. Also, according to the variation in strength parameters, as DOD increased, Φ increased and C decreased.
- The mechanical behavior and characteristics of aged MSW were related to preliminary components and burying conditions in the landfill. Results of this study represented that utilizing DOD parameter was more appropriate than age for evaluating the variation in strength parameters.
- Paste fraction, which represented 40% to 60% of total waste mass, was performed as the main cohesive material in MSW. This fraction supplied almost 85% of total shear strength of aged MSW samples. In contrast, for the fresh MSW, only 10% of shear strength was supplied by the paste fraction of the samples.

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