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Effect of granulated rubber on shear strength of fine-grained sand

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ABSTRACT

Review of the literature related to the mixture of shredded tire and sand shows that, despite of the increase in shear strength due to addition of tire chips, granulated rubber causes reduction in shear strength of sand. In this study, the shear behavior of mixtures of fine-grained sand and 1–5 mm granulated rubber is investigated. Sixty direct shear tests were conducted on sand–granulated rubber mixtures with various rubber contents (0%, 5%, 10%, 20% and 30%) at different relative densities (50%, 70% and 90%) and different normal stresses (34.5 kPa, 54.5 kPa, 74.5 kPa and 104.5 kPa). The obtained results show that the granulated rubber improves the shear strength of fine-grained sand at medium relative density and low normal stress. The degree of improvement in shear strength is a function of rubber content, relative density and normal stress. The results show that at relative density of 50%, by adding 5% granulated rubber, the internal friction angle of sand increases from 35.1° to 39.2°. However, at relative densities of 70% and 90%, addition of granulated rubber to sand decreases its internal friction angle. The results also indicate that the behavior of sand becomes more ductile with increasing granulated rubber content. Adding granulated rubber leads to greater yielding strain and less tangent stiffness of sand. The maximum dilation angle decreases with the decrease in granulated rubber content. The stress ratio of sample at critical state ($\psi = 0°$) decreases with increasing granulated rubber content.

1. Introduction

Storage of scrap tires is very undesirable. It causes environmental pollution and fire and health risks. Therefore, reuse of waste tires is essential to avoid growing storage of discarded tires around the world. Tire chips have good engineering properties such as low specific gravity, high durability and flexibility. In geotechnical engineering, tire chips are used for various applications such as lightweight fills, highway construction, soil reinforcement and soil-retaining walls.

The shear behavior of sand–tire chips (size of 12.5–50 mm) was studied by Ahmed (1993) using triaxial apparatus. He investigated the effects of tire chips content, sample preparation, confining pressure and method of compaction on the shear behavior of the sand–tire chips mixtures, and found that confining pressure and tire chips content are the most effective factors on the shear strength of these mixtures. He also indicated that the optimum ratio of tire chips to sand is about 35% by weight. Zornberg et al. (2004) conducted triaxial tests on the mixtures of sand and rectangular tire chips. They concluded that the highest shear strength of sand–tire chips mixtures occurs under low confining pressure with tire chips content of about 35% of mixture by weight. Similarly, Rao and Dutta (2006) investigated the effect of rectangular tire chips on sand. They found that the highest shear strength of sand–tire chips mixtures occurs for tire chips with length to width ratio of 2 and the content of 20% by weight. Ghazavi and Sakhi (2005) studied the influence of dimensions of rectangular tire chips on the shear resistance of sand–tire chips mixtures. They prepared tire chips in widths of 2 cm, 3 cm and 4 cm and various lengths. In addition, they chose three tire chip contents of 15%, 30% and 50% by volume in the tests. They mixed sand and tire chips uniformly and performed direct shear tests on the mixtures using three normal stresses of 9.8 kPa, 39.2 kPa and 98.1 kPa. They found that with increasing tire chips content, the shear strength of sand–tire chips mixtures increases. The Mohr-Coulomb envelope was nonlinear in almost all sand–tire chips mixtures. This phenomenon was more pronounced in mixtures with greater percentage of tire chips. They also found the optimum lengths for tire chips in widths of 2 cm, 3 cm and 4 cm as 10 cm, 12 cm and 8 cm, respectively. In California bearing ratio (CBR) case, Yoon et al. (2008) carried out plate load tests on sand reinforced with tire chips at different relative

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densities of 40%, 50% and 70%. They determined the bearing capacity ratio (BCR) as 2.5 for reinforcement depth of 0.2 times the plate width. They reported that the values of BCRs decrease with increasing relative density. In addition, Signes et al. (2015) assessed the bearing capacity of sand–granulated rubber mixtures which were used as a sub-ballast layer in new railway lines. The particle size of the granulated rubber was lower than 20 mm. In this experimental study, four percentages of granulated rubber were utilized, varying from 1% to 5% (by weight). The results obtained from plate load test on samples with different percentages of granulated rubber demonstrated that the increase in granulated rubber content leads to decline in CBR value. Hataf and Rahimi (2006) studied the effect of rectangular tire chips with different length to width ratios (aspect ratios) on the bearing capacity of sand using laboratory model tests. They chose tire chips in widths of 2 cm and 3 cm with aspect ratios of 2, 3, 4 and 5. They concluded that the bearing capacity of sand increases with increasing tire chips content. Their results showed that the maximum bearing capacity for tire chips-reinforced sand was 3.9 times that of unreinforced sand at tire chips content of 40% by volume and dimensions of 3 cm × 12 cm. Christ and Park (2010) and Marto et al. (2013) evaluated the shear behavior of sand reinforced with tire chips by conducting direct shear tests. They concluded that tire chips can improve shear strengths of sand. Masad et al. (1996) studied the effect of granulated tire chips with the maximum size of 4.75 mm on shear behavior of sand. They used tire chips content of 50% by volume and conducted triaxial tests with different confining pressures on sand–tire chips mixtures at relative density of 90%. Contrary to previous studies, they observed no increase in shear strength of sand–tire chips mixtures. Similarly, Youwai and Bergado (2003) observed that the shear strength of sand reduces with the addition of 5-mm tire chips. They showed that the peak shear strength of sand–tire chips mixtures can be observed easily when the tire chips content is less than 30% of sand by weight. They also indicated that the axial strain of sand–tire chips mixtures increases with increasing tire chips content. Foose et al. (1996) performed direct shear tests on sand–tire chips mixtures, and observed no peak shear stress for the majority of tests. Edil and Bosscher (1994) indicated that preloading can be used to eliminate plastic compression of soil–tire chips mixtures. Bosscher et al. (1992) showed that an embankment constructed with tire chips-reinforced sand has performed satisfactorily even after being subjected to heavy truck traffic. Humphrey et al. (1993) reported that tire chips are highly compressible on initial loading. However, the compressibility becomes less on subsequent unloading/reloading cycles. A significant consideration of waste tires in geotechnical projects is that such material must be assessed environmentally. Humphrey et al. (1997) studied the water quality effects of tire chip fills placed above the groundwater table and found that most of the inorganic substances that can potentially leach from tires were present at low levels in groundwater. O'Shaughnessy and Garga (2000) performed an environmental assessment of tire-reinforced earth fill. They concluded that the tire-reinforced earth structures should be placed above the permanent groundwater table. Also, Hennebert et al. (2014) evaluated the environmental effect of sand and tire shredded mixtures used in rockfill protection backfill. They studied both issues of water pollution and results of shredded tire ignition. The collected water which was the consequence of tire propagation was measured and compared with existing standards. The danger of tire propagation in the core of embankment was assessed. Eventually, they concluded that it had no significant impact on environment except in the case of tire, whose residue can be destructive and perilous material.

In previous researches related to the mixture of shredded tire and sand, despite the increase in shear strength due to addition of tire chips, granulated rubber causes reduction in shear strength of sand. In this study, a series of direct shear tests is performed to investigate the mechanical characteristics of sand–granulated rubber mixtures. The effects of granulated rubber content, relative density and normal pressure on the behavior of sand are evaluated in terms of volumetric strain-shear strain and shear stress-shear strain behaviors, shear modulus, yielding strain capacity, stress-dilatancy behavior and shear strength parameters.

2. Materials and methods

2.1. Materials

Babolsar fine-grained sand and tire chips in size of 1–5 mm were used in this study. The coefficient of uniformity (C_u), coefficient of curvature (C_c), specific gravity (G_s), effective size (D_{10}) and other engineering properties of the sand are presented in Table 1.

According to ASTM D4254-16 (2016) and ASTM D4253-16 (2016), the minimum and maximum unit weights of sand are 14.7 kN/m^3 and 17.4 kN/m^3, respectively. The particle size distribution curves for sand and tire pieces are shown in Fig. 1. According to ASTM D6270-08 (2012), the tire pieces used in this study are classified as granulated rubber. These tire pieces can be grinded in few phases by grinder machines and removed from steel wires. The other types of tire pieces with larger sizes do not have this specified characteristic. The average unit weight and specific gravity for granulated rubber are 12.05 kN/m^3 and 1.22, respectively.

2.2. Test procedure

The dry unit weight of the mixture in natural state is obtained by the maximum and minimum unit weights of sand-granulated rubber mixtures acquired according to ASTM D4253-16 (2016) and ASTM D4254-16 (2016), respectively.

In this study, a 10 cm × 10 cm shear box (inside diameter = 14.14 cm) was used for direct shear tests (ASTM D3080-94, 2011). The rate of displacement was 0.5 mm/min. In the present study, the percentages of granulated rubber with particle sizes of 1–5 mm were taken as 5%, 10%, 20% and 30% by weight. It is important to mention that the sand–granulated rubber mixtures have different porosities. For various mixtures, weights of sand and granulated rubber were calculated and mixed uniformly. The sand–granulated rubber mixtures were divided into three parts. Each part was poured in the shear test box and compacted in order to reach the required relative density. Direct shear tests were performed on mixtures at four normal stresses of 34.5 kPa, 54.5 kPa, 74.5 kPa and 104.5 kPa. By conducting direct shear tests, the effect of different relative densities (50%, 70% and 90%) on the shear behavior of sand–granulated rubber mixtures was investigated.

3. Results and discussion

3.1. Unit weight

Fig. 2 shows the maximum and minimum unit weights of sand–granulated rubber mixtures with different granulated rubber contents of 0%, 5%, 10%, 20% and 30% by weight. As can be seen, the maximum and minimum unit weights decrease with increasing

Table 1
Engineering properties of Babolsar sand.

D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_c	C_u	G_s
0.2	0.25	0.27	0.23	1.07	1.45	2.65