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ORIGINAL PAPER

Mechanical Behavior of Waste Tire Crumbs–Sand Mixtures Determined by Triaxial Tests

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Abstract In the last three decades, the use of scrap tires in a number of forms such as whole tires, shredded, chips, ground tire or powder tire shapes has already been common in many geotechnical applications. One of the main reasons of using shredded tires is the fact that it is cost-effective and environmental concerns. While, scrap tire improves sand behavior; so, it is suitable to transform tire to shredded for using in many industrial applications. In this research, in order to investigate the behavior of the tire-sand mixtures (small tire crumbs), drained triaxial tests have been performed. Effects of parameters such as size of tires, tire content (by weight) and confining pressure on the sand's behavior have been studied. For achieving this objective, two sets of tire (granulate and powder tire), four various tire contents (5, 10, 20 and 30%) and three confining pressures (50, 100 and 200 kPa) have been employed. The test results showed that unlike some previous studies in which tire crumbs act as reinforcement and increase shear strength of sand–tire mixtures, shear strength mixtures have been found to decrease with the increase in the amount of tire crumbs. This study concentrates on the stress–strain and volumetric strain behavior of the tire-sand mixtures. Moreover, the angle of friction, cohesion and elastic modulus for each mixture are presented.

1 Introduction

Solid waste management is one of the main environmental concerns around the world. The increasing population leads to an increment in the amount of scrap tire annually. Commonly worn tires are accumulated in uncontrolled ways, and released into the environment. Stockpiling of scrap tires provides a favorable environment for the spread of flies and mice. On the other hand, there is the likelihood that the fire has a negative impact on the atmosphere and human health. Due to impossibility of waste tires decomposition, engineers should make good ideas to recycle or reuse them (Edil and Bosscher 1994). In Iran, according to the Ministry of Industries and Mines report, 21% (by weight) of scrap tires generated were recovered in 2006 (Ministry of Industries and Mines 2006). Waste tire can be reused as raw material in rubber product, or fuel for energy production and civil engineering applications (Lee et al. 1999).

From geotechnical engineering perspective, waste tires have interesting properties. Scrap tires have low density, high strength (especially when steel belted), low thermal conductivity, low cost, excellent durability, resilience and high frictional strength. It is due to these properties that the use of scrap tire aggregates

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has been recommended in geotechnical or geoenvironmental applications instead of natural aggregates (Zornberg and Cabral 2004).

In recent years, the use of scrap tires for soil reinforcing has been increasing and practicing engineers employ this technique for different geotechnical applications such as lightweight material, conventional fill for backfill of retaining structures, slope stabilization, vibration isolation, thermal insulation layer, aggregates in leach beds of landfills (Bosscher et al. 1992). Depending on the applications, scrap tires can be used as whole tires, shredded tire (usually 50–300 mm in size), tire chips (the wire removed from a tire and a nominal size of about 12–50 mm), granulated and ground rubber (particle size ranging from 12 to 0.425 mm and 2 to 0.425 mm, respectively).

In the last three decades, due to the increasing interest in the study of the behavior of the soil reinforced with scrap tires, many laboratory researches have been conducted by researchers worldwide, among which Humphrey (1993), Ahmed and Lovell (1993), Edil and Bosscher (1994), Foose et al. (1996), Masad et al. (1996), Bosscher et al. (1997), Reddy & Marella (2001), Yang et al. (2002), Youwai & Bergado (2003), Zornberg and Cabral (2004), Ghazavi and Sakhi (2005), Gotteland et al. (2005), Attom (2006), Rao and Dutta (2006), Lee et al. (2007), Kim and Santamarina (2008) and Tsang et al. (2013), etc. can be referred. These researches have taken into account the number of parameters including (1) size of scrap tire (2) aspect ratio of shredded tires (3) normal stress in direct shear or confining pressure in triaxial tests (4) the ratio of scrap tires and sand mixtures. Almost all results presented in literatures indicate that the tire wastes increased the shear strength of sand. In the following, the results of a number of the laboratory tests conducted by researchers are presented, separately.

Ahmed and Lovell (1993) performed laboratory compression tests with large-scale triaxial apparatus to determine the stress–strain response of sands reinforced with shredded tires (size 12–50 mm). The results of the test revealed that the use of shredded tires in highway construction offers technical, environmental and economic benefits under certain conditions. In additions, they concluded that the mixtures with less than 38% (by weight) of tire shreds have good adequate compressibility, high shear strength

and good drainage characteristics. Edil and Bosscher (1994) also tested tire chips mixed with soils to determine whether this would produce acceptable fills. It was found that even minimal addition of tires, the shear angle was greater than unreinforced sand. Hydraulic conductivity tests were also carried out for varying hydraulic gradients and overburden stresses. It was found that with mixtures that had large voids, the flow tended to be turbulent, and had a very high conductivity. To study the strength behavior, Foose et al. (1996) carried out a number of large-scale shear tests on the tire-sand mixture. They reported that three significant factors affecting the strength of the sand–tire mixtures which are normal stress, tire shredded content and sand matrix unit weight. Furthermore, addition of shredded waste tires to sand increased its shear strength. Wu et al. (1997) conducted triaxial tests on pure tire chips to study the deformation characteristics of tire chips and reported that tire chips increase shear strength and internal friction angle mixtures. Youwai and Bergado (2003) performed a series of triaxial tests on tire-sand mixtures to an assessment of their mechanical behavior. The test results showed the shear strength and unit weight of the sand–tire mixture decreased and strain at failure increased with the increment in their content. In addition, they represented a constitutive model for tire-sand mixtures. Zornberg and Cabral (2004) studied the effect of tire shred content and the tire shred aspect ratio on the performance of the tire-sand mixture with using a large-scale triaxial apparatus. They also stated that the shear strength improvement induced by tire shred inclusions was found to be sensitive to the applied confining pressure, with larger shear strength obtained under comparatively low confinement. To investigate the mechanical behavior of the tire chip–sand mixtures, Gotteland et al. (2005) performed a triaxial test on the tire-sand mixture of varying the tire content and the orientation of chips. The results showed that the tire content has a great influence on the shear strength of the mixture. The strength increases as with the increment of tire content up to an optimum percentage mass of 34%, after which the shear strength decreases. Moreover, the strength is higher when tire chips are placed horizontally. Attom (2006) carried out a number of direct shear tests on three different types of sands with varying gradations. Each type of sand was mixed with four different percentages of shredded tires. The

addition of shredded waste tires increased both the shear strength and the angle of internal friction of the sands. After performing drained triaxial test and one-dimensional compression test on soil reinforced with tire crumbs, Neaz Sheikh et al. (2013) concluded that the peak shear strength and the corresponding axial strain of sand are affected by the presence of tire crumbs and confining pressure. Also, the compressibility tests showed that the settlement is most likely to occur as a plastic strain mainly in the first cycle of loading.

So far, many laboratory investigations have been conducted in respect of sand reinforced with tire chips (usually 10–300 mm in size). However, none of them carried out a detailed investigation on the Strength parameters of sand–tire mixtures with the small size of tire chips (below of 6 mm). In this research, by
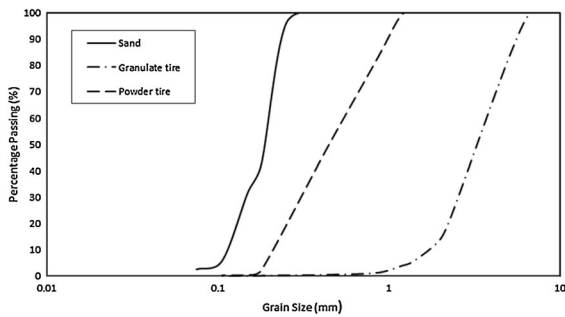
employing a wide range of triaxial tests, the effect of shred tire reinforcement and effective parameters such as tire content, size of shred tire and confining pressure on the behavior of the tire-sand mixtures are investigated which have not been adequately researched in the previous literature.

2 Materials Used and Testing Program

2.1 Sand

Uniform, quartz beach sand obtained from the shore of the Caspian Sea in Babolsar (a city in the north of Iran) was used in this study. To classify test sand, particle size analysis was conducted in accordance with ASTM D422 (2004a) and the grain size distribution of this sand is shown in Fig. 1. The coefficient of uniformity (C_c) was calculated as 1.03, and the coefficient of curvature (C_u) was calculated as 1.8. The sand can be classified as SP in the unified soil classification system (USCS). Maximum and minimum unit weight of the sand are 17.3 kN/m^3 14.7 kN/m^3 respectively.

2.2 Tire Crumb

Tire derived aggregate (TDA) used in this study is an engineered product made by cutting scrap tires into small pieces using specialized equipment. In this study, two sets of TDA (T1 and T2) have been used (Fig. 2) which are purchased from a company in
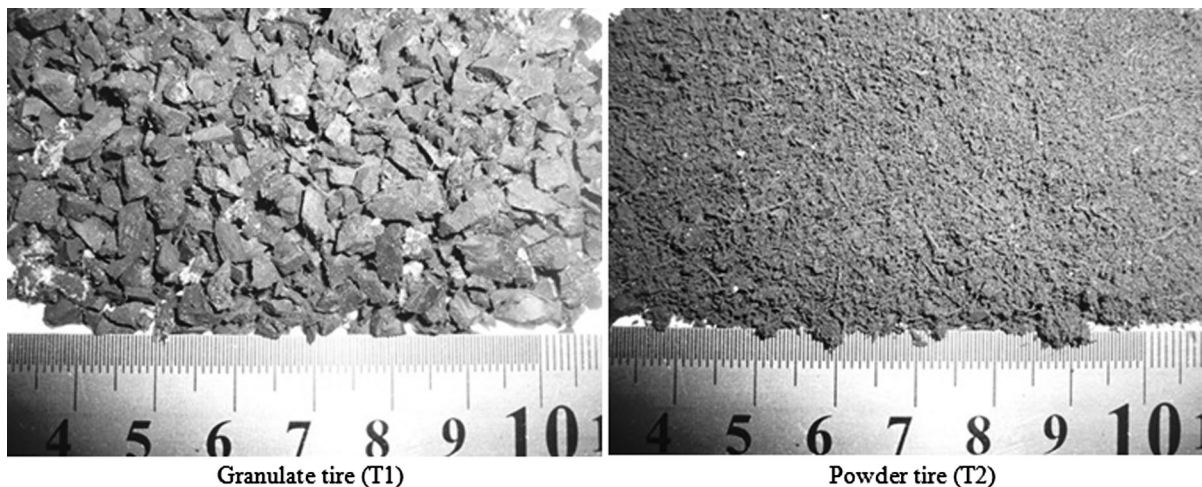

Fig. 1 Grain size distributions of pure sand, granulate and powder tire

Granulate tire (T1)   Powder tire (T2)

Fig. 2 Images of tire crumbs T1 and T2

Tehran. The particle-size distribution of T1 and T2 is shown in Fig. 1. According to CEN Workshop Agreement (CWA) 14243-2002 (2002), T1 and T2 are classified as granulate rubber and powder rubber respectively. The specific gravity of tire crumbs used is 1.12.

2.3 Tire-Sand

The sand and granulate rubber or powder rubber mixtures will be referred to as tire-sand mixtures. The tire-sand mixtures have been prepared for different contents of tire crumbs by weight (0, 5, 10, 20 and 30%). Due to particle segregation between tire crumbs and sand particles, maximum contents of tire crumbs mixed with sand is 30%. All test specimens were made in a 70% relative density. To determine the minimum and maximum density of sand, granulate tire, powder tire, and various mixtures of these materials performed relative density determination tests. The test was done in accordance with ASTM D4253 (2004c) and ASTM D4254 (2004b). The minimum, maximum and used density values of samples were shown in Table 1.

2.4 Test Equipment

The unreinforced and reinforced dry samples were tested in a conventional triaxial testing apparatus which were cylinders with 38 mm diameter and a height of 76 mm. The components of the apparatus are load frame, triaxial cell, specimen base adapter, water distribution panel, volume change unit, twin-burette. In this study, the volume change of samples was measured in order to observe this characteristic during

the shear, and to use such data for area correction. A twin-burette volume change was used to measure the volume change of samples on the cell pressure line.

2.5 Sample Preparation and Test Procedure

A series of (a total of 27 sets) triaxial compression tests were carried out on the sand–tire crumb mixtures for different contents (%) of tire crumbs by weight (0, 5, 10, 20, and 30%). The relative density of the sand–tire mixtures was maintained constant around 70%. Sand and tire crumbs (granulate or powder tire) were mixed manually and were prepared by a dry deposition technique. The samples compacted in five layers through tamping with a tamper. The tamper had a diameter slightly more than the half diameter of the mold. The tests were carried out on the specimens in 50, 100, 200 kPa cell pressure. For all the tests, the sample was loaded under a strain rate of 0.30% per minute. Most of the tests were continued until the load peaks or the 15% strain was reached. For a detailed evaluation of the behavior of samples, corrections such as membrane penetration (Baldi and Nova 1984), membrane force (Head 1982) and cross-sectional area were considered and applied.

3 Test Results and Discussions

3.1 Stress–strain Behavior of Sand–Tire Mixtures

The deviatoric stress–strain and volumetric strain behavior of unreinforced and reinforced sand with different proportions granulate tire at 100 kPa

Table 1 Density and relative density values of samples

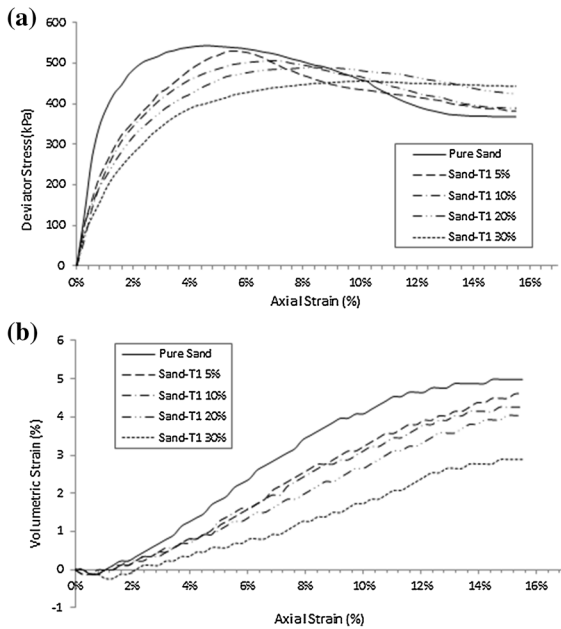| Series	Sample	Min. (kN/m³)	Max. (kN/m³)	Used. (kN/m³)
1	Sand	14.7	17.3	16.42
2	%100 granulate	4.72	5.98	5.53
3	%5 granulate	14.23	16.62	15.8
4	%10 granulate	13.6	15.87	15.11
5	%20 granulate	12.81	15.16	14.36
6	%30 granulate	11.93	14.27	13.47
7	%100 powder	3.03	4.69	4.02
8	%5 powder	13.37	16.02	15.12
9	%10 powder	12.18	14.34	13.61
10	%20 powder	10.95	13.08	12.35
11	%30 powder	9.04	10.48	10

(a)

(b)

Fig. 3 Results of tests on the sand–tire mixtures with different proportions granulate tire at 100 kPa confining pressure: **a** deviator stress–strain behavior, **b** volumetric strain behavior

confining pressure are illustrated in Fig. 3. The effect of tire percentage on the shear strength parameters of the sand–tire mixtures is investigated. Figure 3 shows that tire crumbs have significant influence on the stress–strain behavior of the sand–tire mixtures. It can be seen that with an increment in tire content, the peak stress (maximum deviator stress) decreases, residual strength and the corresponding axial strain also increase. Because of the fact that sand-to-sand interaction is more than the sand-to-tire or tire-to-tire interaction, the peak stress decreases with the increment in the amount of tire crumbs. Decreasing peak stress related to the increment in tire crumbs is partially different from the results of other investigations; Zornberg and Cabral (2004) conducted a triaxial test on samples with dimensions of tire crumbs larger than 10 mm and various aspect ratios of 1, 2, 4 and 8. Because of the amounts of aspect ratios which are greater than one and large dimensions of tire crumbs, the peak stress increases with tire crumbs increment and tire crumbs could act as reinforcement. However, the size of tire crumbs used in this research was small (below of 6 mm) and the aspect ratio was approximately equal to the unit. Under this condition, the tire crumbs cannot represent

the role of reinforcement in the mixture of sand with random fibers.

Before experiments on the sand–tire mixture, some tests with pure sand were done in order to check the reliability and accuracy of the experimental setup. A series of (27 tests) triaxial compression tests were carried out on the sand–tire crumb mixtures; however, each experiment was repeated three times for the same conditions. For example, Figs. 4, 5 and 6 show the deviatoric stress–strain behavior of the tests at the same conditions in three repeats, which at least at all times, the middle curve is used in this paper; so, totally 81 tests were done.

It can be seen that the stress–strain curves compare fairly well with each other. So, the reliability of the data, which is very important in stress–strain experiments, is ensured.

Figure 7 presents the behavior of sand–tire mixtures with 30% granulate tire in terms of axial strain versus deviator stress and volumetric strain at different
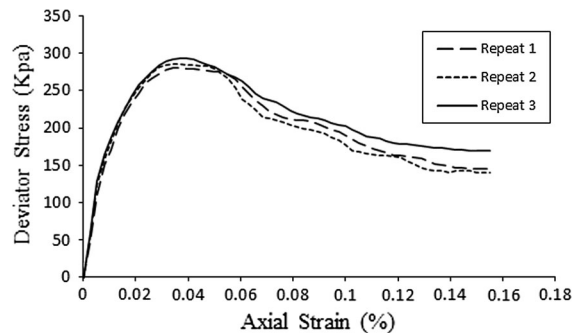

Fig. 4 Deviator stress versus axial strain for pure sand at 50 kPa confining pressure which repeated 3 times
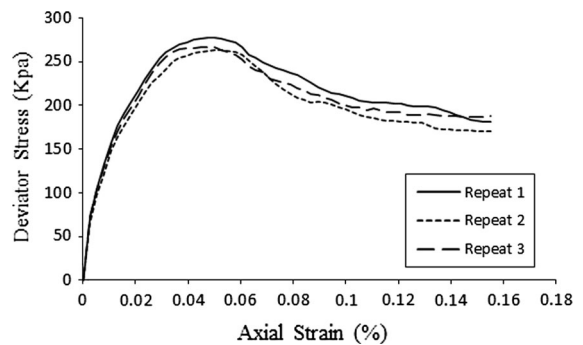

Fig. 5 Deviator stress versus axial strain for sand–granulate tire 10% mixture at 50 kPa confining pressure which repeated 3 times
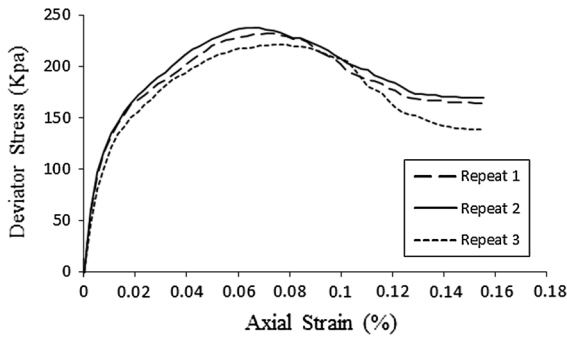
Fig. 6 Deviator stress versus axial strain for sand–powder tire 10% mixture at 50 kPa confining pressure which repeated 3 times
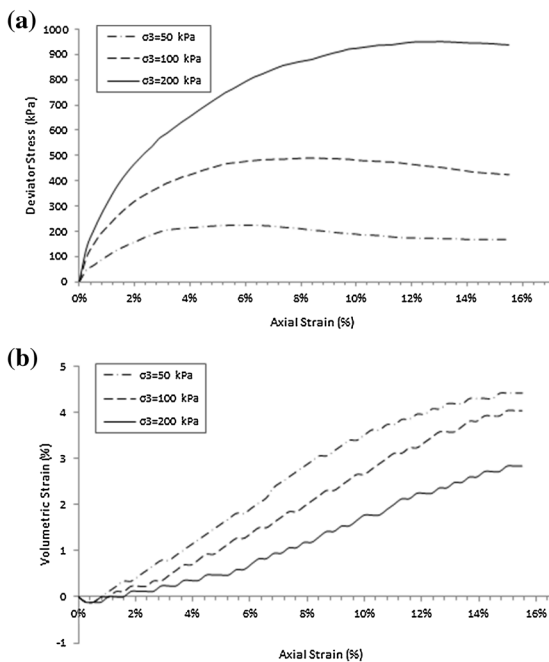

Fig. 7 Influence of confining pressure on the behavior of sand–tire mixtures with 30% granulate tire **a** deviator stress–strain behavior, **b** volumetric strain behavior
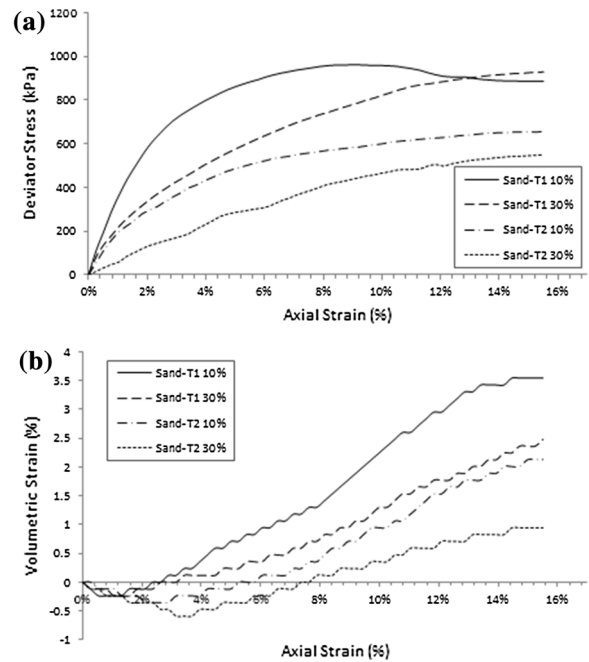

Fig. 8 Influence of tire crumb size on the behavior of sand–tire mixtures at 100 kPa confining pressure, **a** deviator stress–strain behavior, **b** volumetric strain behavior

confining pressure. It can be seen that peak stress increase and the corresponding axial strain decrease with the confining pressure increment. Stress–strain curves of mixtures of sand and high percentage tire crumbs (20 to 30% by weight) mixtures demonstrate tire-like and sand-like behavior under high and low confining pressure, respectively. The tire-sand mixture has no residual strength and larger ductility under higher confining pressure, which is similar to the pure

tire behavior. However, under low confining pressure the peak stress occurs in the strain value of lower than 15%, it has a residual strength and the ductility of the sample is lower.

The effect of tire crumb size on the stress–strain and volumetric strain response of sand–tire mixtures can be analyzed by comparing the behavior of 4 series tests, which were performed using the same confining pressure (200 kPa); but with two tires crumb contents (10, 30%) and varying size of tire crumb (T1, T2). Figure 8 illustrated some of these responses. The comparison of the deviator stress–strain curves shows that size of tire crumb has a significant effect on the stress–strain response. The S-T1 (10, 30%) mixtures have the large value of peak deviator stress compared to the S-T2 (10, 30%) mixtures. The powder tire has greater specific area in comparison with sand particles. Therefore, increment in sand–powder tire contact leads to decrement of sand particles contact possibilities with each other. Because of less shear strength between sand and powder tire, the deviator stress of sand reinforced with powder tire decreased. Moreover, the comparison of the value of the axial strain corresponding to peak deviator stress shows that the

corresponding axial strain increases with the decrement of the size of tire crumbs. In addition, for both sets of tires, ductility which is a significant factor of mixture utilization in geotechnical seismic applications, leads to higher axial strain (Tsang et al. 2009, 2012). Also, the stiffness of the reinforced sand depends on the tire crumbs content and size of the tire crumbs. As it can be seen from Fig. 8, specimens reinforced with granulate tire (T1) have higher stiffness compared to that of specimens reinforced with powder tire (T2).

Figure 9 presents the effect of tire crumb content and confining pressure on the peak strength for the all series of mixtures. It can be observed for two sets of tires that, with an increase in tire content, the peak deviator stress decreases. It should be mentioned that decrement in peak deviator stress for powder tire is more than granulate tire.

Figure 10 shows the effect of the confining pressure and percentage of tire crumb on the peak deviator stress. At all confining pressure, the corresponding axial strain increases with the increasing percentage of tire crumbs. For the samples performed using powder tire, the corresponding axial strain is more than the samples performed using granulate tire.

3.2 Volumetric Stress–Strain Behavior of Sand-Tire Mixtures

The volume change curves for both unreinforced and reinforced sand were also presented in Figs. 6, 7 and 8. These figures depict that unreinforced and reinforced sand exhibits similar trends indicating an initial compression and with further shearing, specimens show an increment in volume. In this study, the effects
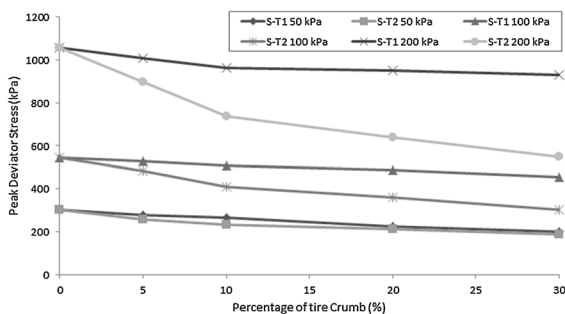

Fig. 9 Influence of percentage of tire crumb and confining pressure on the peak deviator stress of mixtures
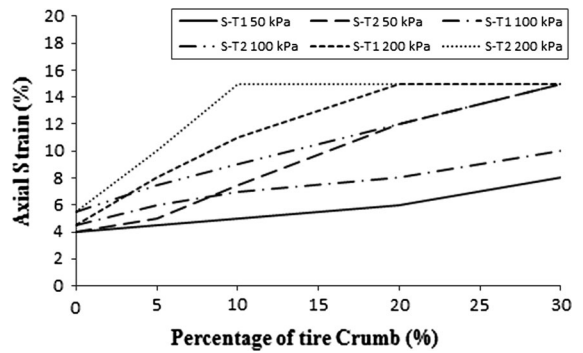

Fig. 10 Influence of percentage of tire crumb and confining pressure on the axial strain corresponding to peak deviator stress of mixtures

of tire crumbs on dilatancy angle of sand are probed. Dilatancy may be described as the change in volume that is associated with shear distortion of an element in the material. A suitable parameter for characterizing a dilatant material is the dilatancy angle, ψ. This angle was introduced by Hansen (1958) and represents the ratio of plastic volume change over plastic shear strain, Vermeer and Brost (1984) as below:

$$tan\,\psi = \frac{d\varepsilon_v^p}{d\varepsilon_d^p} \tag{1}$$

The volumetric strain is calculated as:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_r \tag{2}$$

where ε_a represents axial strain and ε_r is lateral strain. In order to obtain volumetric plastic strain, ε_v^p, by assuming sample homogeneity, the value of lateral plastic strain was considered proportional to axial plastic strain. Therefore the lateral plastic strain represents as:

$$2\varepsilon_r^p = \frac{\varepsilon_a^p}{\varepsilon_a}(\varepsilon_v - \varepsilon_a) \tag{3}$$

Finally, the volumetric plastic strain and plastic shear strain are as:

$$\varepsilon_v^p = \varepsilon_a^p + 2\varepsilon_r^p \tag{4}$$

$$\varepsilon_d^p = \varepsilon_a^p - \varepsilon_r^p \tag{5}$$

Based on Eqs. (1) to (5), the angle of dilation is represented as:

$$tan\,\psi = \left[-\frac{2d\varepsilon_v^p}{3d\varepsilon_a^p - d\varepsilon_v^p}\right]$$

Frequently, separation of elastic and plastic components of strain is not straightforward, and total strain increments are used in the calculation of dilative angle. For many situations, the contribution of elastic strains to total strains may be negligible when yielding is occurring, and the difference between a plastic strain increment ratio and a total strain increment ratio may be small, Wood (1990).

The dilation angles for both unreinforced and reinforced sand were also presented in Figs. 11 and 12. It is evident that the amount of tire crumbs has significant influence on the dilation angle of the mixtures. It can be seen that the dilation angle decreases with the increase in the percentage of tire crumbs in the mixture. Because of the fact that tire crumb size is more than the mean particle size of sand (D50), the dilatancy of the reinforced sand is less than unreinforced sand. Also, as it has been shown in Figs. 11 and 12, by increasing the confining pressure, the range of dilation angles decrease.

3.3 Failure Pattern

Typical pictures of failed samples of unreinforced and reinforced sand are shown in Fig. 13. As could be seen in these photographs, the unreinforced samples fail along a planner shear plane with the angle of $(45 + \Phi/2)$; whereas, samples reinforced with tire failed by bulging. Moreover, the bugling of samples increases when the content of the tire increases. The sand–tire mixture is a cohesive composite material. Thus, this composition leads to bulging at failure condition. Because of the fact that sand reinforced with powder tire has much cohesion in comparison with sand
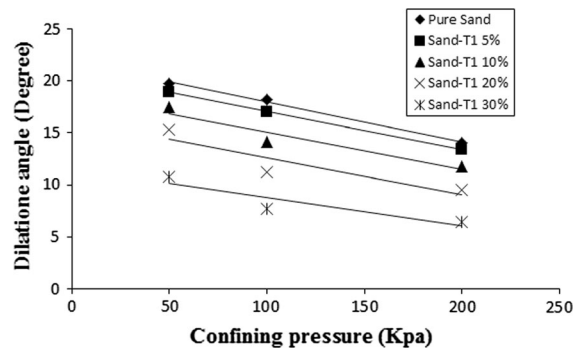

Fig. 11 Dilation angle versus confining pressure for sand–granule tire mixtures for different percentage
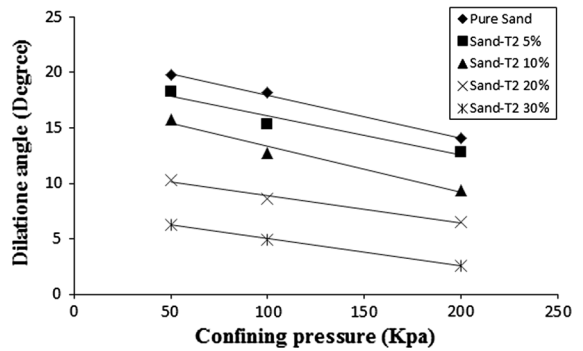

Fig. 12 Dilation angle versus confining pressure for sand–powder tire mixtures for different percentage

reinforced with granulate tire, the comparison between photographs of samples in granulate tire and powder tire show that the samples reinforced with powder tire have more bugling.

3.4 Effect of Tire Crumb on Strength Parameters

A summary of the Mohr–Coulomb shear strength parameters of sand–tire mixtures has been shown in Table 2. The angle of internal friction values varies from 38 to 40 for specimens with granulate tire additions, and from 33 to 39 for specimens with powder tire additions. The internal friction values decrease with increasing the tire content. As it can be seen from Table 2, the cohesion values increase with increasing the tire content. Also, vary from 5 to 23 kPa for the samples reinforced with granulate tire and vary from 14 to 41 kPa for samples reinforced with powder tire. The variations of the soil-tire mixture stiffness for different confining pressure as well as tire percentage have been shown in the Table 2. It can be seen that the stiffness of pure sand is more than sand–tire mixtures. The deformation modulus decreases with the increment of the percentage of tire crumbs in the mixtures. For example, for the sample reinforced with 20% granulate tire, tested at 50 kPa confining pressures, the deformation modulus is 9333 kPa; whereas, for the unreinforced sample it is 20840 kPa. Also, it should be mentioned that decrement in deformation modulus for powder tire is more than granulate tire. It has been found that sand reinforced with tire crumbs exhibits the flexibility behavior. This matter is affected by stiffness characteristics of tire crumbs which are very flexible materials as reported by Humphrey (1993).
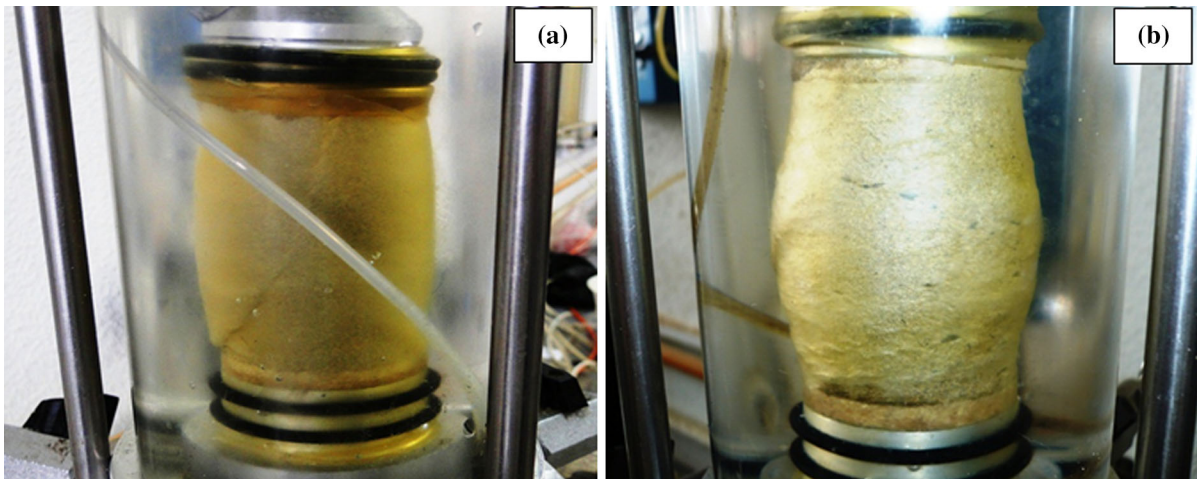
Fig. 13 Typical photographs of failed samples **a** unreinforced sand, **b** reinforced sand with tire crumb

Table 2 Summary of shear strength parameters

Series	Type of specimen	Deformation modulus (kPa)			Shear strength parameters	
		Confining pressure-50 (kPa)	Confining pressure-100 (kPa)	Confining pressure-200 (kPa)	$\Phi(°)$	C (kPa)
1	Sand	20840	38524	54780	40	2
2	S-T1 5%	17452	31864	44986	40	5
3	S-T1 10%	12625	20833	32006	40	8
4	S-T1 20%	9333	17500	23750	39	12
5	S-T1 30%	7290	11280	17332	38	23
6	S-T2 5%	15446	29784	42397	39	14
7	S-T2 10%	9785	15934	30148	38	26
8	S-T2 20%	5674	9682	11792	36	32
9	S-T2 30%	2136	3750	5708	33	41

4 Conclusion

This research presents the results of triaxial compression tests carried out on the reinforced sand with two sets of tire shred, whereas the content of tire crumbs varies from 0 to 30% by weight. The following conclusions are drawn from the current study:

1. The peak shear strength and the corresponding axial strain of sand are affected by the presence of tire crumbs and confining pressure. Unlike some studies in which tire crumbs were used, shear strength of the sand–tire mixtures has been found to decrease with the increment in the amount of tire crumbs in the mixtures. The decrement in the peak strength of the sand–tire mixtures is influenced by the coefficient of friction between tire crumbs and sand. By decreasing of this coefficient, the peak strength of sand–tire mixtures also decreases.

2. The size of tire crumbs for the behavior of reinforced sand is significant. Samples reinforced with granulate tire (T1) demonstrated higher peak strength, and lower axial strain at failure and more reduction in the post-peak loss of strength in comparison with samples reinforced with powder tire (T2).

3. Tire crumb reduces the dilatancy of reinforced sand. The ratio of tire crumb size to the mean diameter of sand also plays an important role in this respect.

4. Close examination of the failed samples reveals that the failure of reinforced sand which was observed by bulging.

5. The stiffness of reinforced sand is influenced substantially by the amount of tire crumbs in the mixtures. The stiffness decreases with the percentage of tire crumbs increment.

6. By increasing the amount of tire crumbs in sand–tire mixtures, the angle of internal friction values and the cohesion values decrease and increase, respectively.

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