Acta Geodyn. Geomater., Vol. 16, No. 3 (195), 269–280, 2019
DOI: 10.13168/AGG.2019.0023
journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

EFFECT OF LOADING FREQUENCY ON THE DYNAMIC PROPERTIES OF SAND-TIRE MIXTURE

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ARTICLE INFO

Article history:
Received 17 January 2019
Accepted 12 June 2019
Available online 26 June 2019

Keywords:
Sand
Tire powder
Shaking table
Shear modulus
Damping ratio

ABSTRACT

Today, the use of waste tires mixed with soil has been expanded in various geotechnical projects to absorb and reduce the vibration caused by seismic and dynamic loads. Therefore, the objective of this work was to evaluate the dynamic properties of such mixtures prior to practical applications. To this reason, 1-g shaking table tests were carried out, and the effects of important parameter like loading frequency on the dynamic behavior of mixtures were investigated. Tire powders were added to the sand with 5 %, 10 %, 15 % and 20 % in gravimetric basis and with a relative density of zero were subjected to sinusoidal loading at frequencies of 0.5, 1, 2, 3, 5, 7 and 9 Hz and input acceleration of 0.1 g and 0.3 g. The results showed that in all cases, the increase in frequency in the same cycles increased the shear modulus and the damping ratio. Also, with increasing shear strain, the shear modulus of the mixture decreased, but the damping ratio increased. On the other hand, by increasing the tire powder, the value of the shear modulus is reduced, but the amount of damping ratio is increased.

1. INTRODUCTION

Soil reinforcement is an effective technique for increasing the strength and stability of geotechnical structures and improving their performance. Several methods have been proposed for this purpose in various scientific sources and have been expanding over the years. The cost of each of these methods is very different, and the conditions under which they can be used depend on the nature, proximity of structures and construction installations. Attempts to find new methods of soil reinforcement and reduction of economic and administrative costs, as well as to reduce the environmental degradation by materials, have attracted the attention of researchers to the use of new recycled materials, such as the waste tire-derived materials. Due to its low specific gravity, high strength and compression, these materials have many applications in geotechnical projects such as reinforcing soft soil in road construction (e.g., Khabiri et al., 2016; Naval et al., 2014; Keskin and Laman, 2014), controlling soil erosion (Poh and Broms, 1995), as aggregates in leach beds of landfills (Kaushik et al., 2016) and lightweight material for backfilling in retaining structures (O'Shaughnessy and Garga, 2000; Lee et al., 1999; Bosscher et al., 1997; Assadollahi et al., 2016). Another important application of waste tires in combination with soil, which has recently been of great interest, is their use as lightweight materials in retaining walls and embankments, machine foundations and railroad track beds in seismic zones. Having high damping characteristic, tires can be used as either soil alternative or mixed with soil to reduce vibration when seismic and dynamic loads are of great concern. So, to investigate the dynamic behavior of soil-tire mixture and various factors affecting it, several studies have been done. Meanwhile, considering that sands constitute a large part of natural sediments and many structures are constructed on these soils, the investigation of sand-tire mixture behavior is a major part of the researches.

Mashiri et al. (2017) carried out a series of bender element tests on specimens of sand mixed with varying proportions of tire chips (TCh). Tests were carried out on STCh mixtures at a constant initial relative density of 50 % for different initial effective confining pressures. The bender element test results indicate that the maximum shear modulus of the STCh mixtures increases with effective confining pressure and decreases with the gravimetric proportion of TCh.

Senetakis and Anastasiadis (2015) carried out a series of resonant column tests on sand - granulated rubber mixtures within a range of rubber content from 0 to 15 % by dry weight of sand–rubber mixtures, at variable isotropic effective stresses, p′, and state of test sample. The results indicated that for a given p′, by increasing the rubber content, the shear modulus decreased, whereas the damping ratio increased. On

Cite this article as Bahadori H, Khalili A: Effect of loading frequency on the dynamic properties of sand-tire mixture. Acta Geodyn. Geomater., 16, No. 3 (195), 269–280, 2019. DOI: 10.13168/AGG.2019.0023

the other hand, the effect of the state of the test sample, namely dry, fully saturated or moist and for a given content of rubber affected material damping but had an almost negligible effect in the obtained small-strain shear moduli.

Ehsani et al. (2015) conducted torsional resonant column and dynamic triaxial experiments to investigate the effect of rubber content and ratio of mean grain size of rubber solids versus soil solids (D50,r/D50,s) on the dynamic response of mixtures in a range of low to high shearing strain amplitude. The results show that tire inclusion significantly reduces the shear modulus and increases the damping ratio of the mixtures. Also decrease in D50,r/D50,s causes the mixture to exhibit more rubber-like behavior.

Mashiri et al. (2013) in another study, to investigate the effect of the level of cyclic shear strain, number of cycles and effective initial confining pressure on the dynamic properties of sand-tire chips (STCh) mixture carried out a series of cyclic triaxial tests. The results indicated that shear modulus of STCh mixtures increases with the increase in the initial effective confining pressure. On the other hand, the shear modulus decreases with the increase in the number of cycles and shear strain. Also, it has been found that at low effective confining pressure, the damping ratio is not significantly affected by the shear strain. However, the damping ratio at high effective confining pressure increases with the increase in the shear strain and increase in the number of cycles.

Although according to the above, numerous studies have been done on the effect of different parameters on the dynamic behavior of the sand-tire mixture, but given the different kinds of exterior cyclic loading affect the natural sand, such as earthquakes, high buildings, high speed rails, wave loads, oil tanks, reservoirs and so on, and they demonstrate different frequencies, so far independent research on the effect of loading frequency on the dynamic properties of the sand-tire mixture has not been carried out. Therefore, in this paper, 1-g shaking table tests were employed to investigate the effect of loading frequency content on dynamic properties of sand-tire mixture. The response obtained from mixture samples during loading with different frequencies and input accelerations were used to generate hysteresis loops of tested samples at different strain amplitudes. Then, hysteresis loops were used to determine the shear modulus and damping ratio at different strain levels. Finally, the effects of loading frequency on the changes of each parameter (G and D) were investigated.

2. EQUIPMENT AND MATERIALS USED IN THE TESTS

2.1. SHAKING TABLE

A hydraulic shaking table with a single degree of freedom, designed and constructed at the Crisis Management Center of Urmia University, was used to conduct the experiments. The dimensions of the shaking table are 2 m × 3 m and the maximum loading capacity is 5 tons, and it is able to simulate two types of harmonic and seismic loading such that appropriate compatibility between input waves and generated waves can be achieved. The shaking table has the capability of working with a maximum acceleration of 1.5 g and a maximum frequency of 20 Hz. The maximum displacement that can be tolerated by this system is 240 mm. It has two propulsion engines, each with a velocity of 150 mm/s and the device also has the ability to simulate the velocity in single or dual-engine form. Soil samples were constructed into a model container placed on the shaking table. This container is made of Plexiglas sheets with a thickness of 2 cm and a size of 180 cm × 60 cm × 80 cm. Figure 1 shows the model container on the shaking table.

2.2. MATERIALS

2.2.1. Soil

Firoozkuh No. 161 sand was used in all the experiments. The Firoozkuh sand gradation curve is similar to that of Toyoura sand. Some specifications of this sand are listed in Table 1 (Bahadori et al., 2008).

2.2.2. Tire Powders

In this study, tire powders were used as a soil reinforcement material. Tire powders are made from discarded tires that have been broken into pieces and sieved by an industrial tire-shredder system. Steel wires and fibers of the waste tires were separated in the laboratory. Figure 2 illustrates the tire powders, while Table 2 demonstrates their physical properties. The particle size distribution for Firoozkuh sand and tire powder is illustrated in Figure 3.

2.3. INSTRUMENTATION

In this study, accelerometers were used to measure the acceleration of the input to the sample as well as to record the acceleration caused by the input excitation at different depths of the soil sample. In order to keep the sensors from bending during sample construction and testing, and to provide a better coupling with the soil mass, the bases of two plates with dimensions 5 cm × 5 cm and 5 cm × 2 cm were made and firmly super-glued to the underneath of the sensor. The displacement transducers (LVDT sensors) were also used to measure linear displacement. To record information, all sensors were plugged into a 16-channel dynamic data logger ART-DL16D. This device instantaneously registers the voltages generated by the above sensors during the test.

3. SAMPLE CONSTRUCTION AND TESTING METHOD

First, as suggested in the literature (e.g., Lombardi et al., 2015), a 2-cm thick foam was used to

Fig. 1 Model container on the shaking table.

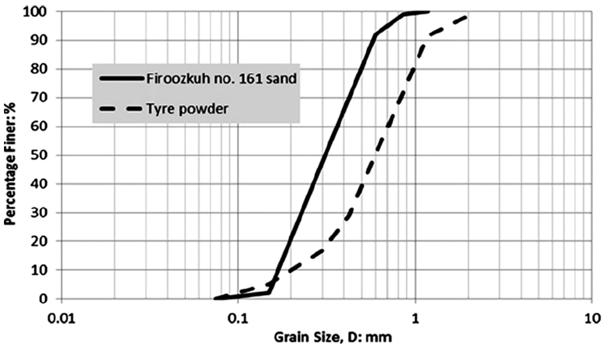

Fig. 3 The particle size distribution for Firoozkuh sand and tire powder.

Fig. 2 Tire powders.

Table 1 Physical properties of Firoozkuh Sand.

Material	D_{10}(mm)	D_{30}(mm)	D_{60}(mm)	G_s	F_c (%)	C_u	C_c	e_{max}	e_{min}
Firoozkuh No.161	0.16	0.21	0.3	2.65	1	1.87	0.88	0.874	0.548

Table 2 Physical properties of Tire Powder.

Material	D_{10}(mm)	D_{30}(mm)	D_{50}(mm)	D_{60}(mm)	G_s (%)	C_u	C_c
Tire Powder	0.21	0.41	0.59	0.7	0.86	3.33	1.143

avoid a direct confrontation of the sample with the rigid body and to mitigate the unfavorable reflections from the boundaries.

Samples were constructed in both unreinforced (pure sand) and reinforced form and with a relative density of zero. In reinforced samples, tire powders were added to the sand with 5 %, 10 %, 15 % and 20 % in gravimetric basis. To prepare the sample, a wet tamping method was utilized in both the unreinforced (pure sand) and the reinforced (sand mixed with tire powders) specimens. In this method, first, the sand was mixed with 5 % water. Soil poured uniformly into the container from four equal heights of 150 mm to reach a total height of 600 mm. To achieve the relative density of the same target for all layers, the soil should be poured consistently from a constant height. Then, each layer was compressed accordingly until a specific density was reached (i.e., relative density equal to zero). To ensure proper bonding between the two layers of the soil, the surface of each compacted layer was scratched before the next layer is poured.

During the compaction process, the accelerometers A_1, A_2, and A_3 were placed at a depth of 150, 300 and 450 mm with respect to the bottom of the container. Also, one accelerometer, A_0, was attached rigidly to the container base to measure base acceleration. Soil compaction around accelerometers placed inside the soil should be carefully monitored to prevent damages and excessive displacements. A displacement transducer (L_1) was placed on the soil surface at the height of 600 mm from the floor of the container to measure the vertical displacement of the surface of the soil. Acceleration was recorded at different depths and displacement on the soil surface was recorded too. The schematic of the instrumented test samples is shown in Figure 4. It has been reported that the rigid container of model can affect the dynamic response of experimental models (El-Emam and Bathurst, 2007) and therefore, to reduce its

Table 3 Variable parameters in shaking table tests.

Soil / Tire Powder	Frequency of loading (Hz)	Acceleration of loading (g)	Number of cycles	Total no.
Sand / 0%	0.5, 1, 2, 3, 5, 7, 9	0.1, 0.3	30	14
Sand / 5%	0.5, 1, 2, 3, 5, 7, 9	0.1, 0.3	30	14
Sand / 10%	0.5, 1, 2, 3, 5, 7, 9	0.1, 0.3	30	14
Sand / 15%	0.5, 1, 2, 3, 5, 7, 9	0.1, 0.3	30	14
Sand / 20%	0.5, 1, 2, 3, 5, 7, 9	0.1, 0.3	30	14

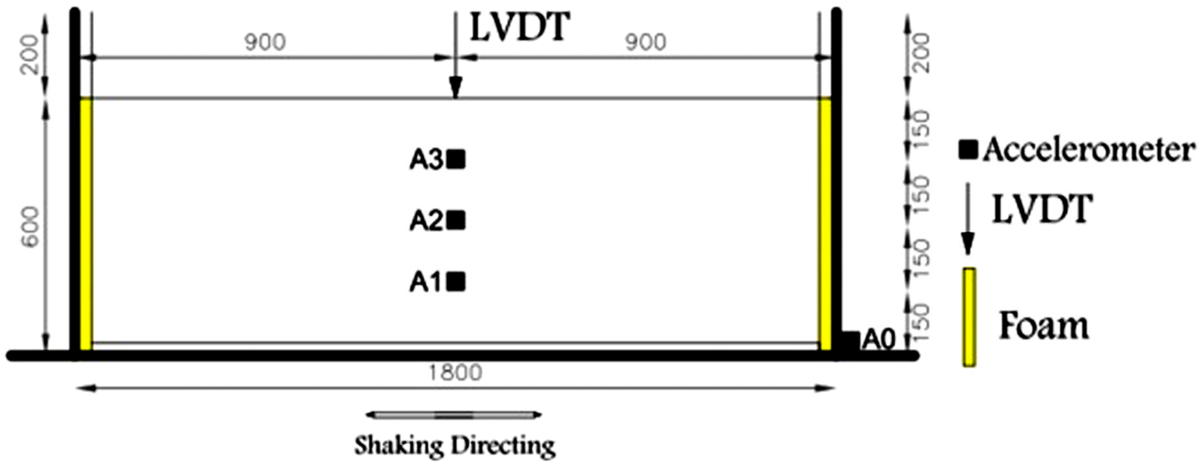

Fig. 4 Schematic form of test samples with instrumentation.

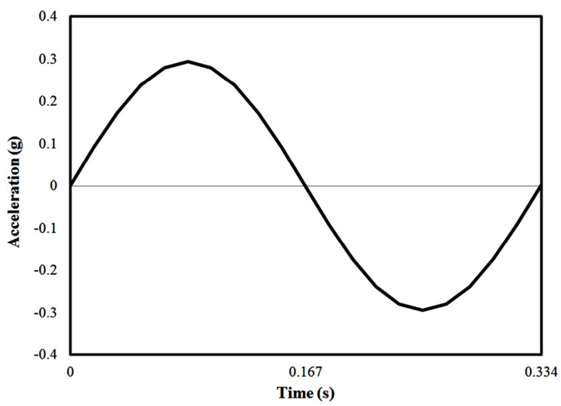

Fig. 5 Typical sinusoidal waveform at loading frequency of 3 Hz and acceleration of 0.3 g (for the time of 1 period).

negative effects, a band-pass filter was applied to the acceleration data to only focus on the frequency range of 0.05-20 Hz.

In this study, 70 shaking table tests were performed to study the effect of loading frequency on dynamic properties of sand-tire powder mixture. Variable parameters in various experiments are listed in Table 3. The test samples were subjected to sinusoidal loading (Fig. 5) at frequencies of 0.5 to 9 Hz and input acceleration of 0.1g and 0.3 g.

4. HYSTERESIS STRESS-STRAIN RELATIONSHIP AND DYNAMIC PROPERTIES OF SOIL

As stated earlier, the main objective of this study is to obtain hysteresis loops for soil samples, using data recorded by accelerometers inside the soil in the shaking table tests, and then, to use these loops to determine the changes in the shear modulus and the damping ratio versus shear strain in the fixed number of cycles (for comparison, the total number of cycles is identical at all frequencies). Similar studies have already been carried out by researchers using the aforementioned concepts to determine the rubber content effects and various parameters on the dynamic properties of soils, especially sand (e.g., Okur and Umut, 2018; Senetakis et al., 2012; Anastasiadis et al., 2012; Koga and Matsuo, 1990; Abdel-Ghaffar and Sčoty, 1979; Kikusawa and Hasegawa, 1985; Ghayamghamian and Kawakami, 2000; Bahadori and Manafi, 2015).

In a study conducted by Sabermahani et al. (2009), the data from accelerometer and LVDT along with the one-dimensional shear beam equation provided by Zeghal et al. (1995) was used to determine the dynamic properties. Elgamal et al. (2005) and Brennan et al. (2005) also used a one-dimensional shear beam equation to determine the dynamic properties in small-scale dynamic centrifuge tests.

The one-dimensional shear beam equation first proposed by Zeghal et al. (1995) is as follows:

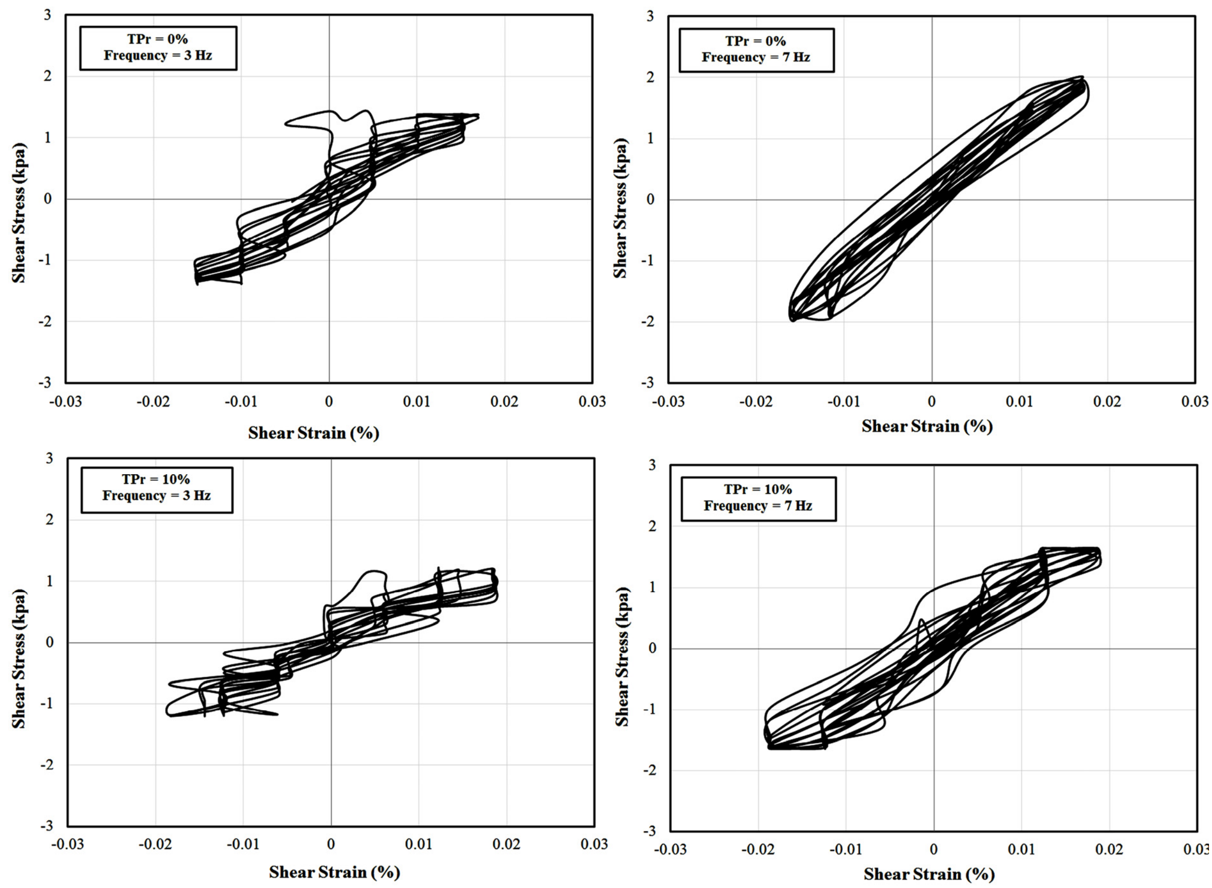

Fig. 6 Typical shear stress-strain behavior at elevation 225 mm at different loading frequency and tire powder ratio for input acceleration of 0.3 g.

$$\frac{\partial \tau}{\partial z} = \rho \ddot{u} \quad (1)$$

Where $\ddot{u}$ and ρ are the acceleration in depth z and soil density, respectively.

From the shear beam equation, the shear stress τ at the desired depth z is obtained by integrating the product of the density ρ (z) in the acceleration (z) in the interval (0, z) as follows:

$$\tau(z) = \int_0^z \rho(z)\, \ddot{u}(z)\, dz \quad (2)$$

Normally, the shear stress is obtained from field measurements using accelerometers that extend to the surface of the earth. However, it is rarely possible to obtain reliable surface acceleration from model experiments (i.e., shaking table or centrifuge). The reason is that the accelerometers must be at an appropriate depth for proper recording of earthquake data in order to have sufficient contact with the body of soil. Therefore, to deal with this issue, it is suggested that, the time history of ground acceleration is obtained by a linear fit of the accelerated data of buried accelerometers in depth:

$$\ddot{u}(z) = \ddot{u}_1 + \frac{\ddot{u}_2 - \ddot{u}_1}{z_2 - z_1}(z - z_1) \quad (3)$$

By replacing z = 0 in the above equation, the acceleration at the ground level will be equal to:

$$\ddot{u}(0) = \ddot{u}_1 + \frac{\ddot{u}_2 - \ddot{u}_1}{z_2 - z_1}(0 - z_1) \quad (4)$$

and therefore, the shear stress at depth z is obtained from the solution of the integral as follows:

$$\tau(z) = \frac{1}{2}\rho z\left(\ddot{u}(0) + \ddot{u}(z)\right) \quad (5)$$

To calculate the shear strain, initially, the displacements must be obtained from the acquired acceleration data. The acceleration data used for calculating displacement of tenths of a second before the seismic loading is continued until a certain amount of time after loading. By doing so, that part of the data related to the noise of the acceleration measuring devices are detected and removed in the data filtering step. To calculate the velocity, the acceleration data is integrated following a band-pass filter (0.05-20Hz). After velocities are determined, the data is filtered again in the same frequency range mentioned. Then, the displacements are obtained by another integration procedure. The following equation is used to calculate shear strain:

$$\gamma = \frac{u_2 - u_1}{z_2 - z_1} \quad (6)$$

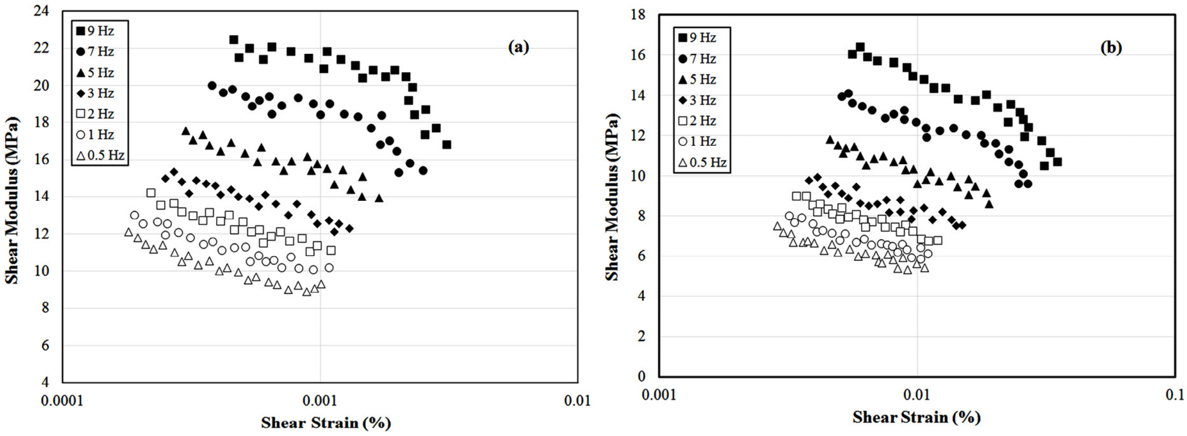

Fig. 7 Variation of shear modulus with shear strain at different loading frequency for pure sand at input acceleration of (a) 0.1 g, (b) 0.3 g.

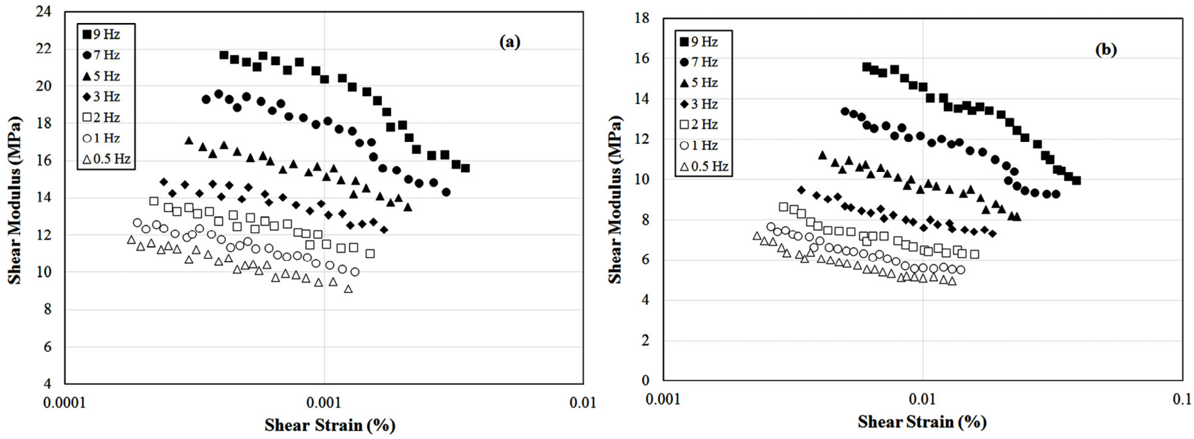

Fig. 8 Variation of shear modulus with shear strain at different loading frequency for sand mixed with 5 % tire powder at input acceleration of (a) 0.1 g, (b) 0.3 g.

In this study, the shear stress and shear strain values were calculated at 225 mm (midpoint between the accelerometers A_1 and A_2) and, 375 mm (midpoint of the accelerometers A_2 and A_3) height from the model container floor and the hysteresis loops were plotted.

Figure 6 shows typical hysteresis loops at different loading frequency and tire powder ratio for input acceleration of 0.3g at 225 mm height from the model container floor for the first ten cycles. (It should be mentioned that the direction of the stress-strain rotation is clockwise). Considering the figure, it is observed that the angle of the loops from horizontal axis increases by increasing the loading frequency. In addition, at a constant testing frequency, by increasing the tire powder, hysteresis loops become progressively flatter and show relatively large shear strain. This is because of losing most of the soil stiffness.

5. RESULTS AND DISCUSSION

5.1. SHEAR MODULUS

Shear modulus can be obtained through a hysteresis loop. The shear modulus for an arbitrary loop is obtained from the following:

$$G = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} \tag{7}$$

Given the importance of G-γ and D-γ curves in dynamic analyses, the changes in shear modulus with shear strain has been studied. Figures 7-11 plot the relationship between the shear modulus and shear strain of samples for different loading frequencies and input accelerations. The results show that in the same cycles the shear modulus especially maximum shear modulus (G_{max}) increases as the frequency increases in all cases, and this increase is observed at lower frequencies and increases with increasing frequency. At a frequency of 9 Hz, the maximum shear modulus (G_{max}) has the largest value and at a frequency of 0.5 Hz, it has the lowest value. On the other hand, the shear modulus decreases with increasing shear strain. It should be noted that since the soil samples have all been tested in a dry state, the range of shear strain variations is limited, which increases somewhat by increasing the frequency.

At a constant testing frequency, the sand mixture with 5 % tire powder has a similar behavior to pure sand, and there is no significant difference between the shear modulus values. However, by increasing the

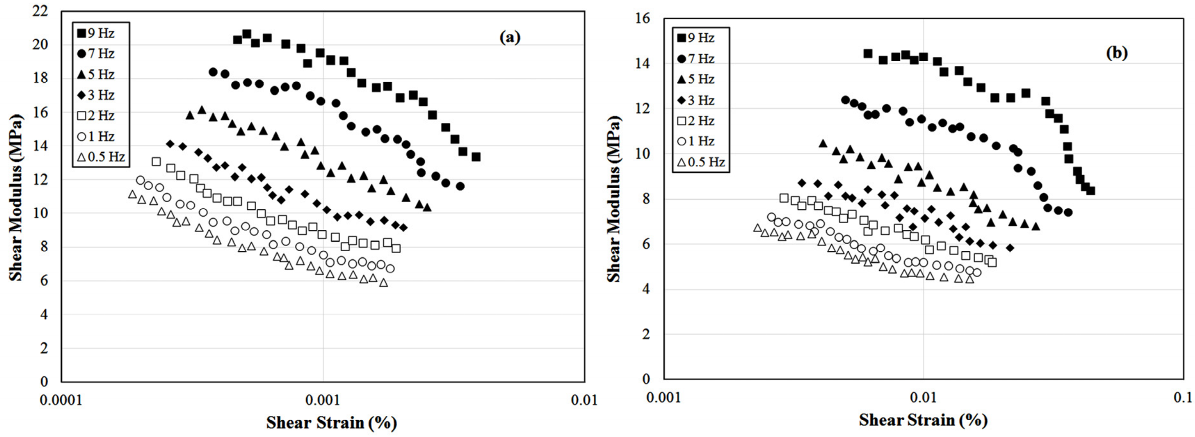

Fig. 9 Variation of shear modulus with shear strain at different loading frequency for sand mixed with 10 % tire powder at input acceleration of (a) 0.1 g, (b) 0.3 g.

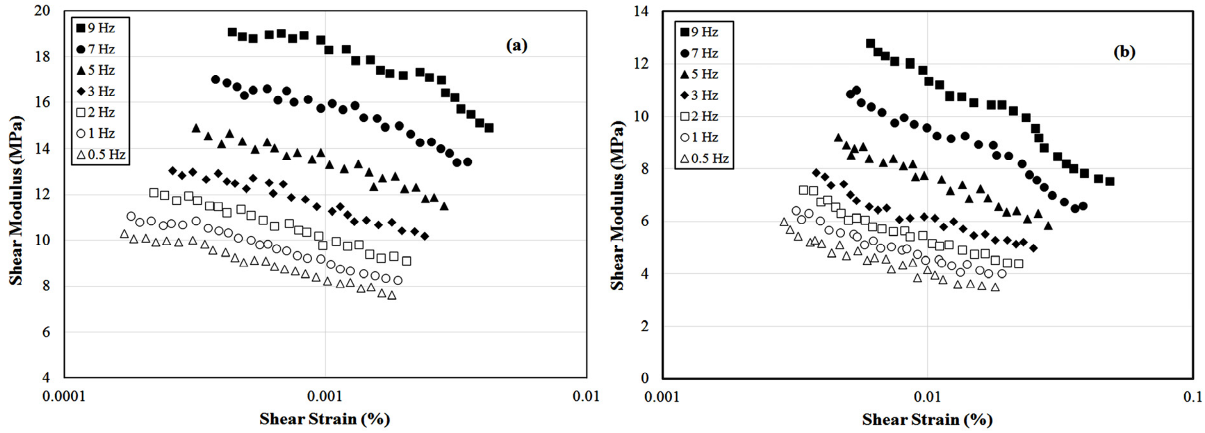

Fig. 10 Variation of shear modulus with shear strain at different loading frequency for sand mixed with 15 % tire powder at input acceleration of (a) 0.1 g, (b) 0.3 g.

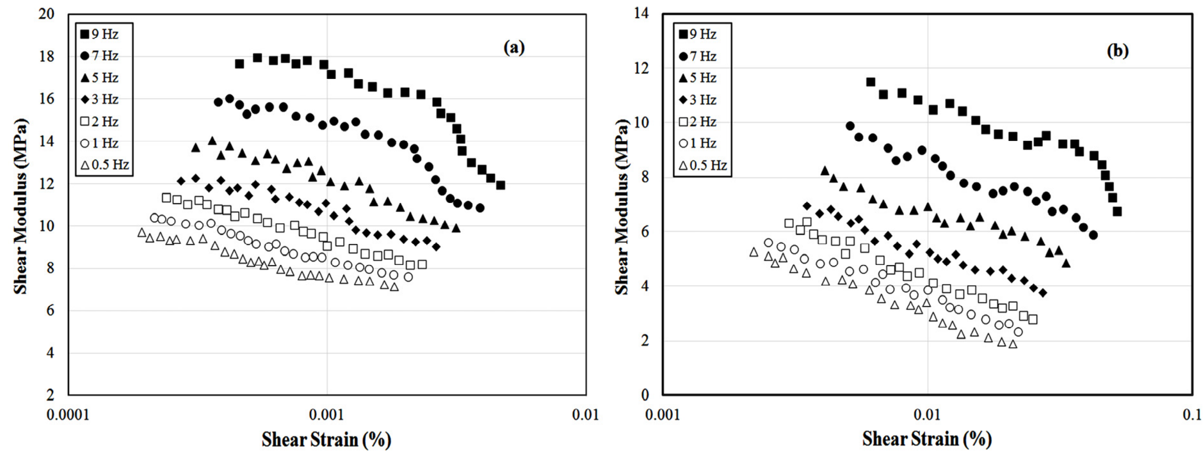

Fig. 11 Variation of shear modulus with shear strain at different loading frequency for sand mixed with 20 % tire powder at input acceleration of (a) 0.1 g, (b) 0.3 g.

tire powder, the shear modulus values of samples reduced so that the sample of sand with 20 % tire powder has the lowest shear modulus between mixtures at all tested frequencies. Moreover, the highest reduction in the shear modulus is from 10 % to 15 % of tire powder. For example, under acceleration of 0.3 g, the G_{max} reduction rate between mixtures with 5, 10, 15 and 20 % of tire powder at various frequencies is about 7 %, 10 %, and 8 % respectively. It should be noted that the effect of loading frequency on the shear modulus is similar in different amounts of tire powder and there is no difference in this.

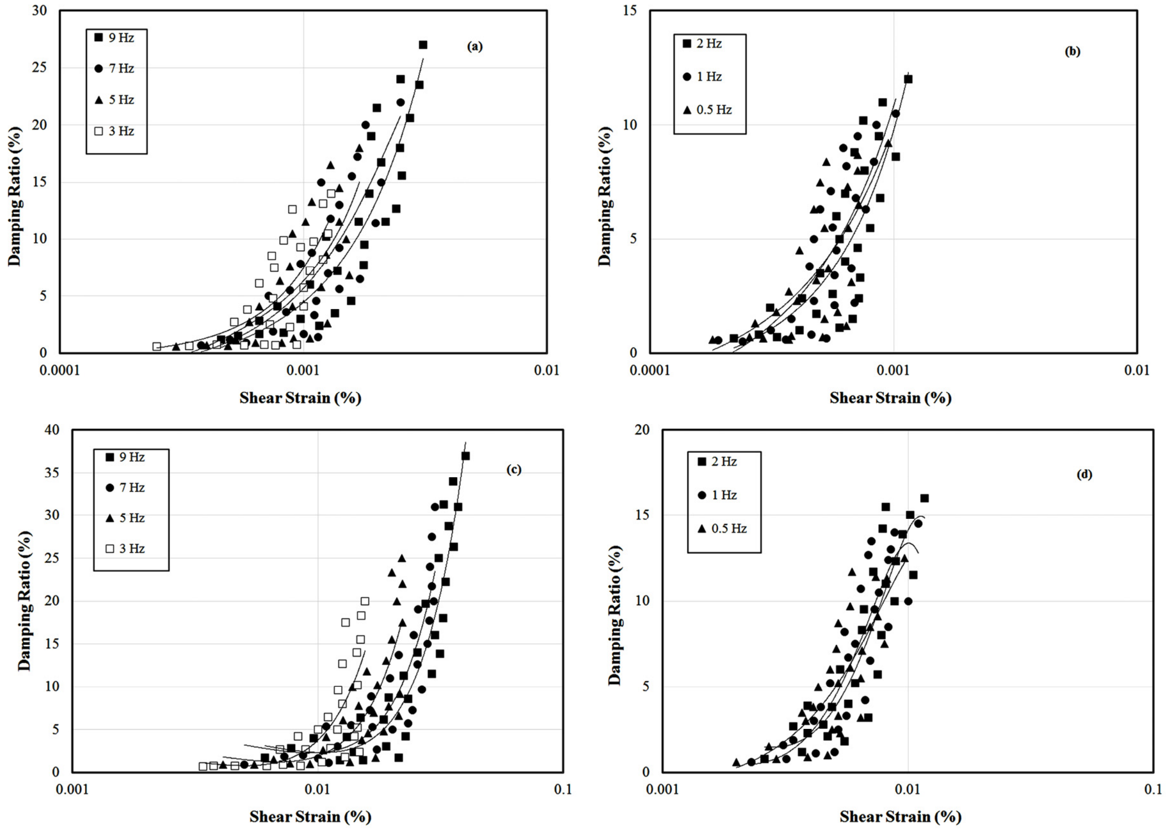

Fig. 12 Variation of damping ratio with shear strain at different loading frequency for pure sand at input acceleration of (a, b) 0.1 g, (c, d) 0.3 g.

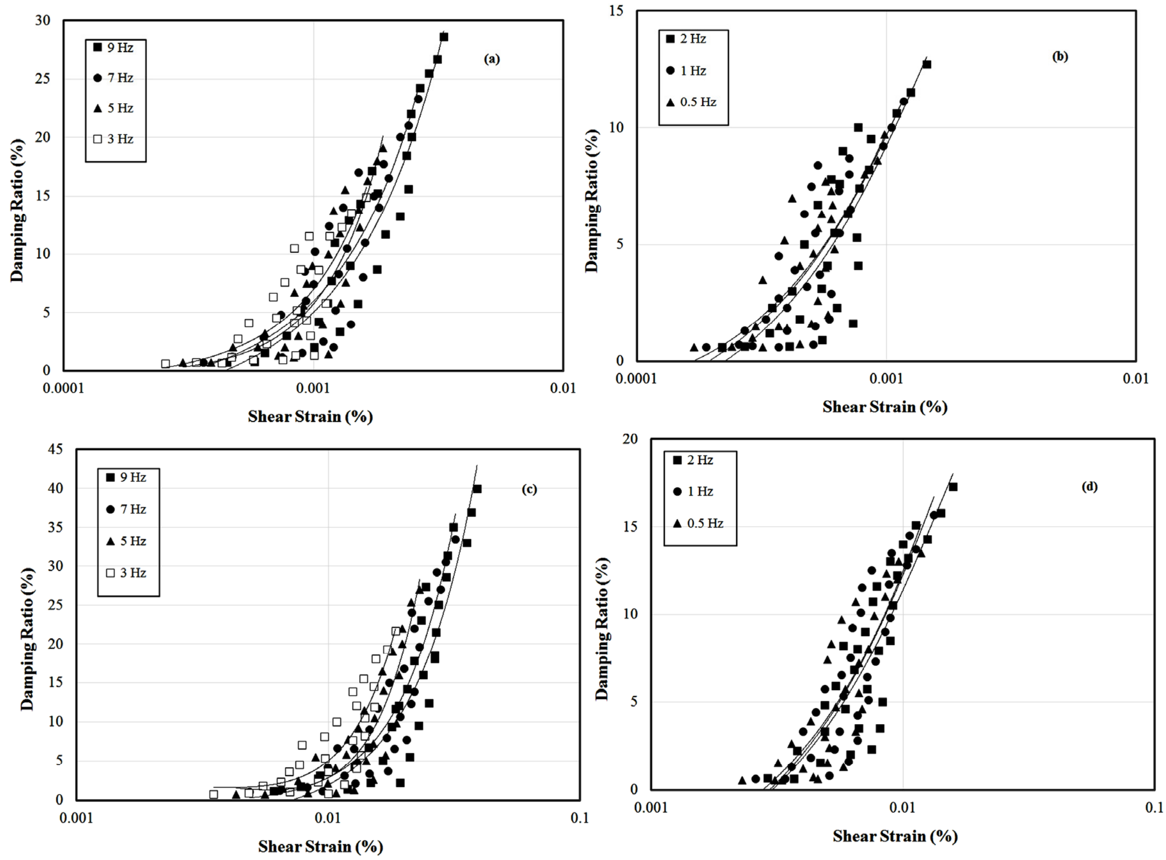

Fig. 13 Variation of damping ratio with shear strain at different loading frequency for sand mixed with 5 % tire powder at input acceleration of (a, b) 0.1 g, (c, d) 0.3 g.

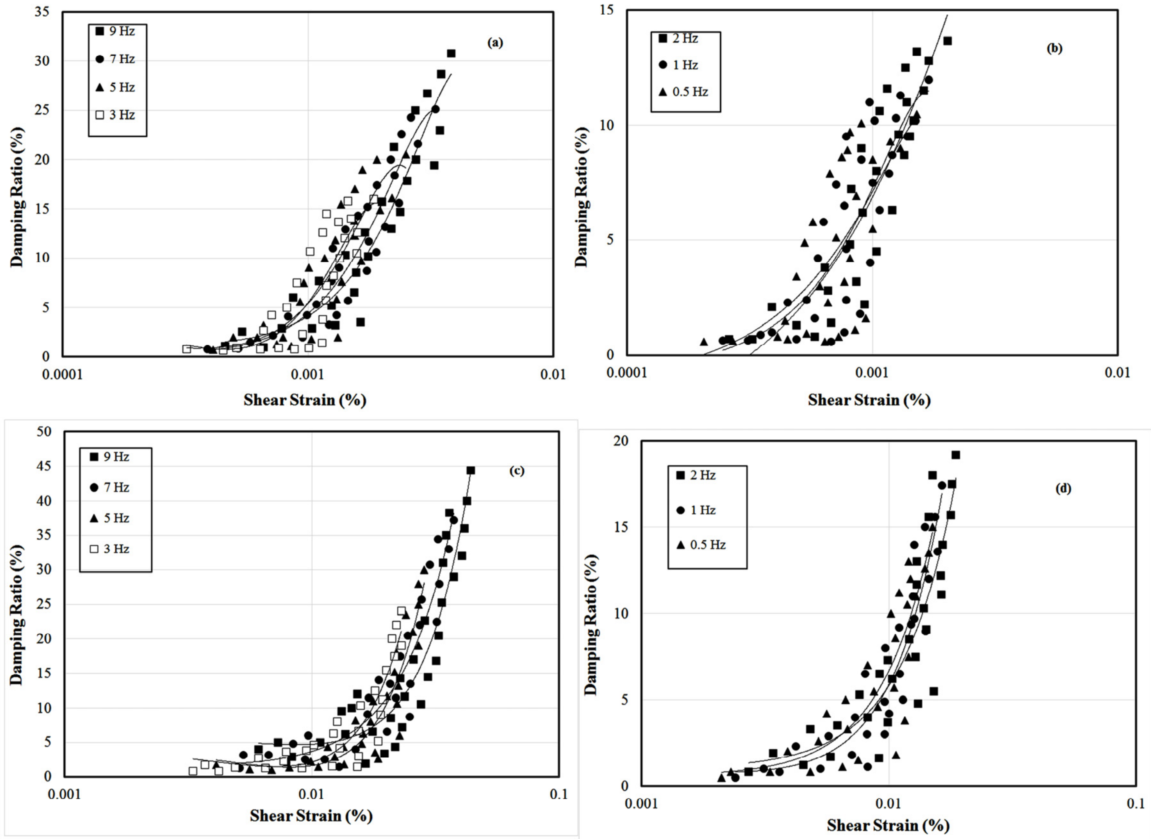

Fig. 14 Variation of damping ratio with shear strain at different loading frequency for sand mixed with 10 % tire powder at input acceleration of (a, b) 0.1 g, (c, d) 0.3 g.

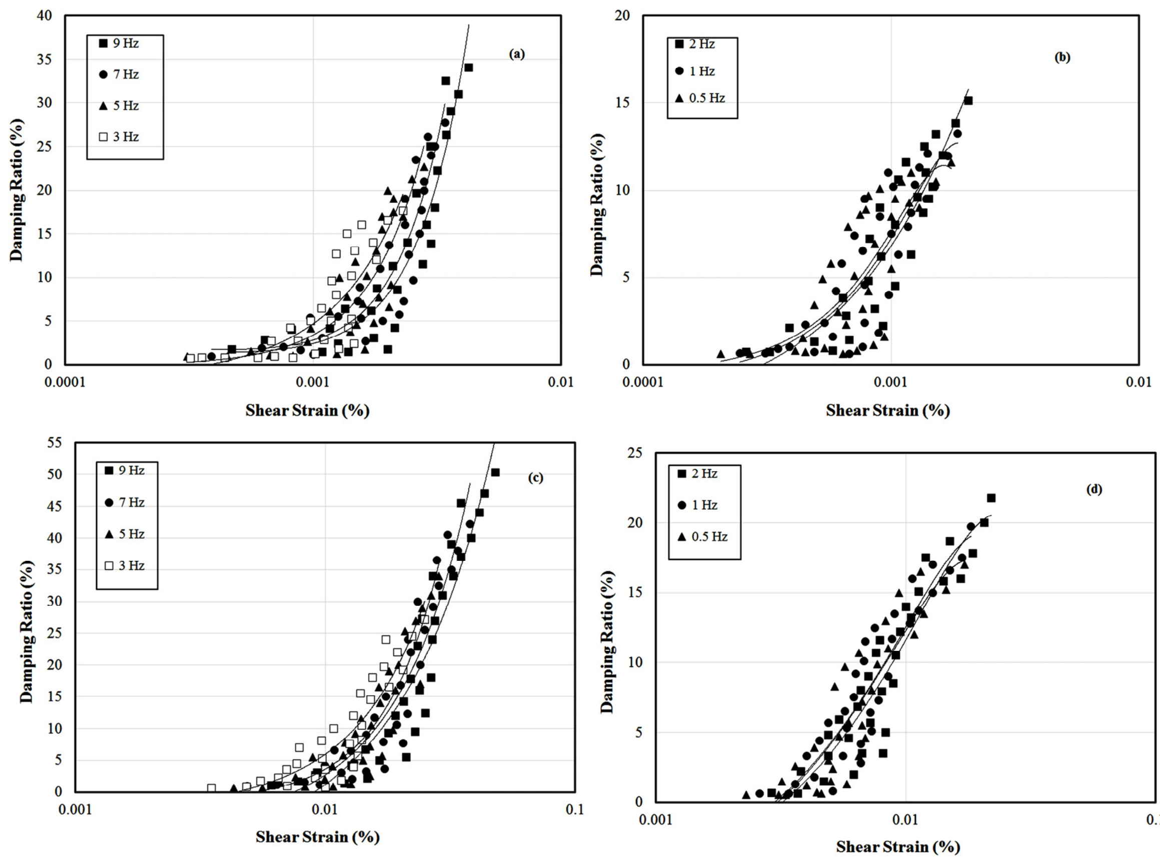

Fig. 15 Variation of damping ratio with shear strain at different loading frequency for sand mixed with 15 % tire powder at input acceleration of (a, b) 0.1 g, (c, d) 0.3 g.

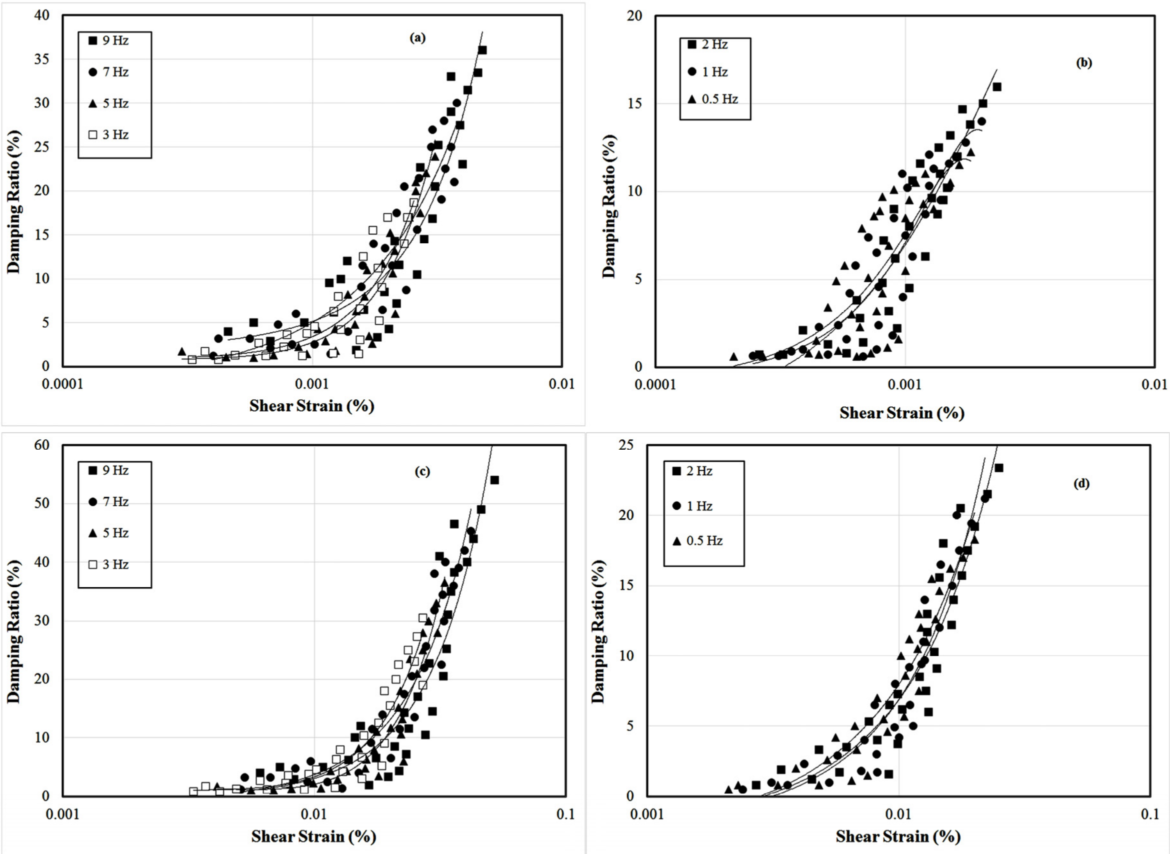

Fig. 16 Variation of damping ratio with shear strain at different loading frequency for sand mixed with 20 % tire powder at input acceleration of (a, b) 0.1 g, (c, d) 0.3 g.

As for the effect of input acceleration on the shear modulus (Figs. 7-11), increasing the input acceleration increases the shear strain and consequently, decreases the shear modulus in all states (the values of shear modulus of samples in various frequencies under the input acceleration of 0.1 g are larger than the shear modulus values under the input acceleration of 0.3 g). Also, at the higher input acceleration, the effects of tire powder on the shear modulus, especially the maximum observed shear modulus (G_{max}), is more pronounced. For instance, at an input acceleration of 0.3 g, the difference between the values of G_{max} derived from different frequencies, between samples with 10 % and 15 % tire powder, about 10 %, while the rate at the acceleration of the 0.1 g is about 7 %.

5.2. DAMPING RATIO

The damping ratio for an ideal loop is obtained from the following equation. First, the energy lost per cycle (ΔW) and the energy stored in each cycle ($W_{elastic}$) must be calculated.

$$D = \frac{1}{4\pi}\frac{\Delta W}{W_{elastic}} = \frac{1}{4\pi}\frac{\oint \tau d\gamma}{0.125\times\Delta\tau\times\Delta\gamma} \qquad (8)$$

The variation of the damping ratio versus shear strain of the soil samples for different frequencies and input accelerations are shown in Figures 12-16.

The results show that, in all cases, damping ratio increases with shear strain. At low strain levels, the damping ratio values at various frequencies are low and yet very close. At higher strain levels, the increase in frequency increases the damping ratio. This increase is more significant at higher frequencies. Also, by increasing the tire powder, the damping ratio values of samples increase so that the sample of sand with 20 % tire powder has the highest damping ratio between mixtures. Similar to the results of the shear modulus, the highest increase in the damping ratio of the sand-tire powder mixture is observed from 10 % to 15 % of tire powder. On the other hand, the damping ratio increases with input acceleration. Also, the effect of tire powder on the increase in the damping ratio is more obvious at higher acceleration. For example, the difference between the maximum damping ratio (at the highest shear strain) under the acceleration of 0.3 g between sand mixtures with 5 and 10 % of tire powder is about 12 %, while at acceleration of 0.1g this value is about 8 %.

6. CONCLUSION

In the present study, the effects of loading frequency on the dynamic properties of sand-tire powder mixture were investigated using shaking table tests. The following conclusions were drawn:

- The shear modulus increases with frequency in the same number of cycles. The trend is more obvious at larger frequencies.
- The effect of loading frequency on the damping ratio at low levels of strain is negligible, and at relatively large strain levels, damping ratio increases with loading frequency.
- The shear modulus reduced by increasing the tire powder. The reduction in the mixture with 5 % tire powder is very low compared to pure sand and the highest reduction is observed in the mixture with 10 % to 15 % of tire powder.
- By increasing the tire powder, the damping ratio values of samples increased so that the mixture with 20 % of the tire powder has the highest damping ratio.
- In all cases, the shear strain increased by increasing the amplitude of the input acceleration, and as a result, the shear modulus decreased and the damping ratio increased. Also, in higher input acceleration, the difference between the values of shear modulus and damping ratio of sand mixtures with tire powder is more visible.

ACKNOWLEDGMENTS

This research was conducted at the Crisis Management Center of Urmia University. Therefore, the authors of this article would like to thank all the officials of the Center, particularly Mr. Omeily.

LIST OF NOTATION

C_c – Coefficient of curvature
C_u – Coefficient of uniformity
D – Damping ratio
D_{10} – Grain diameter at 10 % passing
D_{30} – Grain diameter at 30 % passing
D_{50} – Grain diameter at 50 % passing
D_{60} – Grain diameter at 60 % passing
e_{min} – Minimum void ratio
e_{max} – Maximum void ratio
F_c – Fines content
G – Shear modulus
g – Acceleration due to gravity
u_i – Displacement of position i
$\ddot{u}_1$ – Acceleration at position i
$W_{elastic}$ – Maximum stored elastic energy per cycle
z_i – Depth of position i
ΔW – Energy loss per cycle
ρ – Soil density
τ – Shear stress
γ – Shear strain

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