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Effect of aging on dynamic properties of municipal solid waste: A case study of Kahrizak Landfill, Tehran, Iran

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Abstract. The effect of aging on dynamic properties of Municipal Solid Waste (MSW) including damping ratio and shear modulus was investigated in the current research. For this purpose, a series of cyclic Consolidated Undrained (CU) triaxial tests were performed on fresh and old reconstituted cylindrical specimens, taken from Mansoory Prototype Landfill (MPL) placed in Kahrizak Landfill, Tehran, Iran. The results showed that the shear modulus of old samples (7.5 years old) was more than that of the fresh ones. This trend can be attributed to decomposition of waste over time, which leads to reduction in organic content and, consequently, increment of fibrous waste particles (plastics) of the old samples. On the other hand, the results also indicated that the damping ratio was partially dependent on the composition of the specimen and it slightly decreased with increasing the age of MSW. The high percentage of organic content in fresh specimens can be considered as the main reason for this behavior. Finally, the normalized shear modulus reduction and strain-dependent material damping curves were prepared for both ages of retrieved MSW from Kahrizak Center Landfill (KCL). The results of the current study are in the range reported in the technical literature and can be used as reliable data for seismic purposes.

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1. Introduction

The increasing worldwide rate of urbanization and, consequently, more MSW production have led to severe shortage in the number of places where a landfill can be built. On the other hand, safe placement of more waste in the existing landfills requires accurate engineering analyses and constructions. The stability of such engineering constructions is greatly dependent on reasonable characterization of static and dynamic responses of the waste material. Despite the great efforts into increasing the understanding of reliable characteristics of MSW and risk reduction of landfills, several failures have occurred in many locations around the world. These catastrophic failures are prone to cause several irreparable environmental and societal impacts.

During Northridge earthquake, several landfills were subjected to strong shakings, according to Matasovic et al. [1]. The Chiquita Canyon landfill experienced a mass movement of wastes against a lined slope. The landfill was located 12.2 km from the epicenter and its geo-membrane liner was torn at the top of the slope due to the mass movement of waste [2].

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In another case, OII landfill located in Monterey Park, California, undergone a significant crack on the northern slope of the landfill due to the mentioned earthquake. Fortunately, these events did not cause significant financial and human losses. However, they drew worldwide attention to increasing the overall knowledge of MSW materials under dynamic loads, especially in high seismic regions.

In this regard, the city of Tehran, as the capital of Iran, is under the great threat of huge earthquakes as it is located adjacent to several active faults like Mosha, Kahrizak, and Rey. In addition, the history of the occurring earthquakes in the region and the existence of Kahrizak Landfill demonstrate the necessity of further attempts on assessing the dynamic properties of MSW under seismic loads.

The equivalent linear technique is the most common method in assessing the dynamic behavior of MSW. The reliability of this technique largely depends on the sound investigation into factors including the MSW unit weight profile, small-strain shear modulus ($G_{\max}$) or shear wave velocity ($V_{s.}$), strain-dependent normalized shear modulus reduction ($G/G_{\max}$), and material damping relationships. These factors have been the subject of significant attention over the past 15 years [3]. As mentioned before, damping ratio and shear modulus of MSW are the required parameters for the equivalent linear seismic response analysis of MSW [2]. It should be stated that shear modulus refers to the stiffness of waste materials while damping ratio is a measurement of energy dissipation. Different factors such as shear strain, number of cycles, confining pressure, etc. can change the values of the mentioned parameters in laboratory testing programs. It is established beyond doubt that the most important factor on dynamic properties of geologic materials is cyclic shear strain. Accordingly, the variations of dynamic properties of these materials under different testing conditions are generally shown against the shear strain values.

2. Background

Being aware of waste engineering behavior and parameters helps to design a safe engineering landfill site. Up to now, relatively comprehensive researches have been done to evaluate static behavior of landfill sites and its shear resistance parameters [4-16]. In addition, designing a landfill site against cyclic or seismic loading necessitates knowing dynamic parameters of Municipal Solid Waste (MSW). These parameters are:

- The maximum shear modulus ($G_{\max}$) and/or the maximum shear wave velocity ($V_{s\max}$);
- Shear modulus (scant shear modulus) (G);
- Damping ratio (D).

The development of shear wave velocity profile is necessary to estimate the small-strain stiffness of the landfill using the following equation, according to Zekkos et al. [17]:

$$G_{\max} = \rho \times {V_s}^2, \quad (1)$$

where $G_{\max}$ is the small-strain shear modulus, ρ is the mass density of the material, and V_s is the shear wave velocity of the material. The shear velocity of waste materials in a landfill is usually measured by various in situ seismic methods [18,19], e.g.:

- Intrusive methods such as down-hole and cross-hole;
- Nonintrusive methods such as Spectral Analysis of Surface Wave (SASW) and Continuous Surface Wave System (CSWS).

Various researchers have reported shear wave velocities of different MSW landfills using a variety of methods [16,20-24]. Some of them assumed a value for MSW unit weight and calculated $G_{\max}$ values for the waste body [20,25]. Also, in a few cases, the authors represented a site-specific $G_{\max}$ profile by measuring both MSW in situ unit weight and shear wave velocity in the same site [19,26,27]. In this regard, Ramaiah et al. [28], based on statistical analysis, showed that non-invasive methods and, in particular, the surface wave methods were the most popular ones in field measurement of V_s of MSW. The great advantage of these measurements is the ability of assessment at known levels of stress and strain ($< 10e-4\%$) without any soil disturbance. Both the Continuous Surface Wave System (CSWS) and Spectral Analyses of Surface Waves (SASW) methods use Rayleigh (surface) waves, which propagate within a zone approximately one wavelength in depth, according to Wrigh et al. [29]. Ramaiah et al. [28] also proposed a linear model for variation of MSW V_s with the depth of up to 30 m, which was consistent with the recommended values by other researchers.

Normalized shear modulus reduction and material damping relationships are critical requirements for seismic design of landfills. Different researchers have investigated these parameters and recommended their own curves. In this regard, the majority of the proposed curves are primarily based on back analyses of the seismic response of the OII Landfill in Southern California, while the amount of laboratory investigations into MSW is limited [30].

According to Hossain et al. [31], difficulties such as the health issues associated with testing waste materials, sample disturbance, and largeness of testing material are of the main reasons for laboratory testing limitations.

As mentioned before, the stress-strain response of MSW under dynamic loads is found to be affected by several factors including aging or degradability of waste material. The effect of age or degradation of MSW on its dynamic properties has been reported by various researchers. Zekkos [32] evaluated the effects of different parameters on the dynamic properties of MSW samples from Tri-City Landfill. The author reported that the composition of the waste was the most important factor that significantly affected both the absolute value of shear modulus as well as the shape of the shear modulus reduction curve and the material damping curves. He stated that as the amount of fibrous materials increased, the normalized shear modulus reduction curves shifted to the right while material damping tended to decrease at large strains. In fact, the greater amount of fibrous material could be considered as the simulation of aged samples due to the low degradability of these constituents. Hossain et al. [31] performed a series of resonant column tests on MSW samples at different stages of decomposition. The authors reported that the normalized shear modulus reduction and damping curves were significantly affected by the degree of decomposition. The increase was attributed to the breakdown of fibrous nature of solid waste particles as they degraded. Ramaiah et al. [33] conducted an extensive testing program, including field and laboratory measurements, for the effect of different parameters on cyclic behavior of MSW samples from two landfills located in Delhi, India. Their results demonstrated that the fibrous waste constituents had significant impact on the stiffness and material damping of MSW. The reported data were in accordance with the findings by Zekkos [32].

It should be noted that site-specific data are always preferable to general recommendations and past experience, since waste materials may differ due to a number of reasons. In this regard, the effect of aging of waste, as the overall objective of this research, on dynamic properties of MSW materials is investigated. For this purpose, a series of cyclic Consolidated Undrained (CU) triaxial tests were performed on reconstituted cylindrical specimens with two different ages: the fresh specimens and the 7.5 years old ones. Also, Continuous Surface Wave System (CSWS) was employed to evaluate MSW's maximum shear modulus.

3. Methodology

3.1. Landfill characteristics and location

Kahrizak Landfill with an area of 1,200 hectares is located 20 km southwest of Tehran, Iran. This landfill, as the largest waste disposal facility in Iran, has been the final destination of the produced municipal waste in Tehran and its surrounding towns for more than 40 years. It must be stated that the daily production of waste in Tehran is approximately 11000 tons (0.98 kg per capita). However, the dominant method for dealing with the massive amount of entering MSW is disposal without any special pretreatment methods.

In this regard, based on an extensive academic research program, Geotechnical Engineering Research Center (GERC) of Iran University of Science and Technology (IUST) decided to build and operate the first engineered landfill, named Mansoory Prototype Landfill (MPL), in Kahrizak area to evaluate the real behavior of Tehran's MSW in landfills by measuring the parameters such as temperature, leachate, amount of released gas, and landfill settlement by passing time.

Design of cells in MPL was based on regulations and standards applied to sanitary landfills and mainly based on EPA guidelines. Each closed cell of MPL consists of wastes with a specific age and the capacity of each cells is about 4600 tons of MSW (Figure 1). The locations of sampling and the performed in situ CSWS tests are also shown in Figure 2. Regarding the overall objective of the current research, sampling was conducted on fresh and aged wastes. The fresh waste samples were taken from the MSW disposed at the input of the recycling facilities located in the landfill, while excavation of test pits by mechanical digger was performed for sampling of old waste as shown

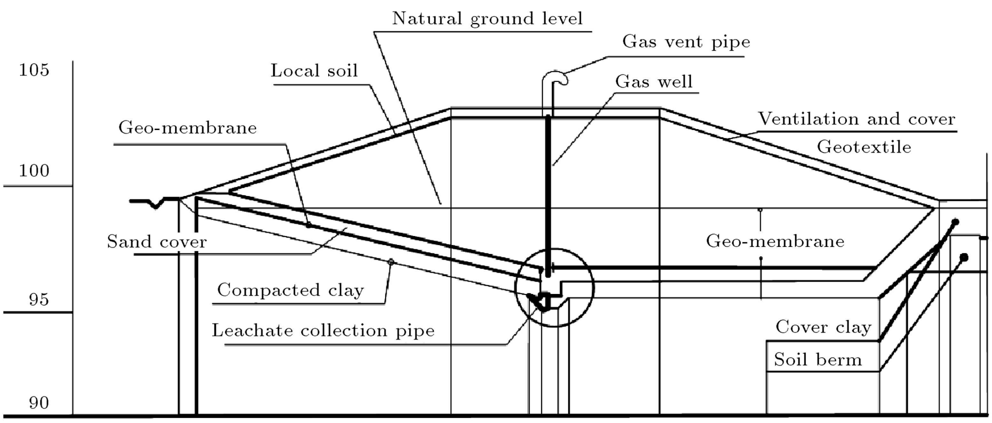


Figure 1. Schematic section of landfill.

Figure 2. Location of old and fresh MSW landfills in KCL.

in Figure 2. After the mentioned stage, irrespective of age of waste, samples were put in plastic drums and transported to the GERC of IUST. The samples were placed in thick plastic bags and preserved in a refrigerator at a temperature lower than 5°C to avoid any degradation before testing program, referring to Keramati et al. [34].

3.2. Measurement of in situ shear wave velocity and $G_{\max}$

In this study, Continuous Surface Wave System (CSWS), as an in situ nonintrusive method, was employed to assess the effect of aging on shear wave velocity of MSW. The CSWS system uses a ground vibrator as the source of energy and propagates Rayleigh (surface) waves within a zone approximately one wavelength in depth in the range of 5-700 HZ, according to Stokoe [35]. The generated waves at a single known frequency are recorded by geophones, which should be placed in line with the vibrator. In the final step, the analogue signal from each of these geophones is digitized and recorded with respect to time by means of a processing unit (Figure 3).

As mentioned, the shear wave velocity can be related to maximum shear modulus by Eq. (1). The controversial factor in this equation is the unit weight of MSW at a known depth. In this regard, Zekkos et al. [36] proposed a convenient hyperbolic equation to estimate the MSW unit weight as a function of depth. The following equation presents the proposed hyperbolic equation:

$$\gamma = \gamma_i + \frac{z}{\alpha + \beta z}, \tag{2}$$

where γ_i is near-surface in-place unit weight (kN/m^3), z is depth (m) at which the MSW unit weight γ is to be estimated, and α (m^4/kN) and β (m^3/kN) represent modeling parameters.

The parameter α is a function of the rate of unit weight increase with depth near the surface while β is a function of the difference in unit weight between the surface and the great depth, where the unit weight profile becomes nearly constant. These parameters are dependent on the compaction effort and soil amount of landfill. Considering the lack of applicable specific density equipment such as compactors as well as the thickness of 2 to 3 meters for the fresh waste layer in Kahrizak Landfill, the values of α and β, based on the table proposed by Zekkos et al. [36], were assumed 2.5 and 0.15, respectively. Figure 4 illustrates the unit weight profile of fresh and 7.5 years old MSWs from KCL and MPL landfills.

The test results yield a $G_{\max}$ of 12500 kN/m^2 for fresh MSW with 9 kN/m^3 of unit weight, and 25000 kN/m^2 for 7.5 years old MSW with 12 kN/m^3 of unit weight, corresponding to the applied confining stress to the desired depth of laboratory testing according to Khaleghi [37]. Figure 5 illustrates the resulting profiles of fresh and aged MSWs by this method. It should be mentioned that the higher values of upper layers are because of the presence of daily and final clayey covers.

3.3. Material characterization and specimen preparation

Visual inspection or physical characterization of collected samples is essential for classifying the MSW

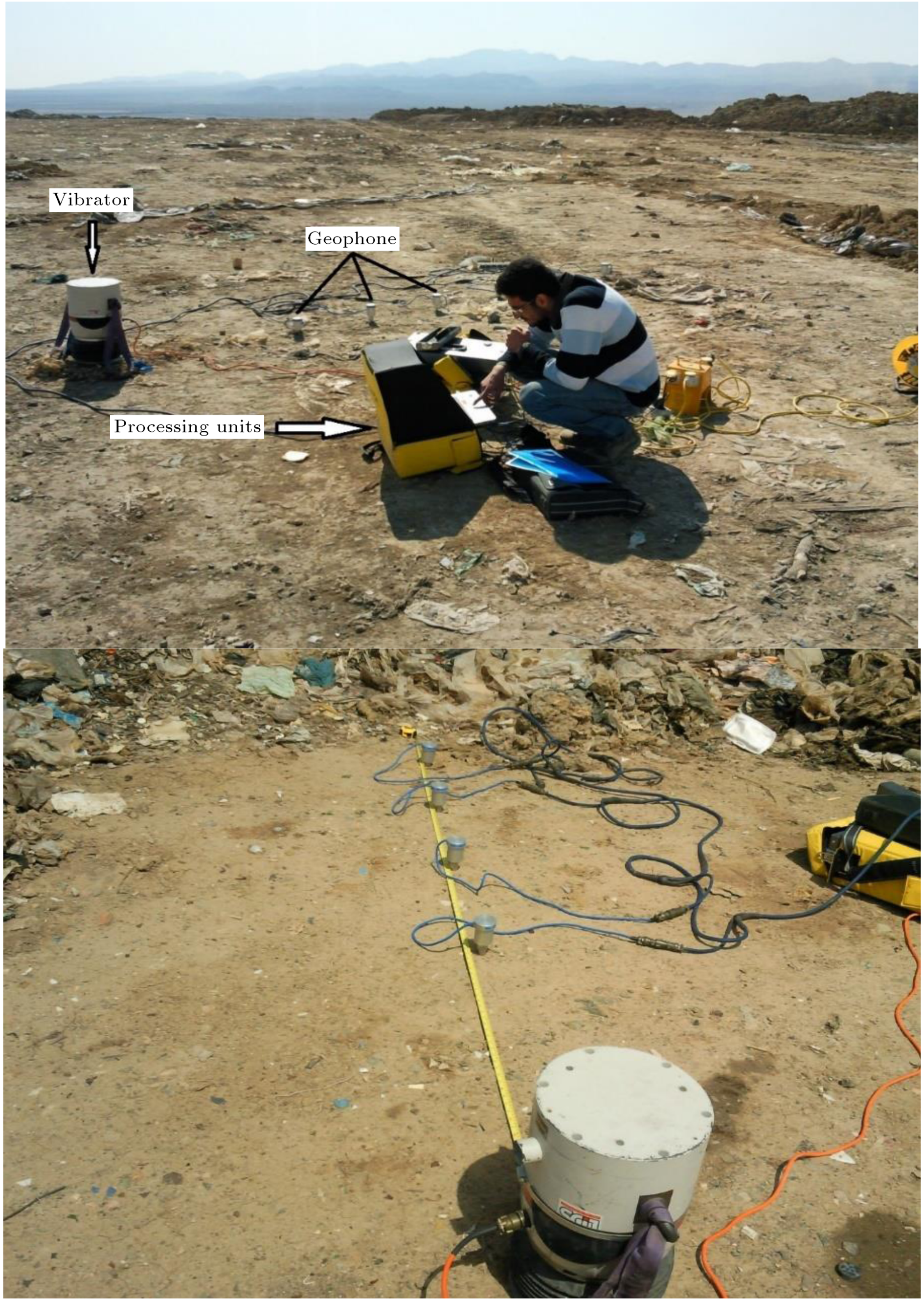


Figure 3. CSWS test on 7.5 years old waste.

and consequently, evaluating its dynamic properties. For this purpose, with the aim of identifying the specimen reconstitution, the MSW bulk samples were classified into five categories of metal and glass; rock and ceramic; paper, cardboard, and wood; plastics and textile; and paste (organic contents). Organic contents, as defined in this project (kitchen and green waste), were expected to degrade rapidly. This means reduction in the compressible components and increase in incompressible components (fibers including plastics) with the passage of time. In fact, the accelerated decomposition of the MSW considerably changes the geotechnical characteristics of the waste in the landfill according to Adil Haque [38]. Therefore, the stability of MSW is expected to be affected. Figure 6 presents the fresh and 7.5 years old MSW compositions and Figure 7 presents the visual changing of the MSW materials with increasing the age to 7.5 years old. Also, following the ASTM D2216 procedure, the average moisture contents of fresh and 7.5 years old samples were obtained 148% and 84%, respectively. The obtained results for moisture content demonstrate the high percentage of organic content in fresh samples of MPL, which have a decreasing trend with progression of degradation.

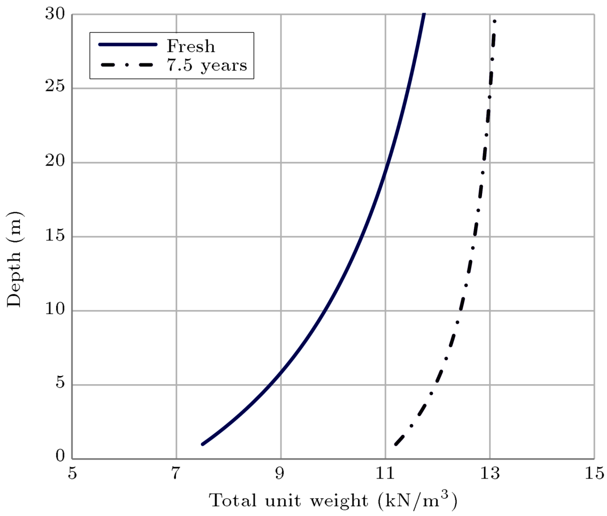


Figure 4. Fresh and 7.5 years old unit weight profiles according to Zekkos et al. [36].

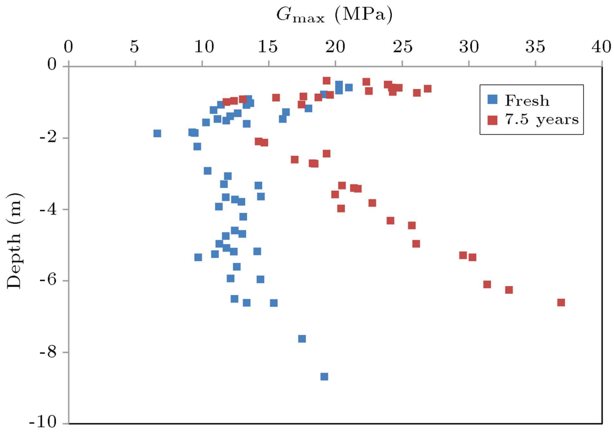


Figure 5. $G_{\max}$ results of CSWS method by Khaleghi [37].

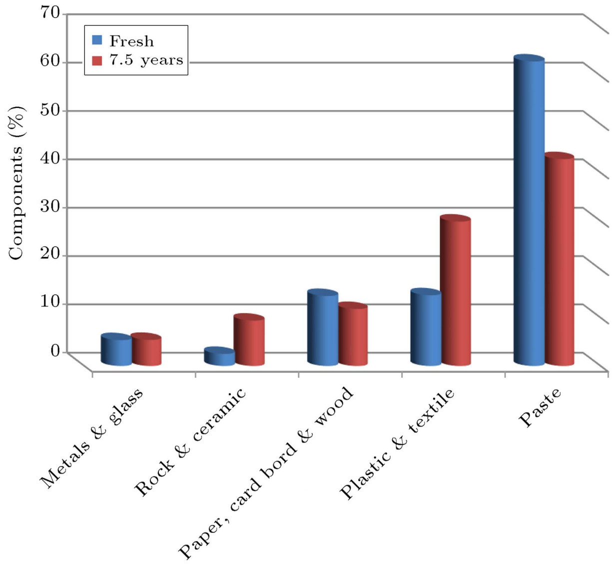


Figure 6. Changing the MSW composition with increasing the age.


(a)


(b)

Figure 7. Visual changing of the MSW with increasing the age: (a) Fresh MSW from KCL and (b) 7.5 years old MSW from MPL.

In the next step, the specimens were reconstituted in a sample preparation mold in 6 layers using a constant-weight hammer that was dropped repeatedly from a constant height to achieve target unit weights of 9 and 12 kN/m^3. These unit weights represent the medium effort of compaction for fresh and 7.5 years old MSWs in KCL and MPL. It should be noted that, depending on the size of the prepared specimen, limitations exist on the maximum advisable particle size. In this regard, referring to Zekkos [32], the maximum size of stiff bulky waste particles was considered 1/6 the specimen diameter while for soft fibrous waste particles, the size was limited to 1/3 the specimen diameter. Therefore, some components were removed prior to sample preparation to prevent the possible problems (such as unexpected tearing of membrane) in prepared samples.

4. Cyclic triaxial testing procedure

A cyclic triaxial testing device with the specimen diameter of 100 mm and the height of 200 mm was used to investigate the dynamic behavior of reconstituted specimens of fresh and 7.5 years old MSWs. The configuration of the device allowed accurate measurements of the shear modulus at shear strains of about 0.08% to 4%. Also, a data logger with the recording rate of 60 Hz was used during the compression phase to record deviator stress, pore pressure, and axial load. The internal pressure sensors (pore pressure and confining stress) were installed on the bottom pedestal while the displacement transducer and load cells were placed on the top cap. It is important to note that the confining stress capacity of the cell was up to 1000 kPa pressure. The process of testing is summarized as follows.

After placing the sample in the apparatus, it was saturated according to ASTM D3999 [39]. The objective of the saturation phase of the test was to fill all the voids in the specimen with water without undesirable pre-stressing of the specimen or allowing the specimen to swell. Saturation is usually accomplished by applying back pressure to the specimen pore water in order to drive air into the solution after saturating phase, which is the function of both time and pressure, according to D4767 [40]. Also, it should be noted that the applied back pressure was held the same for all the samples to facilitate the comparability and increase the accuracy of results.

Specimens were considered to be saturated when the value of B was equal to or greater than 0.8. This value ($B = 0.8$) was selected based on the reported results of Shariatmadari et al. [41]. The authors demonstrated that the MSW particles were highly compressible and this restricted the contribution of the pore water pressure to the effective stress level. According to this fact, B factor was kept at 0.8 in all the tests.

After the saturation procedure, the maximum back pressure was held constant and the chamber pressure was increased until the difference between the chamber pressure and the back pressure equaled the desired effective consolidation stress. Consolidation phase would start when the drainage valve of specimen opened under the requested stress conditions. When the volume change of specimen equaled zero and the pore water pressure stayed constant at the back pressure level, the consolidation phase was assumed to be finished. Due to the very low permeability of these materials, consolidation process took about 10 to 14 hours for MSW materials.

Considering the undrained condition of samples during the loading, the drainage valve should be closed when the consolidation stage was completed to ensure the constant condition. Also, the loading stage on each specimen was continued up to 15 cycles of loading.

In general, a total of 24 strain-controlled cyclic triaxial tests on MSW samples under an isotropic confining stress of 75 kPa with different unit weights of 9 and 12 kN/m^3 were conducted. All the tests were conducted in an undrained saturated condition according to D3999-91. Table 1 shows the details of the performed tests on fresh and 7.5 years old MSW samples.

5. Results and discussion

In this research, a total of 24 dynamic triaxial tests were conducted to investigate the dynamic behavior of MSW materials under the aging effect of samples with different unit weights. All the samples were tested under an effective confining stress of 75 KPa, a loading frequency of 0.1 Hz, and unit weights of 9 and 12 kN/m^3. In this research, the 10th cycle, for each test, was assumed to be the base of analysis with the aim of calculating the dynamic parameters. Also, the Poisson's ratio was estimated to be 0.5. This estimation is in accordance with the reported data by Sharma et al. [42] and Kavazanjian [43]. The authors stated that the Poisson's ratio of samples with high percentage of organic content, in saturated condition or bioreactor landfills, could exceed 0.4 and varied up to 0.5.

Figure 8 represents the typical hysteresis loops

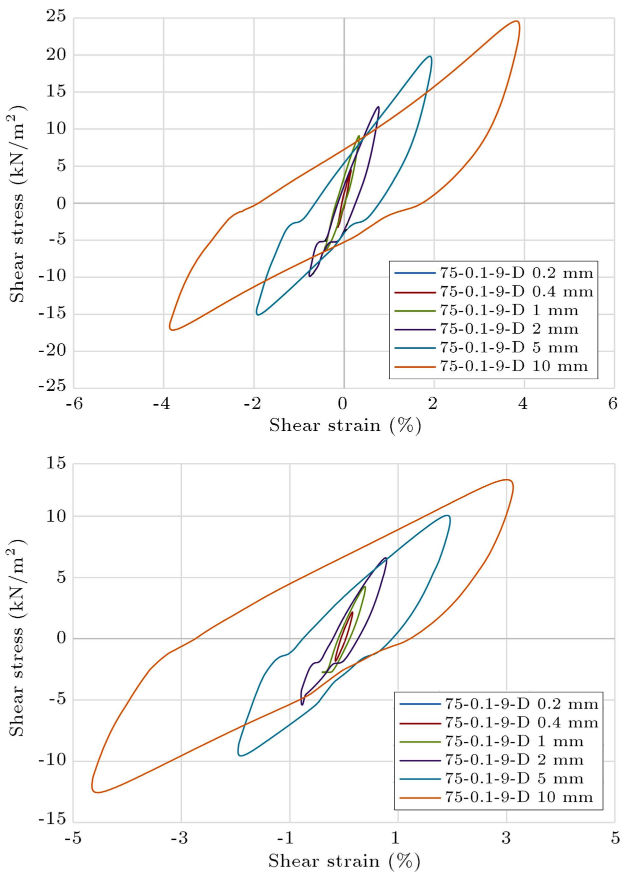


Figure 8. The cycle hysteresis loop for test series "7.5y-9-75-0.1" and "F-9-75-0.1".

Table 1. Summary of the cyclic triaxial tests conducted as a part of the current study.

No.	Age of MSW	Unit weight (kN/m^3)	Consolidation stress (kPa)	Frequency (Hz)	Loading amplitude (mm)	Axial strain (%)	Test ID
1	Fresh	9	75	0.1	0.2	0.05	F-9-75-0.1-0.2
2	Fresh	9	75	0.1	0.4	0.1	F-9-75-0.1-0.4
3	Fresh	9	75	0.1	1	0.25	F-9-75-0.1-1
4	Fresh	9	75	0.1	2	0.5	F-9-75-0.1-2
5	Fresh	9	75	0.1	5	1.25	F-9-75-0.1-5
6	Fresh	9	75	0.1	10	2.5	F-9-75-0.1-10
7	Fresh	12	75	0.1	0.2	0.05	F-12-75-0.1-0.2
8	Fresh	12	75	0.1	0.4	0.1	F-12-75-0.1-0.4
9	Fresh	12	75	0.1	1	0.25	F-12-75-0.1-1
10	Fresh	12	75	0.1	2	0.5	F-12-75-0.1-2
11	Fresh	12	75	0.1	5	1.25	F-12-75-0.1-5
12	Fresh	12	75	0.1	10	2.5	F-12-75-0.1-10
13	7.5 yrs.	9	75	0.1	0.2	0.05	7.5y-9-75-0.1-0.2
14	7.5 yrs.	9	75	0.1	0.4	0.1	7.5y-9-75-0.1-0.4
15	7.5 yrs.	9	75	0.1	1	0.25	7.5y-9-75-0.1-1
16	7.5 yrs.	9	75	0.1	2	0.5	7.5y-9-75-0.1-2
17	7.5 yrs.	9	75	0.1	5	1.25	7.5y-9-75-0.1-5
18	7.5 yrs.	9	75	0.1	10	2.5	7.5y-9-75-0.1-10
19	7.5 yrs.	12	75	0.1	0.2	0.05	7.5y-12-75-0.1-0.2
20	7.5 yrs.	12	75	0.1	0.4	0.1	7.5y-12-75-0.1-0.4
21	7.5 yrs.	12	75	0.1	1	0.25	7.5y-12-75-0.1-1
22	7.5 yrs.	12	75	0.1	2	0.5	7.5y-12-75-0.1-2
23	7.5 yrs.	12	75	0.1	5	1.25	7.5y-12-75-0.1-5
24	7.5 yrs.	12	75	0.1	10	2.5	7.5y-12-75-0.1-10

of specimens in the range of the applied shear strain. Calculation of damping ratio and shear modulus has been provided in many references, e.g., Yegian et al. [44] and Karg and Haegeman [45]. The influence of different factors including aging of samples and number of cycles on shear modulus and material damping of MSW is presented separately in the following sections.

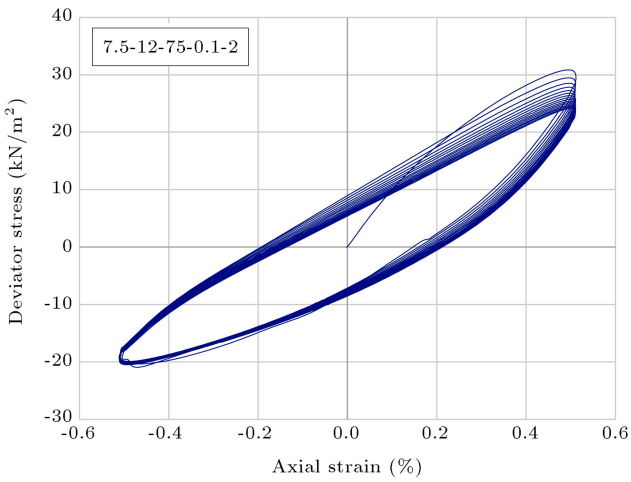
5.1. Effect of number of cycles

In order to clarify the possible effects of number of cycles on dynamic parameters, two tests were conducted on samples in different laboratory conditions with various confining stresses, ages, and axial strains with up to 12 loading cycles. The variations of shear modulus and damping ratio with shear strain, calculated at different loading cycles, are shown in Figure 9. The presented curves demonstrate a slight increase in shear modulus values while the material damping is almost constant in both samples. The results are in accordance with the results of Naveen et al. [46], who evaluated the effects of number of cycles on wastes with different confining stresses. The reason for this behavior can be related to the existence of compressive particles in MSW samples, which significantly reduce the mentioned effect on MSW in comparison with soil curves.

5.2. Effect of Aging

Figure 10 shows the variations of the shear modulus values under the increment of the shear strain for both ages. According to this figure, with increasing the shear strain from 0.08% to 4%, in both tests series, the secant shear modulus decreases. Also, with increasing the age of MSW from fresh to 7.5 years, shear modulus tends to increase.

The reason for the observed trend can be the decomposition of waste over time, which leads to reduction in organic content and consequently, increment of plastic materials. In fact, the increment of plastic material percentage roots in low degradability of these particles in comparison with organic contents. It should be noted that this difference in the shear moduli is more significant in low strain ranges due to the higher effectiveness of fiber reinforcement. The discreteness of



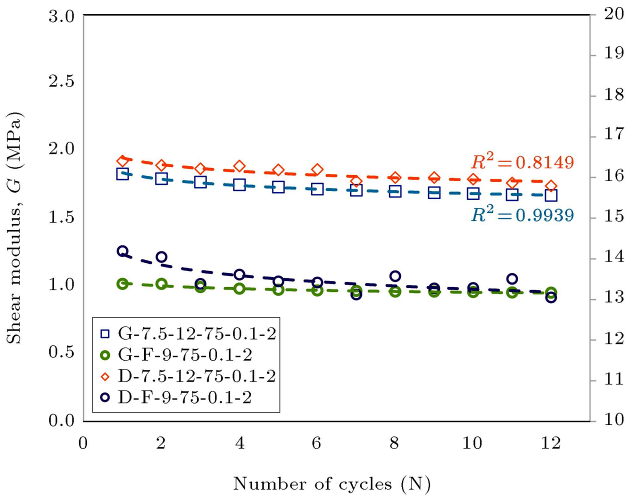


Figure 9. Effect of number of cycles on dynamic properties of MSW.

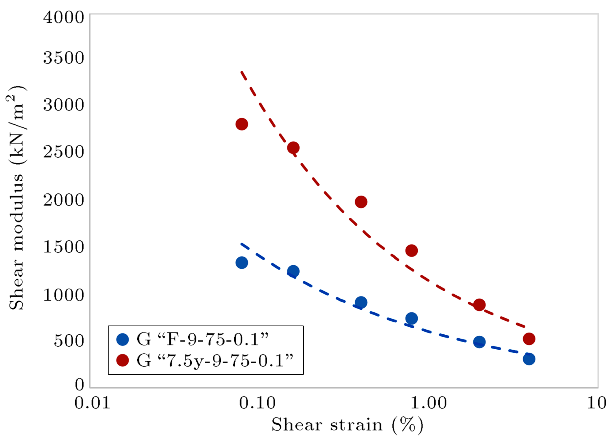


Figure 10. Change in shear modulus with increasing the age in different shear strains.

particles in higher strain ranges decreases the impact of reinforcement. In this regard, as the strain goes up, the shear moduli of both samples converge.

According to Figure 11, as expected, with increase

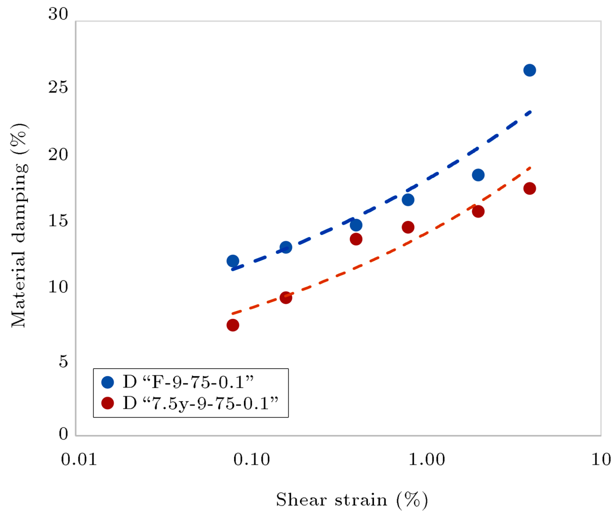


Figure 11. Change in material damping with increasing the age in different shear strains.

in the values of shear strain, in both tests series, the material damping tends to increase. This behavior demonstrates that the specimens have enough time to damp the energy in high strain levels. The results also show that damping ratio of fresh samples is slightly more than that of the old ones. It can be due to high content of organic materials in the fresh samples, which play the role of a damper themselves. It should be stated that the degradability of organic content over time is the main reason for reduction in damping ratio of the 7.5 years old waste.

The results of the current research are in good agreement with the results of Adil Haque [38].

He measured and defined the waste dynamic properties based on a series of resonant column tests as a function of decomposition, and reported that the reason for this behavior can be the decreasing trend of the size of components by progression of decomposition.

The normalized shear modulus reduction and material damping curve as functions of shear strain for both ages are indicated in Figures 12 and 13 based on the results. According to the figures, the normalized shear modulus reduction and material damping curve have a good correlation with the results of the data in the literature and can be used for seismic design purposes in the KCL. The reason for the lower values of the normalized shear modulus in the KCL in both fresh and 7.5 years old MSWs may be related to two factors; the first factor is the high percentage of the organic materials in comparison with the data in the literature and the second factor is the differences between the compositions of the reconstituted sample in the CTX device and the large and stiff in-place MSW materials in the field where CSWS method was performed. Thus, the higher values of the G_{max} are admissible.

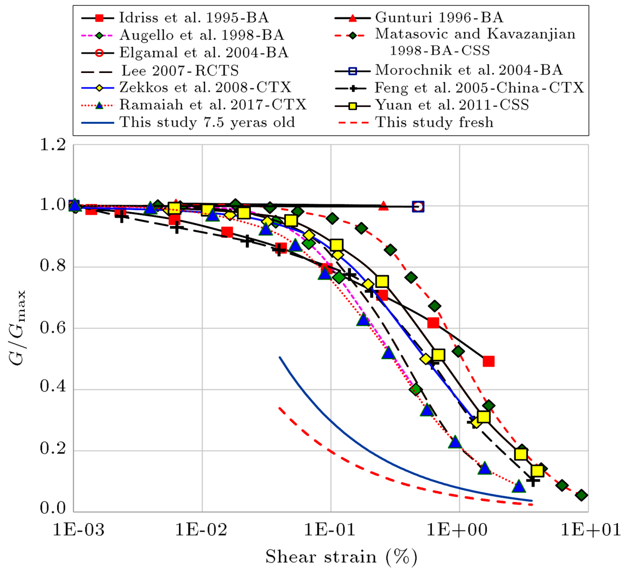


Figure 12. Comparison of the results of the performed cyclic triaxial tests and the literature, normalized shear modulus reduction curve.

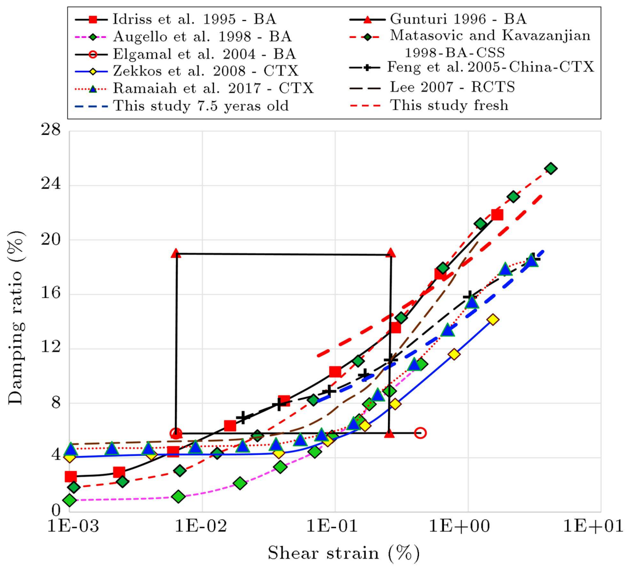


Figure 13. Comparison of the results of the performed cyclic triaxial tests and the literature, material damping curves as a function of shear strain.

6. Conclusions

In this study, 24 cyclic triaxial tests with the diameter of 100 mm in a variety of strain levels were performed to evaluate aging effect on the dynamic properties of MSW. The specimens were driven from an MPL prototype in Kahrizak Landfill, Tehran, Iran. A Continuous Surface Wave System (CSWS) was also utilized to evaluate subsurface shear wave velocity as well as the maximum shear modulus.

The results showed that the shear modulus in old samples (7.5 years old) was more than that in the fresh ones with the same unit weight. It can be due to decomposition of waste over time, reduction in organic content, and consequently, increase in fiber content. It should be noted that this difference in the shear moduli was more significant in low strain ranges. In fact, the increase in discreteness of samples in higher strain ranges caused the shear moduli of both samples to converge. The results also showed that the damping ratio, which was completely dependent on the constituents of the specimen, had decreasing trend over the passage of time. It could be due to high content of organic materials in the fresh sample, which played the role of a damper themselves.

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