Influence of Optimized Tire Shreds on Shear Strength Parameters of Sand

Mahmoud Ghazavi[1] and Masoud Amel Sakhi[2]

Abstract: This paper presents the usefulness of optimizing the size of waste tire shreds on shear strength parameters of sand reinforced with shredded waste tires. A relatively, uniform sand has been mixed with randomly distributed waste tire shreds with rectangular shape and compacted at 2° of compaction. Waste tire shreds were prepared with a special cutter in three widths of 2, 3, and 4 cm and various lengths for each shred width. Three shred contents of 15, 30, and 50% by volume were chosen and mixed with the sand to obtain a uniformly distributed mixture. In order to compare the shear strength of different sand–tire shred samples, two compaction efforts in terms of sand matrix unit weights of 15.5 and 16.8 kN/m^3 were considered. The results show that the influencing parameters on shear strength characteristics of sand–shred mixtures are normal stress, sand matrix unit weight, shred content, shred width, and aspect ratio of tire shreds. With the selected widths of shreds, compaction efforts, shred contents, and the variations of aspect ratios, it is possible to increase the initial friction angle ϕ_1 up to 113.5%, that is $\phi_1=67°$. The average value for the influence of aspect ratio variations on increase in friction angle of the mixtures for all tests has been found to be about 25%. These average values for lower and higher compacted samples containing different widths and aspect rations were 37.6 and 17.2%, respectively. It has been investigated that for a given width of tire rectangular shreds, there is solely a certain length, which gives the greatest initial friction angle for sand–tire shred mixtures. This is the main contribution of this paper.

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CE Database subject headings: Tires; Shredding; Recycling; Shear strength; Shear tests; Optimization.

Introduction

With the development of societies and use of various vehicles, many waste tires enter the environment, causing serious problems. The number of waste tires in the United States accounts for about 250 million. In Canada this figure is about 28 million. Only 30% of the above numerous waste tires are stocked in landfills (CCME 1994). Such wastes cannot generally be deposited in landfills since they require large spaces. In the United Kingdom, the number of waste tires is about 25 million. In the United Kingdom, the contribution of waste tires in producing electricity is estimated to be 20% of total fuel (the first writer heard from local TV news).

Recently an increasing attraction has been paid to find applications for such materials in civil engineering. Waste tires are used for reinforcing soft soil in road construction (Bosscher et al. 1997; Nightingale and Green 1997; Heimdahl and Druscher 1999), to control ground erosion (Poh and Broms 1995), for stabilizing slopes (Poh and Broms 1995; O'Shaughnessy and Garga 2000a), as lightweight material for backfilling in retaining structures (Bosscher et al. 1997; Sumanarathna et al. 1997; Tatlisoz et al. 1997; Allman and Simundic 1998; Lee et al. 1999; Garga and O'Shaughnessy 2000; O'Shaughnessy and Garga 2000a), as aggregates in leach beds of landfills (Hall 1991; Ahmed and Lovell 1993; Park et al. 1993), as an additive material to asphalt (Foose et al. 1996; Tuncan et al. 1998; Heimdahl and Druscher 1999), as sound barriers (Hall 1991), as limiting for freezing depth (Humphrey et al. 1997), as a source for creating heat (Lee et al. 1999), as a fuel supplement in coal-fired boilers (Ahmed and Lovell 1992; Park et al. 1993), for vibration isolation (Eldin and Senouci 1993), as cushioning foams (Bader 1992; Ahmed and Lovell 1992), and for low strength but ductile concrete (Eldin and Senouci 1993).

The above applications can be expanded or extended to other, similar, practical situations if the effects of adding shreds to soil characteristics are investigated. Bosscher et al. (1993) reported that an embankment constructed with sand–tire shreds satisfactorily operated even when subjected to heavy loads. They also found that the long-term settlement of such embankment could be alleviated if a soil cap with a thickness of 1 m overlies the sand–shred mixtures. This cap not only reduces the ongoing settlement, but also prevents tire shreds from possible igniting.

Bosscher et al. (1997) performed large-scale models of tire–chip embankments in a confining wooden box at the Univ. of Winconsin. They also constructed and loaded a test embankment parallel to the access road to a landfill near Madison, Wis. They showed that tire chip–soil mixtures exhibit a significant initial plastic compression under load. This could be as high as 40% of the initial placement thickness for pure tire chips. They also demonstrated that the inclusion of 30% sand by weight in the tire chip matrix increases the modulus to a level comparable of pure sand. Moreover, they found that when tire chips are used as a placement

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for fill under a road and covered with a 1 m thick gravel soil cap, the overall performance is similar to most gravel roads.

Edil and Bosscher (1992) conducted direct shear tests on sand reinforced with tire shreds. They found that a random addition of 10% shreds by volume to outwash sand gives greater shear strength than of the sand tested alone.

Bosscher et al. (1993), Ahmed and Lovell (1992), and Humphrey and Manion (1992) reported that regular compaction procedure can be applied to soil–shred mixtures. Bosscher et al. (1993), and Ahmed and Lovell (1992) believe that vibratory compaction does not significantly induce compaction in the sand–tire shred mixtures.

Foose et al. (1996) conducted comprehensive large direct shear tests on sand reinforced with tire shreds. They found that normal stress, shred orientation, compaction degree of sand–tire mixtures, shred contents, and shred length had influence on shear strength parameters of the mixtures. Among them, vertical stress, shred contents, and mixture compaction had greater effects. Foose et al. (1996) obtained an initial angle of friction of 67° for sand reinforced with shreds, whereas the sand alone had a friction angle of 34° at the same sand matrix unit weight. They also found that strength envelops for the mixtures consisting of dense sand were nonlinear.

Wu et al. (1997) carried out triaxial tests on tire chips with sizes in the range of 2–38 mm. They obtained friction angles of 40–60° for sand–chip mixtures. Dilation behavior was also observed in samples.

Tweedie et al. (1998) conducted a full-scale instrumented retaining wall test facility to investigate the feasible use of tire shreds as retaining wall backfill. The objectives of tests were to determine the lateral pressure magnitude and its distribution. They found that the horizontal stress for the tire shreds decreased with increasing outward rotation of the wall. They also investigated that during several days, creep movement in shreds happened.

It should be noted that in the design of geotechnical projects where tire shreds and chips are used either alone or mixing with soil, generally stability and serviceability are of great importance. For service, the compressibility may be more critical particularly when greater shred and chip tire contents are used and subjected to low normal pressures. Bosscher et al. (1997) have shown that tire chip–soil mixtures exhibit a significant initial plastic compression under load. Edil and Bosscher (1994) and Humphrey and Manion (1992) have demonstrated that tire shreds and tire shred mixtures are highly compressible at low normal pressures. However, most of the compression that occurs is plastic, which can be reached once one load application is imposed on tire shreds. Therefore, preloading can be used to eliminate plastic compression once the fill has been constructed. Confining pressure has also been advantageous to reduced compressibility. Bosscher et al. (1993) and Humphrey and Manion (1992) have mentioned that a 1 m thick soil cap can significantly reduce the compressibility and deflection of overlying pavement. Bosscher et al. (1993) has also reached the same finding by performing laboratory experiments and finite element analyses. As mentioned before, Bosscher et al. (1997) demonstrated that the inclusion of 30% sand by weight in the tire chip matrix increases the modulus to a level comparable of pure sand. Moreover, they found that a 1 m soil cap overlying tire chips used as a placement for fill leads to have an overall performance similar to most gravel roads. Garga and O'Shaughnessy (2000) described the construction of a 57 high by 17 m wide instrumented test fill, comprising both retaining wall and reinforced slope section. Approximately 10,000 whole waste tires and tires with one sidewall removed, tied together, were used. They found that the higher compressibility of tire retaining walls compared with the backfills may result in the development of negative friction on the back of the wall which can significantly increases the active pressure acting on the back of the wall. However, a reduction in the active thrust can be achieved by inclining the wall.

A significant consideration of waste tires in geotechnical projects is that such material must be assessed environmentally. Humphrey et al. (1997) investigated the water quality effects of tire chip fills placed above the groundwater table. This study reveals that most of the inorganic substances that can potentially leach from tires are naturally present at low levels in groundwater. No evidence was also found that tire chips increased the concentration of substances that had either primary or secondary effects on drinking water standard. This was demonstrated over a period of 2 years.

An environmental assessment of tire-reinforced earthfill was carried out by O'Shaughnessy and Garga (2000b), constructing a fill with 57 m by 17 m of 10,000 waste tires embedded in sand and cohesive clay. They also conducted laboratory tests on water samples taken from the earthfill. They concluded that insignificant adverse effects of waste tires on groundwater quality had occurred over a period of 2 years. They also found that the possibility of release of any toxicant was higher when using newly discarded tires, thus tire-reinforced earth structures should be built using scrap tires which have been stockpiled or have been used for some time and should ideally be placed above the permanent groundwater table.

The above findings are insufficient to assess the environmental impact of waste tires and thus further investigations are required to demonstrate them.

Despite some disadvantages of waste tires due to environmental considerations, susceptibility to ignition, and suitable shelters for insects and animals causing diseases, it is still necessary to find feasible, economical, and environmentally sound applications for the use of waste tires in the form of whole, shreds, or chips. The latter two may be preferable due to easily removing steel fibers used in tires for reinforcement. It is also important to take economical aspects of such materials into consideration.

Although a number of characteristics of tire shreds and chips have been investigated, it is still necessary to carry out further research on the subject. It was mentioned that the shred size has an important influence on shear strength parameters of sand reinforced with tire shreds (Foose et al. 1996). To the best knowledge of the authors, there is no research work showing the influence of aspect ratio (length to width) of tire shreds on soil shear strength. The authors believe that tire shreds, like other reinforcing material, should have an influence on behavior and strength of sand–shred mixtures.

The main objective of this paper is to investigate the influence of the aspect ratio of tire shreds on shear strength characteristics of sand. Large direct shear tests have been carried out for 2° of compaction, three shred contents, three widths for shreds, and various aspect ratios for a given width. This paper appears to be the first, which investigates the influence of shred aspect ratios on shear strength parameters of sand–tire shreds mixtures.

Materials

A relatively uniform sand has been chosen. Different shred contents, shred widths, and different aspect ratios have been mixed

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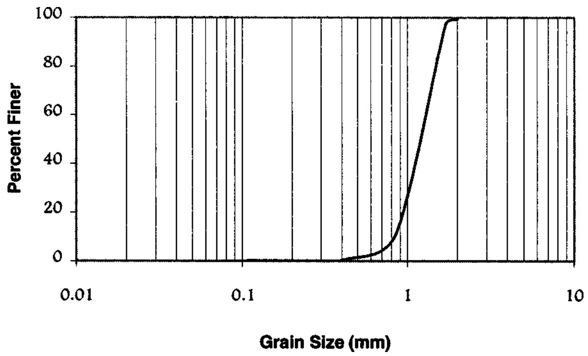

Fig. 1. Size distribution of sand

with the sand at two different sand matrix unit weights and tested in large shear box. The sand alone was tested in direct shear test. The grain size distribution was obtained based on *ASTM D854-63* (1995). Fig. 1 shows the grain size distribution of the sand.

The specific gravity of the sand was measured according to *ASTM D854-92*. Other details of the sand are presented in Table 1. The waste tires chosen for the present study are normally the most popular, which are used in Iran for a national vehicle, called Paykan. The waste tires for this study were taken from a large deposit. The smoothness of surfaces of waste tires was very different, however, most of them had smooth surfaces due to excessive use. Thus, efforts were made to select some waste tires with relatively smooth surfaces. A special cutter was used to prepare the tire shreds. Six tensile laboratory tests experiments were conducted to measure mechanical properties of the shreds. Table 2 shows the obtained data.

The widths of the shreds are 2, 3, and 4 cm. For width of 2 cm, the aspect ratios are 1, 2, 3, 4, 5, 6, and 7. For the shreds with a width of 3 cm aspect ratios are 3, 3.5, 4, and 5. Finally aspect ratios of 1, 2, 3, and 4 are chosen for shreds with a width of 4 cm. A limited number of aspect ratios for 3 cm wide shreds is considered, since initially this width was not included in the test layout but added subsequently. The width of the direct shear test mould is also limiting the greater widths to be tested. Fig. 2 depicts samples of shreds with various aspect ratios.

Direct Shear Test Apparatus

Although triaxial test apparatus may be preferable to perform experiments on sand–tire shred mixtures, the size of the shreds may damage the plastic membrane confining the mixture sample. Therefore, the authors chose a large-scale direct shear test apparatus. The device has a cross section of 30 by 30 cm. A hydraulic piston exerting force to a plate can apply normal stresses limited to a maximum value of 500 kPa. The shear force is applied and recorded by a digital cell.

Table 1. Specifications of Sand

Description	Value
Effective size, D_{10}	0.83 mm
D_{30}	1.1 mm
Mean size, D_{50}	1.4 mm
D_{60}	1.5 mm
Uniformity coefficient	1.81
Curvature coefficient	0.97
Unit weight at lower compaction, γ_m	15.5 kN/m^3
Unit weight at higher compaction, γ_{m}	16.8 kN/m^3
Friction angle at higher compaction	31°
Friction angle at higher compaction	41°
Specific gravity, G_s	2.63

Table 2. Details of Tire Shreds

Specific gravity	Thickness (mm)	Failure tensile strength (kN/m^2)	Elasticity modulus (kN/m^2)
1.3	2–6	1,115	23,530

Sample Preparation

In the test program, three tire shred contents of 15, 30, and 50% by volume have been used. It should be noted that since mixtures of sand–shreds are different in nature, a sound criteria is required to compare compaction degree for various mixtures. A matrix unit weight for the sand is used, which is defined as the weight of the sand divided by volume of the sand matrix (Foose et al. 1996). The use of equal energy per unit volume for all compacted sand–shred mixture leads to inaccurate results, since some energy released from the hammer to the mixture may be damped due to the presence of tire shreds, especially in mixtures containing greater shred contents. The use of the sand matrix unit weight remedies this.

For various mixtures, the weights of the sand and tire shreds were calculated and mixed uniformly. The mixtures were divided into three parts. Each part was poured in the shear test box such that the mixture remained uniform. Bosscher et al. (1993) constructed an embankment subjected to the traffic in the field. They compared the performance of tire shred–sand mixtures with that of individually spread layers of tire chips and soil used in various different embankment sections. They found that the section containing tire shred–sand mixtures showed higher performance while the section constructed of individual layers of tire chips and sand, one at the top of the other, had the poorest performance. Therefore, in the present experiments, care was taken to distribute the tire shreds randomly in the mixtures as much as possible. This was controlled by eye observation. Whenever this failed, the procedure of mixing was repeated. Each layer was compacted using a vibrating hammer to reach a prescribed thickness determined prior to starting a test. When the specimen was prepared at a prescribed sand matrix unit weight, the normal stress was applied and then the sample was sheared. The procedure was identically repeated for another normal stress. Three normal stresses of 9.8, 39.2, and 98.1 kPa were used in all tests. All shear tests were conducted using a strain-controlled procedure. The velocity of the

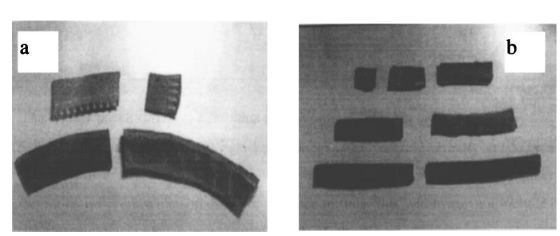

Fig. 2. Two types of tire shreds with different aspect ratios: (a) width=3 cm and (b) width=2 cm

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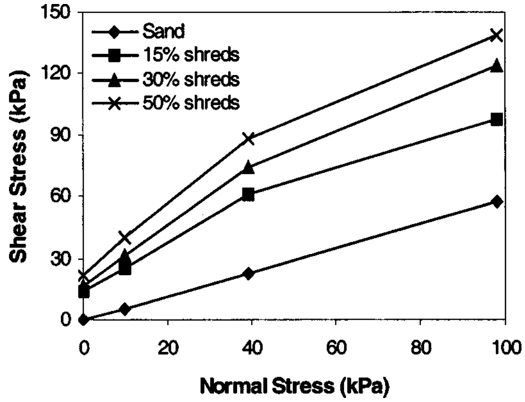

Fig. 3. Variation of shear stress with normal stress on samples with 4×8 cm shreds at $\gamma_m = 15.5$ kN/m^3

half box was kept 1.5 mm/min for all tests. Some tests were randomly repeated to ensure that the procedure adopted in all experiments were indicative and repeatable.

A series of CBR tests were also conducted on same specimens as prepared and tested in direct shear device. It is interesting to mention that the results of these tests have an excellent compatibility with those obtained from direct shear tests, as expected. The results were presented elsewhere (Amel-Sakhi 2001).

Results

For each width, aspect ratio, tire shred content, and sand matrix unit weight, direct shear tests were performed using three normal stresses of 9.8, 39.2, and 98.1 kPa. The inclusion of all figures in this paper is cumbersome and makes the paper lengthy. Only a limited number of them are presented here. Figs. 3 and 4 illustrate the variation of shear stress versus normal stress for 4×8 cm tire shreds at lower and higher sand matrix unit weight, respectively. Similar trend were observed for mixtures containing 2×10 cm and 3×12 cm shreds at two compaction degrees (Amel-Sakhi 2001).

A number of points can be drawn from above figures. These can be summarized as:

1. At a given normal stress applied on specimens, the shear resistance of the shred–sand mixtures is greater than that of the sand alone at the same sand matrix unit weight.
2. The shear resistance of the mixtures increases with increasing tire shred contents.
3. An apparent cohesion is obtained in samples containing tire shreds. This cohesion becomes greater in samples containing a greater quantity of shreds. This parameter also is greater in more compacted specimens.
4. The Mohr–Coulomb envelope is nonlinear. This phenomenon is more pronounced in mixtures with greater percentage of tire shreds.
5. Based on the above findings, the general trend observed in the tests are in excellent agreement with that of Foose et al. (1996). This demonstrates the acceptability of the present experiments performed to optimize the shred dimensions to gain higher shear resistances. It should, however, be noted that the values of cohesion obtained here for sand–tire shred mixtures is greater than those reported by Foose et al. (1996).

From the database provided from the performed tests, the values of initial friction angle ϕ_1 for different sand–tire shred contents at two compaction conditions are obtained. These are shown in Figs. 5 and 6 for the shred widths of 2 cm at two sand matrix unit weight. In these figures, for comparison, the friction angle of the sand alone at the same sand matrix unit weight is also shown to demonstrate the effects of reinforcement. Some interesting points can be inferred from these figures, which are:

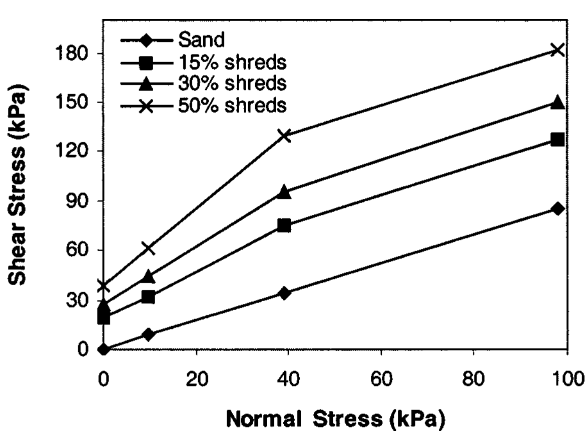

Fig. 4. Variation of shear stress with normal stress on samples with 4×8 cm shreds at $\gamma_m = 16.8$ kN/m^3

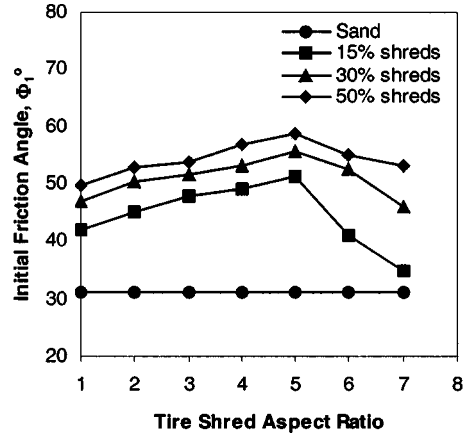

Fig. 5. Variation of initial friction angle versus shred aspect ratio for shreds width $= 2$ cm and $\gamma_m = 15.5$ kN/m^3

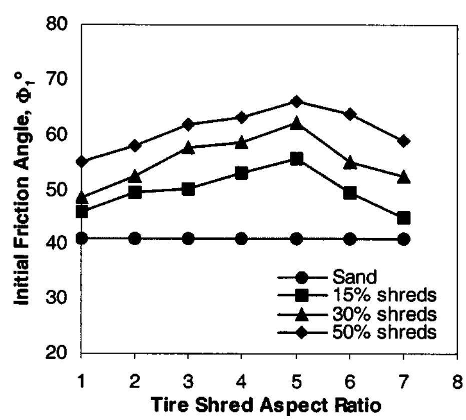

Fig. 6. Variation of initial friction angle versus shred aspect ratio for shreds width $= 2$ cm and $\gamma_m = 16.8$ kN/m^3

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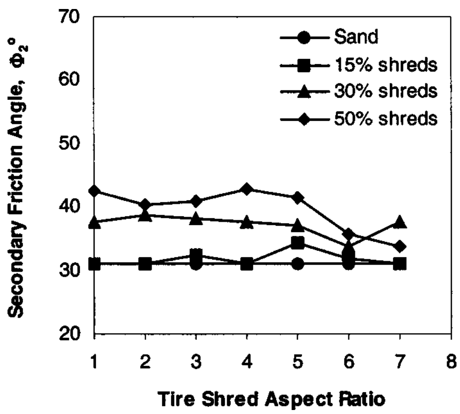

Fig. 7. Variation of secondary friction angle versus shred aspect ratio for shreds width=2 cm and γ_m=15.5 kN/m^3

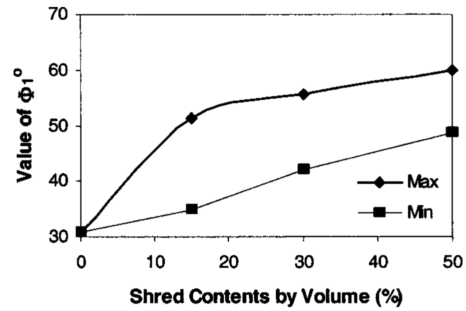

Fig. 9. Variations of initial friction angle ϕ_1 with shred contents (γ_m=15.5 kN/m^3)

1. The addition of tire shreds to sand can increase the initial friction of the sand significantly. For mixtures with 2 cm wide tire shreds, at a compaction of γ_m=15.5 kN/m^3, the friction angle of the mixtures containing 15% shreds by volume, increases by 65.8%. The increase in ϕ_1 for mixtures with 30 and 50%, respectively, account for 79.9 and 89.7%. For compacted samples at γ_m16.8 kN/m^3, these values increase, respectively, by 37.2, 52.1, and 61.8% for samples containing 15, 30, and 50%. A similar trend can be observed for mixtures containing 3 and 4 cm wide tire shreds (Amel-Sakhi 2001).
2. The initial friction angle of sand–tire shred mixtures increases with increasing tire shred contents.
3. The ratio of length to width of tire shreds has a significant influence on initial friction angle of the mixtures. It can be seen that for a given shred width, there is solely an optimized length giving the greatest friction angle regardless of the shred contents and compaction efforts. This is more significant in more compacted mixtures. For 2, 3, and 4 cm wide shreds, the optimum dimensions are found to be 2×10 cm, 3×12 cm, and 4×8 cm, respectively (Amel-Sakhi 2001).
4. An addition of 15% tire shreds by volume to the sand, the initial friction angle increases 13–66%. In lower sand matrix unit weight, if the volume increases to 30%, ϕ_1 increases 36–80%, and finally if the shreds account for 50% in the mixtures, ϕ_1 increases 57–94%. In more compacted specimens, these quantities account for 10–39%, 19–52%, and 35–63%, respectively, depending on the shred dimensions. These values show the importance of optimizing tire shred sizes to gain higher shear resistance. It was generally found that the friction angle of sand–shred mixtures increases by using optimum shred aspect ratio and by increasing shred contents and mixture compaction. The addition of tire shreds can increase ϕ_1 by about 10–94%, depending on shred width, shred aspect ratio, shred content, and mixture compaction.

The variations of secondary friction angle in sand–tire shred mixtures ϕ_2 in terms of aspect ratios of tire shreds are shown in Figs. 7 and 8 for 2 cm wide shreds.

From Figs. 8 and 9, it is seen that the values of ϕ_2 generally approach the friction angle of the sand alone and their deviations from the sand friction angle are insignificant. This is more pronounced in more compacted mixtures. For other shred widths, a similar trend was observed (Amel-Sakhi 2001). This trend is similar to findings of Foose et al. (1996) who did experiments on sand–tire shreds and Gray and Ohashi (1983), Maher and Gray (1990), and Benson and Khire (1994), who investigated the resistance of sand reinforced with randomly distributed fibers. This phenomenon will be discussed subsequently.

Figs. 9 and 10 show the maximum and minimum initial friction angles obtained from using various aspect ratios for tire shreds at compactions of 15.5 and 16.8 kN/m^3, respectively. These figures demonstrate the influence of size optimization of tire shreds.

During shearing loading on mixtures of sand–tire shreds at two compaction degrees of γ_m=15.5 and 16.8 kN/m^3, dilation characteristics were exhibited. Fig. 11 depicts these for samples containing 2×10 cm tire shreds. For brevity, only results on sand-optimized shred mixtures with γ_m=16.8 kN/m^3 cm and under

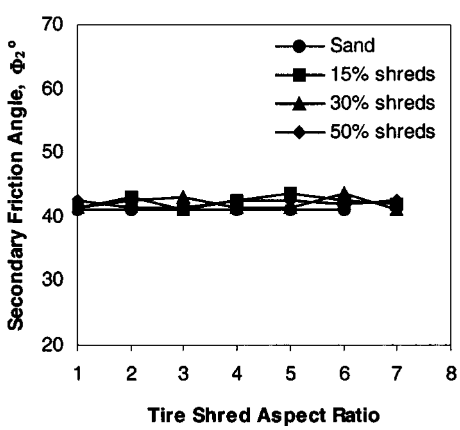

Fig. 8. Variation of secondary friction angle versus shred aspect ratio for shreds width=2 cm and γ_m=16.8 kN/m^3

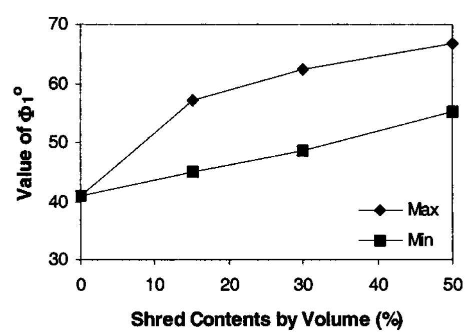

Fig. 10. Variations of initial friction angle ϕ_1 with shred contents (γ_m=16.8 kN/m^3)

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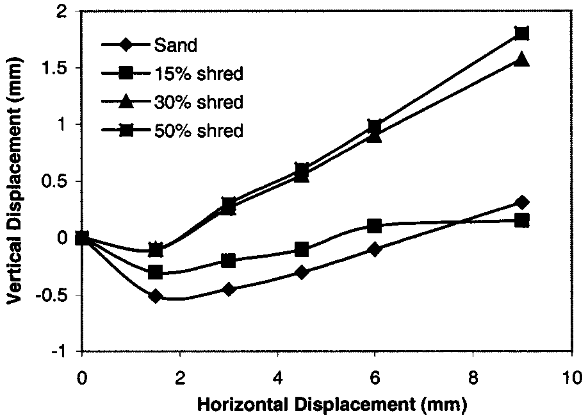

Fig. 11. Vertical displacements versus horizontal displacements for mixtures containing 2 cm×10 shreds (γ_m=16.8 kN/m^3, σ_n=9.8 kPa)

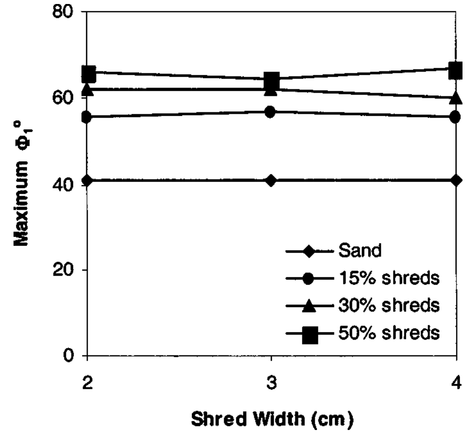

Fig. 13. Maximum initial friction angle ϕ_1 versus optimized shred width for compacted samples at γ_m=16.8 kN/m^3

normal stress of 9.8 kPa are presented here. More data are available for other shred widths, aspect ratios, compaction energy, and normal stresses (Amel-Sakhi 2001). The sand alone was dilated under compaction of γ_m=16.8. The dilation phenomenon observed in these tests was also experienced by others (for example, Foose et al. 1996).

Figs. 12 and 13 show that in the mixtures having lower shred contents, shreds of 2 and 4 cm widths are more effective than 3 cm wide shreds. However, at 50% shred content, the mixtures containing 3 cm wide shreds offer slightly greater friction angle. In samples compacted at γ_m=16.8 kN/m^3 and containing 50% shreds, higher friction angle is obtained from using 2 and 4 cm shreds. Mixtures having 15 and 30% shreds of 2 and 4 cm widths possess slightly greater friction angles.

As shown in Fig. 13, with respect to the materials chosen, the greatest possible value of about ϕ_1=67° was obtained for mixtures having 50% shreds with dimensions of 4×8 cm at γ_m=16.8 kN/m^3.

Fig. 14 illustrates the optimum aspect ratio versus the shred width for the material tested for all samples containing different shred contents and compaction. It should be noted that the information given in this figure may be valid for the materials used in this study. From Fig. 14, the optimal aspect ratio versus the shred width may be expressed approximately as

$$\left(\frac{L}{B}\right)_{\text{optimum}} = -1.5B + 8.17 \qquad (1)$$

where L=optimum length for the shred having a width of B.

Eq. (1) may be used for other tire shred widths mixed with the sand used in the present study.

Discussion

The main objective of the present study has been to investigate to what extent the optimization of tire shreds mixed with sand can enhance the shear resistance of the mixtures. This can be examined by comparing the results obtained in this research with those of Foose et al. (1996). They obtained ϕ_1=55° for mixtures of sand and 10 cm shreds at γ_m=16.8 kN/m^3, whereas in roughly similar conditions, the authors found ϕ_1=62.2° by optimizing tired shreds. It should be noted that the tires selected for tests by the authors were roughly smooth. The authors believe that if tires had been chosen similar to those used by Foose et al. (1996), greater friction angles would have been obtained.

An apparent cohesion is created in sand–tire shreds. This increases with increasing shred contents. This may be attributed to penetration of sand grains into tire shreds due to insignificant elastic deformation at no normal stress. When shear stress is applied, this bridging resistance appears in the form of cohesion. With the presence of more tire shreds in the mixtures, the inter-

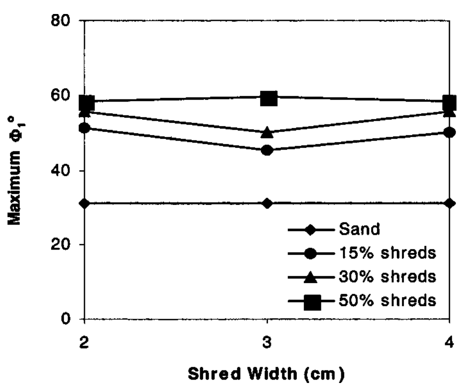

Fig. 12. Maximum initial friction angle ϕ_1 versus optimized shred width for compacted samples at γ_m=15.5 kN/m^3

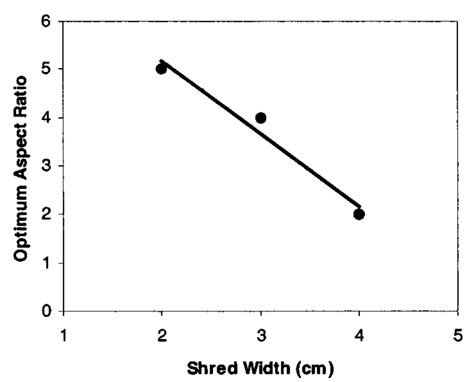

Fig. 14. Variation of optimum tire shreds versus shred width

locking effect becomes more significant, resulting in higher apparent cohesion. It should be noted that this is different from the cohesion existing in clayey soils.

When lower normal stresses are applied, the sand grains tend to penetrate slightly into shreds. If shear stresses are applied, more penetration may occur. This results in creating a lateral pressure imposed from the sand grains to the shreds. At this stage, the resistance of the sand is attributed to two components; the lateral pressures induced from sand grains to shreds and the friction mobilized between sand–shred, shred–shred, and sand–sand.

At greater normal pressures, samples tend to become more compacted since the static loading can increase the compaction of samples just before applying shear stress. When shear stresses are applied, it is unlikely that sand grains penetrate into shreds and the sample tends to dilate, resulting in increasing the volume of mixtures. This is obvious due to increasing the sample thickness. This dilation causes the friction between sand–shred and shred–shred decreases. This event leads to a decrease in the friction angle. The dilation causes tire shreds to become less effective and the sand controls the sample resistance. This is why the secondary friction angle ϕ_2 approaches the sand friction angle or slightly greater. The mentioned characteristics become more significant in more compacted mixtures and with the presence of more shreds.

As shown above, by optimizing shred sizes, it is possible to increase the initial friction angle of the mixtures. It was found that this increase on the average accounts for about 25% for all samples. These average values for lower and higher compacted samples containing different widths and aspect ratios of tire shreds were 31.8 and 17.2%, respectively.

For a given shred width, in small aspect ratios for tire shreds in the mixtures, less friction exits between the shreds and sand grains. Furthermore, the anchored length of those shreds randomly distributed and oriented in shear zone is short. The shear resistance increases in terms of anchored lengths of shreds up to a certain value.

On the other hand, for a given shred width, if the shreds are longer than a certain quantity, the movement of the mixture due to shearing loading, causes some of these shred lengths due to their continuity, and are possibly curved and separated from sand grains and other shreds in their vicinity. This may be more critical for shreds oriented close to shear box walls and shearing plane. This, however, results in reduction of shear stresses transferred at the sand–shred interface. Therefore, there is solely a critical length

Based on the two latter discussions, for a given shred width, there is a unique length giving the greatest friction angle for the materials used. This is called optimum aspect ratio. This optimum aspect ratio corresponding to a certain shred width remains the same regardless of compaction degree and shred contents in the sand–tire shred mixtures.

In the present experiments, the increment of two subsequent aspect ratios was taken as unity. However, this may not be the correct optimum aspect ratio for the widths of shreds used. To find the best optimum aspect ratio for a given width of shreds, extensive tests may be required, however, this may not be economical.

The influence of optimizing tire shreds on shear strength characteristics of sand–shred mixtures is encouraging, as discussed above. From an environmental point of view, it is worth using waste tires in various applications. However, economical aspects of making shreds from waste tires are an important point. It seems that additional expenses are required to make shreds in certain dimensions. Making shreds generally and optimizing their dimensions particularly remain to be extensively assessed.

Conclusions

The influence of dimensions of rectangular shreds prepared from waste tires on the shear resistance of sand–shred mixtures has been investigated by performing large direct shear tests. Sand alone and sand–shred mixtures having 15, 30, and 50% shreds of 2, 3, and 4 cm width and various aspect ratios were tested at two different compaction levels. It has been found that shred contents, shred width, shred aspect ratio for a given width, compaction, and normal stress are influencing factors on shear strength of the mixtures. A number of findings can be cited.

Dilation characteristics were observed in sand–shred mixtures, especially in samples having greater shred content and more compaction.

In almost all soil–shred mixtures, the Mohr envelopes were nonlinear.

The friction angle of mixtures increases by using optimum shred aspect ratio and by increasing shred contents and mixture compaction. The tire shreds cause ϕ_1 to be increased by about 10–94%, depending on shred width and aspect ratio, shred content, and mixture compaction.

An optimization of aspect ratios of shreds having widths of 2, 3, and 4 cm can increase ϕ_1 on average by 25%. It has been found that regardless of compaction level and shred contents in the mixtures, for a given width, there is only a certain length that gives the greatest value of ϕ_1. The absolute greatest value of about $\phi_1 = 67°$ was obtained by using 50% shreds with dimensions of 4×8 cm at $\gamma_m = 16.8$ kN/m^3.

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References

Ahmed, I., and Lovell, C. (1992). "Use of rubber tires in highway construction." *Utilization of waste materials in civil engineering construction*, ASCE, New York, 166–181.

Allman, M. A., and Simundic, G. (1998). "Testing of a retaining wall constructed of waste tyres." *Proc., 3rd Int. Congress on Environmental Geotechnics*, Vol. 2, Lisbon, Portugal, 655–660.

Amel-Sakhi, M. (2001). "Influence of optimized tire shreds on strength of sand-reinforced with tire shreds." MSc thesis, Isfahan Univ. of Technology, Isfahan, Iran.

Bader, C. (1992). "Where will all the tires go?." *Municipal Solid Waste Manage.*, 2(7), 26–30.

Benson, H., and Khire, V. (1994). "Reinforcing sand with strips of reclaimed high-density polyethylene." *J. Geotech. Eng.*, 120(5), 838–855.

Bosscher, P. J., Edill, T. B., and Edlin, N. N. (1993). "Construction and performance of a shredded waste tire test embankment." *Transportation Research Record 1345*, Transportation Research Board, Washington, D.C.

Bosscher, J., Edill, T. B., and Kuraoka, S. (1997). "Design of highway embankments using tire chips." *J. Geotech. Geoenviron. Eng.*, 123(4), 297–304.

Council of Ministers for The Environment (CCME). (1994). “Harmonized economic instruments for used tires.” *Final Rep. Prepared for the Canadian Council of Ministers for the Environment, Apogee Ref. 363 CCME, No. CCME-SPC-EITG-92E.*, Canada.

Edil, T. B., and Bosscher, P. J. (1992). “Development of engineering criteria for shredded waste tires in highway applications, final report.” *Res. Rep. No. GT-92-9*, Wisconsin Dept. of Transportation, Madison, Wis.

Edil, T. B., and Bosscher, P. J. (1994). “Engineering properties of tire chips and soil mixtures.” *Geotech. Test. J.*, 17(4), 453–464.

Eldin, N. N., and Senouci, A. B. (1993). “Rubber-tire particles as concrete aggregate.” *J. Mater. Civ. Eng.*, 5(4), 478–496.

Foose, J., Benson, H., and Bosscher, J. (1996). “Sand reinforced with shredded waste tires.” *J. Geotech. Eng.*, 122(9), 760–767.

Garga, V. K., and O’Shaughnessy, V. (2000). “Tire-reinforced earthfill. Part 1: Construction of a test fill, performance, and retaining wall design.” *Can. Geotech. J.*, 37, 75–96.

Gray, D. H., and Ohashi, H. (1983). “Mechanics of fiber reinforced in sands.” *J. Geotech. Eng.*, 109(3), 335–353.

Hall, T. (1991). “Reuse of shredded tire material for leachate collection system.” *Proc., 14th. Annual Conf. Dept. of Engineers. Prof. Devel*, Univ. of Wisconsin, Madison, Wis., 367–376.

Heimdahl, C., and Druscher, A. (1999). “Elastic anisotropy of tire shreds.” *J. Geotech. Geoenviron. Eng.*, 125(5), 383–389.

Humphrey, D. N., Katz, L. E., and Blumenthal, M. (1997). “Water quality effects of tire chip fill placed above the groundwater table.” *ASTM STP 1275*, M. A. Wasemiller and K. B. Hoddinott, eds., Philadelphia, 299–313.

Humphrey, D. N., and Manion, W. P. (1992). “Properties of tire chips for lightweight fill.” *Proc., Grouting, Soil Improvement, and Geosynthetics*, Vol. 2, ASCE, New York, 1344–1355.

Humphrey, D. N., and Nickels, W. L. (1997). “Effect of tire chips as lightweight fill on pavement performance.” *Proc., 14th Int. Conf. on Soil Mechanics and Foundation Engineering*, New Delhi, India, 1617–1620.

Lee, J. H., Salgado, R., Bernal, A., and Lovell, C. W. (1999). “Shredded tires and rubber-sand as lightweight backfill.” *J. Geotech. Geoenviron. Eng.*, 125(2), 132–141.

Maher, M. H., and Gray, D. H. (1990). “Static response of sands reinforced with randomly distributed fibers.” *J. Geotech. Eng.*, 116(11), 1661–1677.

Nightingale, D. E. B., and Green, W. P. (1997). “An unsolved riddle: tire chips, two roadbeds, and spontaneous reactions.” *ASTM STP 1275*, M. A. Wasemiller and K. B. Hoddinott, eds., Philadelphia, 265–285.

O’Shaughnessy, V., and Garga, V. K. (2000a). “Tire-reinforced earthfill. Part 2: Pull-out behavior and reinforced slope design.” *Can. Geotech. J.*, 37, 97–116.

O’Shaughnessy, V., and Garga, V. K. (2000b). “Tire-reinforced earthfill. Part 3: Environmental assessment.” *Can. Geotech. J.*, 37, 117–131.

Park, J., Kim, J., and Edil, T. (1993). “Sorption capacity of shredded waste tires.” *Proc., Green 93, An Int. Symp. on Geotechnical Related to the Environment*, A. A. Balkema, Rotterdam, The Netherlands, 341–348.

Poh, P. S. H., and Broms, B. B. (1995). “Slope stabilization using old rubber tires and geotextiles.” *J. Perform. Constr. Facil.*, 9(1), 76–80.

Sumanarathna, I. H. D., Mallawarctchie, D. P., and Kulathilaka, S. A. S. (1997). “Stabilization of slopes by anchored type retaining structures.” *Proc., 14th Int. Conf. of Soil Mechanics and Foundation Engineering*, New Delhi, India, 1261–1264.

Tatlisoz, N., Benson, C., and Edil, T. (1997). “Effect of fines on mechanical properties of soil-tire chip mixtures.” *ASTM STP 1275*, M. A. Wasemiller and K. B. Hoddinott, eds., Philadelphia, 93108–93108.

Tuncan, M., Cetin, A., Tuncan, A., and Koyuncu, H. (1998). “Assessment of waste tires and plastic on asphalt concrete pavement mixtures.” *Proc., 3rd Int. Congress on Environmental Geotechnics*, Vol. 2, Lisbon, Portugal, 667–672.

Tweedie, J. J., Humphrey, D. N., and Sanford, T. C. (1998). “Tire-shreds as lightweight retaining wall backfill.” *J. Geotech. Geoenviron. Eng.*, 124(11), 1061–1070.

Wu, W. Y., Benda, C. C., and Cauley, R. F. (1997). “Triaxial determination of shear strength of tire chips.” *J. Geotech. Geoenviron. Eng.*, 123(5), 479–482.

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