Laboratory Investigations on the Shear Behaviour of Sand-Tyre Derived Aggregate Mixtures

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ABSTRACT: A significant amount of research has been carried out in recent years to investigate possible options on the reuse of scrap tyres in civil engineering applications. One of the sustainable options is to utilise scrap tyre as tyre shreds/tyre chips (generally called as Tyre Derived Aggregate, TDA) and sand mixture as a lightweight fill material in the construction of infrastructure. Utilising TDA in infrastructure projects has multiple benefits including environmentally sustainable recycling and reuse of the scrap tyre thereby easing the consumption of natural fills, reduced material costs and enhanced geotechnical properties of the soil. Understanding the shear and volume change behaviours of TDA and sand mixture is critical before recommending the mixture as a suitable lightweight-reinforcing structural fill. In this study, the effect of the addition of TDA on the shear behaviour of sand was investigated using large scale direct shear and triaxial apparatus. It has been observed that TDA has significant influence on the shear and volume change behaviours of sand. Also, overall improvements in the soil characteristics, such as enhanced shear strength, can be achieved by the addition of TDA in sand.

KEYWORDS: Tyre derived aggregates, Sand, Triaxial testing, Direct shear testing

1. INTRODUCTION

Recent reports highlight that many developed and developing countries are in danger of being overrun by scrap tyres. For example, in 1990, about one billion of scrap tyres were stockpiled in USA. Even after major clean-up operations, 70 million scrap tyres still remain to be cleaned up. In Australia, a large number of end-of-life tyres are being disposed through landfill, stockpiles, exported as baled tyres or illegally dumped. Recent reports (e.g. Mountijoy et al., 2015) estimated that 51 million equivalent passenger unit (EPU) tyres reached their end of life in 2013-14. If this trend continues, within next two decades, around 680 million waste tyres may end up in the landfill. Recently, there is a ban on the disposal of scrap tyres in landfill worldwide and effective recycling solutions may urgently need to be investigated. Existing techniques of scrap tyre recycling include reclamation of the original synthetic through de-vulcanization, re-utilisation as a low-grade rubber replacement, and combustion as an energy source in concrete kilns, paper mills and boilers. As a result, an increased recovery rate of scrap tyres in the USA, Japan and EU has been reported. Hence there is a high potential on the availability of scrap tyre as secondary raw materials which can be effectively used in different engineering projects. Recently, a lot of research studies were being carried out on the potential use of scrap tyre in engineering applications. Nevertheless, only a limited amount of scrap tyres are used in some civil engineering applications such as earthquake damping, rubber-modified asphalt, concrete filler/aggregate, lightweight structural fill, slope stabilisation, ground erosion mitigation, and soil reinforcement (Edeskar, 2004).

A large number of research studies investigated the engineering properties of tyre derived aggregates (TDA) (e.g. tyre shred, chips and crumbs) including its potential engineering applications (e.g. Edil and Bosscher, 1994; Foose et al., 1996; Masad et al., 1996; Tatlisoz et al., 1998; Lee et al., 1999; Youwai and Bergado, 2003; Ghazavi and Sakhi, 2005; Zornberg et al., 2004; Hataf and Rahimi, 2005; Rao and Dutta, 2006; Lee et al., 2007; Sheikh et al., 2013; Mashiri et al., 2015a and Mashiri et al., 2015b). A few studies found that the addition of tyre crumbs (granulated rubber) in sand reduced the shear strength of sand (e.g. Masad et al., 1996; Youwai and Bergado, 2003; Sheikh et al., 2012). Ahmed (1993) and Zornberg (2004) observed that the behaviour of sand-tyre mixture varied from sand-like to rubber-like with increasing amount of tyres in the mixture. Foose et al. (1996) carried out large scale ring shear tests to evaluate the effect of shredded tyre fragments in reinforcing the sand. They found that shear strength of sand was dependent on the normal stress, shred content and sand matrix unit weight. Rao and Dutta (2006) reported an increase in the apparent cohesion with increase in the shred content based on triaxial testing. Vinod et al. (2015) found that shear strength of sand increased with the addition of tyre shreds. Mashiri et al. (2015) highlighted significant shear strength improvement together with the reduction of dilatancy of sand with the inclusion of tyre chips, especially in sand-rubber behaviour zone where both sand and tyre chips form the skeleton of the matrix material. Recently, Indraratna et al. (2018) reported the potential of a scrap tyre (crumbs) with steel furnace slag and coal wash as an energy absorbing capping layer for transport infrastructure development.

This study evaluates the shear behaviour of sand-TDA mixtures, using large scale direct shear testing and triaxial testing to evaluate the possible benefits of replacing soil with scrap tyre-soil mixtures. Effects of different parameters such as the amount of TDA, confining pressure, relative density, the number of cycles and cyclic shear strain amplitude on the monotonic and cyclic behaviour have been investigated and reported.

2. MATERIALS AND METHODS

In this study, a series of monotonic shear tests were conducted on sand-TDA mixtures. The direct shear tests were carried out in a large scale direct shear box with 300 mm x 300 mm cross-section and 190 mm height. The triaxial tests were carried out on specimens with 50 mm diameter and 100 mm height. The particle size distribution of the beach sand used for the study is shown in Figure 1.

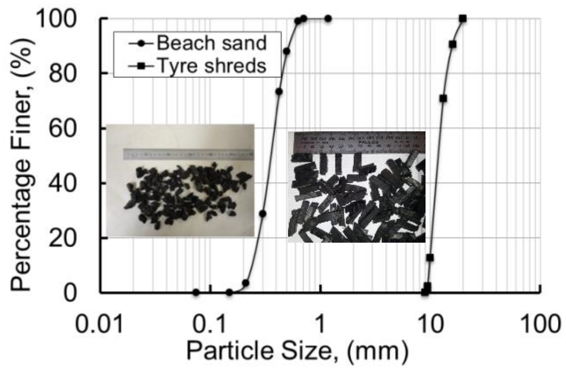

Figure 1 Particle size distributions of Sand and Tyre Shreds (inset: tyre shred and tyre chips)

The specific gravity of the sand was measured as 2.67. The minimum and maximum dry unit weights of sand were 14.60 kN/m^3 and 16.41 kN/m^3, respectively. The scrap tyres in the form of tyre shreds and tyre chips are used for the testing program (see inset of

Figure 1). The size distribution of TDA is presented in Figure 1. The specific gravity of the TDA was measured as 1.13. This is within range of the specific gravities of scrap tyres (1.02 to 1.30) reported by different investigators (e.g., Humphrey et al., 1993; Edil and Bosscher, 1994; Foose et al., 1996; Ghazavi and Sakhi, 2005). The tyre chips having a width of 5 mm (smaller dimension) and an aspect ratio of 4 was selected for the testing purpose.

3. SAMPLE PREPARATION

The sand and tyre shred samples were prepared by thoroughly mixing and placing three layers of sand and tyre shred (TS) (equal mass) in the shear box. Each layer of sand-tyre shred (STS) mixture was compacted in the shear box to achieve the required sand matrix unit weight. The STS mixtures were prepared at a relative density of 75%, corresponding to a sand matrix unit weight of 15.91 kN/m^3. The sand matrix unit weight (γ_m) is defined as:

$$\gamma_m = m_s g / (V_s + V_{vTS}) \tag{1}$$

where, m_s is the mass of sand in t, g is the acceleration due to gravity (9.81 m/s^2), V_s is the volume of sand particles (m^3) and V_{vTS} is the volume of voids of TS (m^3). The tests have been carried out on STS mixtures with different gravimetric percentages of TS (e.g. 0%, 10% and 30%). The gravimetric percentage of TS is defined as the ratio of the mass of tyre shreds to the total mass of sand and tyre shreds. The STS mixtures were sheared at a constant horizontal strain rate of 0.367 mm/min.

Similarly, triaxial specimens (50 mm diameter and 100 mm height) of sand and tyre chips mixtures (STCh mixtures). The STCh mixture was poured into the mould in three equal layers to ensure homogeneity. The specimen was compacted by tamping the walls of the mould to achieve the required relative density of 50%. All the samples were saturated to a B- value > 0.95 using back pressure technique. The specimens were consolidated at different effective confining pressures before shearing. A strain rate of 0.2 mm/min was adopted for all the monotonic shear tests. The monotonic tests were carried out on STCh mixtures with different gravimetric proportion of tyre chips (TCh), χ = 0, 10, 20, 30 and 40% (χ represents the gravimetric proportion of TCh in STCh mixtures) and effective confining pressures.

4. RESULTS ON THE SHEAR BEHAVIOUR OF SAND – TYRE SHRED MIXTURES

Figure 2 shows the effect of tyre shreds on the shear behavior of sand. It is evident from Figure 2 that TS have a significant influence on the shear behaviour of sand. The shear stress of sand increases with the increase in the gravimetric percentage of TS. The increase in the shear stress with TS content is a result of the increased interlocking between sand/tyre shred and tyre shred/tyre shred fragments.

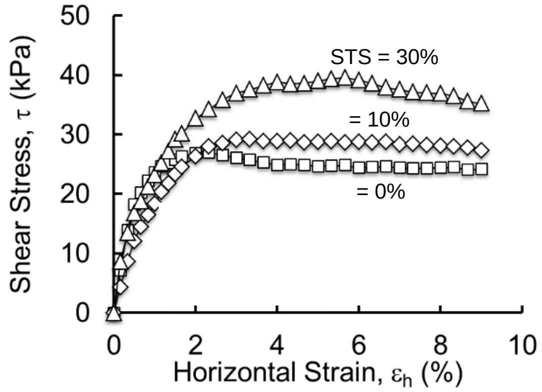

Figure 2 Variation of shear stress with horizontal strain (after Vinod et al., 2015)

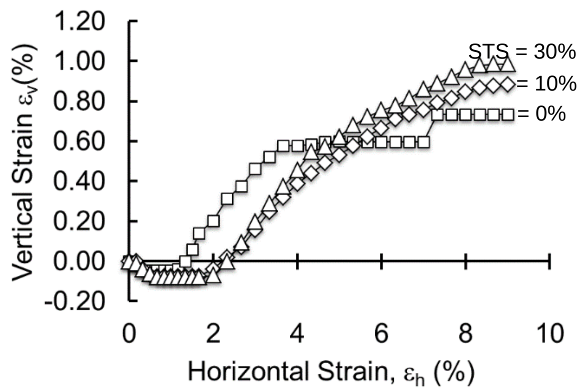

Figure 3 Variation of vertical strain with horizontal strain (after Vinod et al., 2015)

Figure 3 shows the influence of tyre shred on the vertical strain (volume change) behaviour of sand. It is evident that all the samples show an initial compression at early stages followed by vertical expansions during shearing. It is noted that STS mixtures show a higher value of ε_v (or dilation) for $\varepsilon_h > 4\%$.

Figures 4 and 5 show the effect of normal stress on the shear and volume change behaviour of STS mixture. As expected, the stiffness (refers to modulus (shear or young's) in the initial linear elastic portion) and shear stress increase with the increase in the normal stress (Figure 4). Moreover, the horizontal shear strain corresponding to the peak shear stress increases with the increase in the normal stress. It can be noticed that a distinct peak shear stress becomes less prominent with the increase in the normal stress.

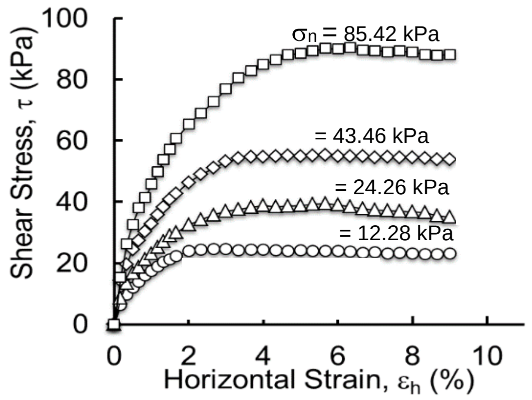

Figure 4 Variation of shear stress with horizontal strain for different confining pressure (after Vinod et al., 2015)

Figure 5 shows the effect of normal stress on the vertical strain for STS (30%) mixture. As anticipated, the vertical strain decreases with the increase in the normal stress. In other words, the dilation of the mixture decreases with the increase in the normal stress.

Figure 6 shows the variation of peak shear stress with normal stress for STS (10%) and STS (30%). Also, presented in this Figure 6, the results of sand-tyre shred mixtures (STS) at γ_m = 16.8 kN/m^3 in Foose et al. (1996) for comparison. It is evident that the direct shear test results from the current study compare well with the experimental results of Foose et al. (1996). It is noted that STS mixture shows a bilinear shear envelope very similar to Foose et al. (1996). For instance, STS (30%) shows two distinct friction angles before and after a normal stress of 24.48 kPa. However, a detailed experimental investigation has to be carried out at low normal stress to confirm the bilinear trend for the higher percentages of TS in STS mixtures. Moreover, the friction angle increases with the increase in the percentage of TS in the mixtures. The increase in the friction angle of the STS mixtures is due to the mobilized interactions between sand-shred, shred-shred and sand-sand (Al-Refeai, 1990).

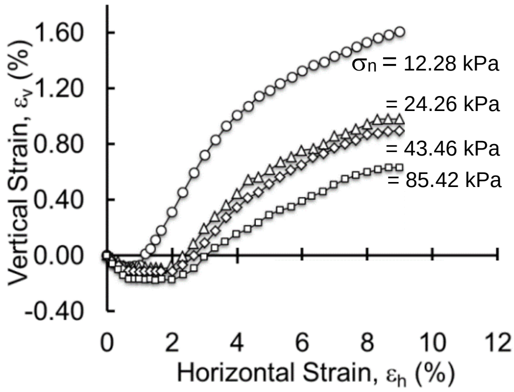

Figure 5 Variation of vertical strain with horizontal strain for different confining pressure (after Vinod et al., 2015)

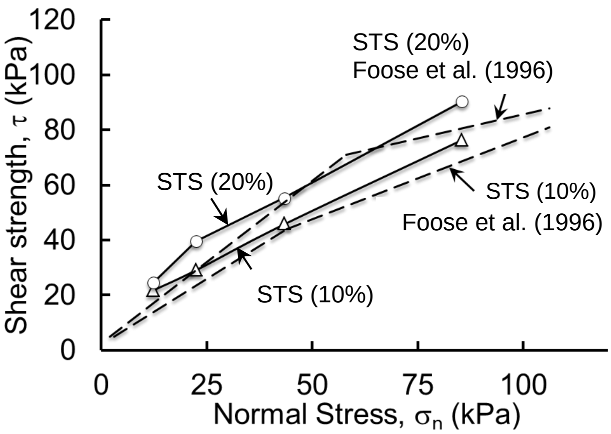

Figure 6 Variation of shear stress with normal stress for sand-tyre shred (STS) mixtures (after Vinod et al., 2015)

5. RESULTS ON THE SHEAR BEHAVIOUR OF SAND – TYRE CHIP MIXTURES: TRIAXIAL

Figure 7 shows the effect of tyre chips on the shear behaviour of sand. It is evident from Figure 7 that the TCh has a significant influence on the shear behaviour of sand. The deviatoric stress and the stiffness of sand is increased with the addition of tyre chips. Figure 8 shows the effect of tyre chips on the volume change behaviour of sand. It is shown that the dilative behaviour of sand decreases with the inclusion of TCh > 10%.

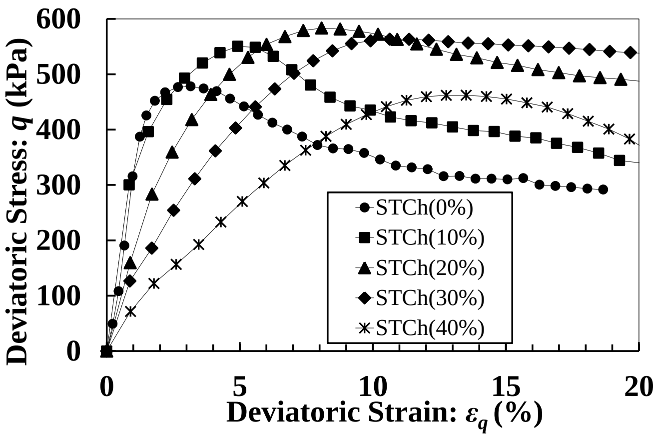

Figure 7 Variation of deviator stress with deviatoric strain for different proportion of TCh (after Mashiri et al., 2015a)

Figure 9 shows the influence of confining pressure on STCh (35%) mixtures during shearing. As expected, the confining pressure has a significant influence on the deviator stress and volume change behaviour. The deviator stress increases and volume change decreases with the increase in the confining pressure (Figure 10).

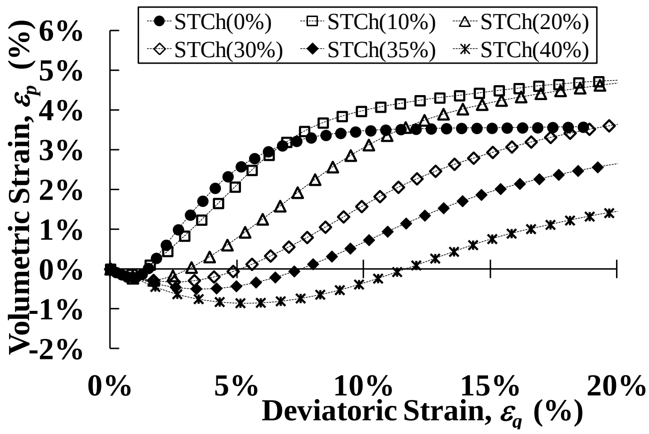

Figure 8 Variation of volumetric strain with deviatoric strain for different proportion of TCh (after Mashiri et al., 2015a)

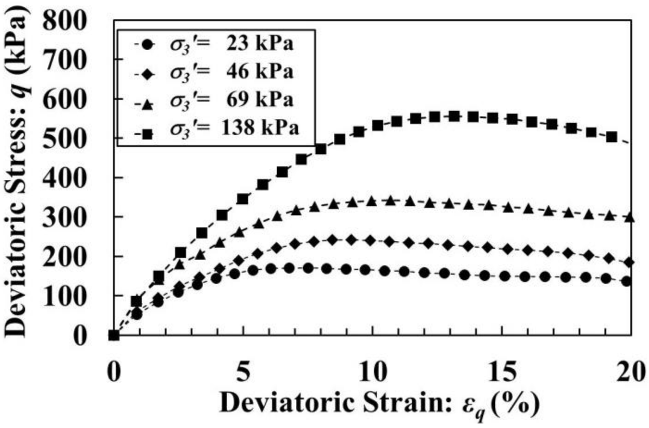

Figure 9 Variation of deviatoric stress with deviatoric strain for different confining pressure (after Mashiri et al., 2015a)

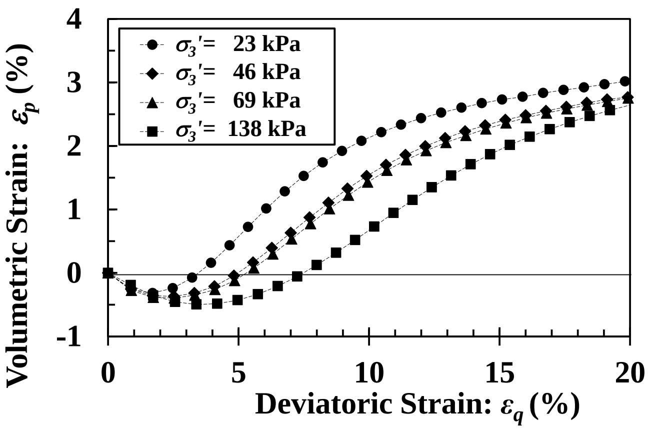

Figure 10 Variation of volumetric strain with deviatoric strain for different confining pressure (after Mashiri et al., 2015a)

Figure 11 shows the variation of peak shear strength and constant stress ratio with normal stress for STCh (35%). The constant stress ratios correspond to a deviatoric stress at $\varepsilon_q > 20\%$. It is evident from Figure 11 that the peak shear stresses and constant stress ratio envelope increases linearly with normal stress. Both the curves show a cohesion intercept (c_0) when extrapolated to lower confining pressure. However, more experimental data is required at very low confining pressure to confirm this trend. However, this behaviour is consistent with the results reported in earlier researcher studies (e.g. Masad et al.,1996; Zornberg et al., 2004).

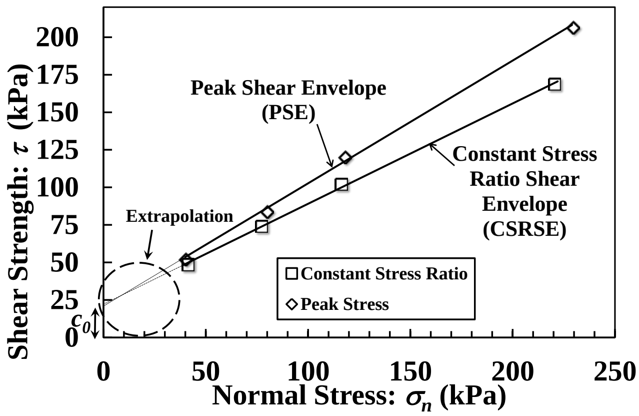

Figure 11 Typical shear envelope for STCh mixtures (after Mashiri et al., 2015a).

5. CONCLUSIONS

This paper presents the laboratory test results on the shear and volume change behaviour of sand-TDA mixtures. It was found that the tyre shreds (TS) have a significant influence on the shear and vertical strain behaviour of sand. The shear stress of sand increases with the increase in TS. For example, a 47% increase in peak shear stress was observed with the addition of TS = 30% at σ_n = 24.48 kPa. A more ductile behaviour was observed with the addition of TS. Moreover, the friction angle increases with the increase in TS. A bilinear shear envelope has been observed for the STS (30%). However, more data are required for adequate validations.

The monotonic tests clearly show that the shear and volumetric strain behaviour is influenced by the amount of TCh and confining pressure. The deviator stress increases with the increase in the amount of TCh up to a gravimetrric propotion of 35%. The dilation of sand is also reduced significantly with the addition of TCh. The peak shear stresses and constant stress ratio exhibit a linear relationship with the normal stress.

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