An Investigation of Waste Tyre Shreds as Reinforcement Material for Typical South African Sandy Soils

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ABSTRACT

End-of-life tyres are increasingly presenting waste management challenges owing to the large volumes disposed of annually. These waste tyres possess unique properties that can once again reused in a sustainable materials stream to supplement the resource intensive geotechnical engineering industry. This study investigates the effect of waste tyre shreds randomly included in typical South Africa sands to enhance the engineering properties. A series of shear strength tests were performed on the sand-tyre shred mixtures of Cape Flats and Klipheuwel sands using a large direct shear box of dimensions 300mm x 300mm. Two relative sizes of tyre shreds, 10-15 mm and 50-60 mm, were mixed with sand various concentrations by weight. The results revealed a general increase in the shear strength parameters of both types of sand on inclusion of the tyre sheds. The possibility of using waste tyre shreds in geotechnical applications specifically as lightweight fill and reinforcement material for the construction of highway embankments could provide an alternative use for the discarded tyres.

1. INTRODUCTION

The increasing number of motor vehicles all over the world has resulted in large quantities of waste tyres generated annually. The bulk of these discarded tyres, mostly destined to landfills, are currently stockpiled and dumped in open spaces, posing a hazard to the environment, as they are a potential source of fires and provide breeding grounds for mosquitoes and other pests. Management of waste tyres has, for the most part, proved to be a major challenge because of the large volumes and quantities that are disposed of. There is therefore a growing need to find alternative uses of post-consumer tyres for purposes of waste minimisation and resource recovery. As a waste minimisation measure, discarded tyre material is increasingly being re-used in the construction industry for infrastructure projects such as highway embankments. Tyres are made of rubber and therefore possess favourable qualities such as light weight, high elastic strength, are practically non-destructible, highly permeable and are easy to compact (Ahmed, 1992) encouraging their use as a construction material. Shredded waste tyres are now used as subgrade reinforcement for constructing roads over soft soils, as aggregate in leach beds for septic systems, as an additive to asphalt, as a substitute for leachate collection stone in landfills, and as sound barriers (Foose et al, 1996).

Extensive research has been conducted to assess the engineering behaviour of different tyre shreds-soil composites to facilitate their use in construction and provide the various parameters required for design. Proctor tests conducted by Bosscher et al. (1993) and Humphrey and Manion (1992) revealed that the unit weight of the mix was controlled by the quantity of sand in the mixture. Ahmed (1993) undertook large scale triaxial tests on tyre shred-soil mixtures and established that a concentration of 38% tyre shreds by weight achieved favourable engineering properties such as good compaction characteristics, high shear strength, low unit weight, good drainage characteristics and adequate compressibility. Balachowski and Godtteland (2007) found that an optimum shred dosage of 30% achieved maximum shear strength while Youwai and Bergado (2003), Zornberg et al. (2004) and Bergado et al. (2005) reported a concentration of 35% tyre shred by weight was the optimum for reinforcement of granular soils. Vinot and Singh (2013) performed strength tests on tyre shred-sand composite using the large direct shear box reporting an optimum shred content of 30%. Most of the studies have, however, been undertaken outside of the South African context and it is essential to understand the engineering behaviour and response of local soils on addition of the tyre material. The objective of the study was therefore to investigate the reinforcing effect of tyre shreds in typical South African sands on shear strength parameters of the soils. A proper assessment of the mechanical behaviour of tyre-shred sand mixtures and successful implementation could lead to more utilization of waste tyres in the civil engineering industry. The re-use of this tyre material for soil reinforcement especially in large earthwork projects will consume vast quantities of the recycled tyres and provide cost effective construction of even more robust earth structures.

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2. MATERIALS AND EQUIPMENT

2.1 Materials

2.1.1 Soil Material

The soils used in the study were Cape Flats sand and Klipheuwel sand obtained from Philippi Quarry in Cape Flats region and Kerfontein quarry-Malmesbury in the Western Cape. Cape Flats sand is classified under Unified Soil Classification System (USCS) as a uniformly graded sand while Klipheuwel sand classified as well-graded sand with little fines. Table 1 shows the soil physical properties of both the sands.

Table 1: Mechanical Properties of the sands

Soil Property	Cape Flats Sand	Klipheuwel Sand
Specific gravity, G_s	2.66	2.64
Particle Range (mm)	0.075-1.18	0.075-2.36
Mean Grain Size, D_{50}	0.5	0.72
Maximum Dry Density (Mg/m^3)	10.5	10
Angle of friction ($^\circ$)	40.6	44.6

2.1.2 Waste Tyre Material

2.2 The tyre waste used was in the form of shreds comprising two ranges of sizes, 10-15mm and 50-60mm (Figure 1), sourced from the South Africa Tyre Recyclers plant based in Atlantis, Western Cape. The shredding of the different sizes at the plant was done through primary and secondary process to produce the different sizes which were then separated manually by a grading process using laboratory sieve analysis. From shear strength tests undertaken on the shredded tyre material, the strength parameters of friction angle obtained were 22.1° and 24.9° for the 10-15mm and 50-60mm sizes while cohesion values were 13.3kPa and 19.4 kPa respectively.

Figure 1: a) 10-15 mm size tyre shreds   Figure 1: b) 50-60 mm size tyre shreds

2.2.1   2.2 Test Equipment

The laboratory strength tests for the study were conducted using automated large direct shear equipment, the ShearTrac-III (Figure 2). The ShearTrac-III is a load frame system used for running fully automated direct shear tests and it consists of a square shear box of dimensions 305 mm x 305 mm and a height of 200 mm. The box is horizontally split into two halves fixed together and held tightly in place by screws that pass vertically through the walls of the upper half and into the lower box. The box is placed in a rectangular brass container so designed that the bottom half of the shear box is rigidly held and prevented from moving laterally to ensure that the bottom half of the shear box slides relative to the upper half box. The ShearTrac-III loading frame contains two embedded control systems and components that generate the vertical and horizontal forces on sample with a maximum axial load capacity of 44 kN. It is fitted with transducers to measure the vertical and horizontal forces and displacements with maximum horizontal and vertical displacement of 100 mm and 90 mm respectively. ShearTrac-III operates as an intelligent loading system using feedback from transducers to provide real-time control of the load frame. The system uses shear software which runs the test and receives the data from vertical or horizontal load and displacement sensors. Two LCDs and keypads on the front panel allow manual control of the operation of the load frame and monitor the system status.

Figure 2: Automated large direct shear testing system (Geocomp ShearTrac-III Manual)

3.   METHODOLOGY

3.1   Sample Preparation

The soils were oven dried and then mixed with the tyre shreds at concentrations for 10%, 20%, 30%, 40% and 50% by weight for both shred sizes of 10-50 mm and 50-60mm. The control tests for the study comprised the unreinforced specimens of only the clean sands as well as pure tyre shreds samples (100% tyre sheds). The composite mixtures of the sand-tyre sheds specimens were prepared in accordance with Section 7.5 of the ASTM D3080-2003. A pre-calculated quantity of each type of sand was mixed with the required amount of tyre shreds from each single size at the different shred dosages to generate a relatively homogeneous mixture. The pre-mixed materials were then carefully placed into the shear box to avoid the segregation of tyre shreds from the sand and compacted in three layers till the box was filled with the sand-tyre shred composite (Figure 3). The process of compaction of the specimen in the box was carried out by applying to 25 blows to each of the three layers using a hand tamper having a standard weight of 2.5 kg and a free fall height of 300 mm. The compacted layer boundaries were such that there was no alignment with the shear plane defined by the contact between the two halves of the shear box.

Figure 3: Specimen of compacted tyre shred-sand composites placed in the shear box

3.2 Testing Process

Direct shear strength tests were performed under consolidated drained conditions in accordance with ASTM D3080-2003 standard. The shear box containing the compacted sample was placed in the rectangular brass container of the frame of testing machine (Figure 4) and tightened to prevent any unnecessary movements during the test that may cause disturbance. Before the test was run, the upper box was slightly lifted off from the lower half to provide a small clearance gap between the two halves. This was to avoid friction between two halves of shear box from contributing to shearing resistance values of the specimen during the test. Three repeatability tests to assess consistency of the results were conducted on tyre shreds-sand composites containing 10-15 mm shred size with the shred content of 30% by dry mass at a normal pressure of 50 kPa. The maximum shear stresses obtained were 60.8 kPa, 61.2 kPa and 60.8 kPa at peak horizontal displacements of 11 mm, 11.1 mm and 10.9 mm respectively thus confirming the reliability and reproducibility of experimental data from the tests.

For each of the unreinforced sand, pure tyre shreds and blended tyre shred-sand material, three similar samples were prepared and tested at three different normal applied pressures of 50, 100 and 200 kPa in order to determine the shear strength parameters. Running of the tests comprised two phases, the consolidation phase and the shear phase. The first phase of the test is consolidation of the specimen in the shear box by applying normal confining pressure. This was followed by the shearing phase at which a controlled constant shear load was applied at a rate of 1.3 mm/min to move the bottom half shear box by sliding relative to the upper fixed box. The shear rate used for shearing tyre shreds sand mixtures was as suggested by Foose et al. (1996). The computer loaded or unloaded the load frame until the readings from the transducers equal the values required to meet the test specifications. The test conditions were set and stored in a template file that was created before running the test to store the generated data. All test data was processed by the in-built soil testing software and stored in files that could be accessed through the computer connected to the machine. The data such as shear stresses, horizontal and vertical displacements stored in tabular form and in figures were exported to excel sheets for analysis. A total of 75 direct shear tests on the various specimens were undertaken.

Figure 4: Compacted sample shear box placed in load frame for testing

4. RESULTS AND DISCUSSIONS

4.1 Peak Shear Stresses

Load displacement curves for the tests undertaken were used to obtain maximum shear stresses achieved by each test specimen at different applied vertical pressures (normal stresses) of 50 kPa, 100 kPa and 200 kPa (Table 2). These were peak shear stresses for the tests on the unreinforced (0%) and pure tyre shreds (100%) samples as well as the tyre shred-sand specimens with different shred dosages of 10%, 20%, 30%, 40% and 50%. In the study all the peak shear stresses occurred at a horizontal displacement less than 40 mm. However, for the graphs the exhibited no peaks, the failure was taken to correspond to 15% shear strain corresponding to the displacement of 45 mm. As shown in Table 2, the shear stress of sand was influenced by the amount of tyre shreds added. The addition of shreds to both Cape Flats and Klipheuwel sands improved their peak shear stresses up to an optimum concentration beyond which it decreased. Specifically, the Cape Flats sand reinforced with 10% tyre shred by dry weight showed an improvement in its peak shear stress which varied as applied normal stresses increased. The peak shear stress was enhanced from 49.9 kPa for unreinforced sand to 53.2 kPa in the reinforced sand. Higher contents of tyre shreds in the composite resulted in a better degree of strengthening as indicated on obtaining a maximum shear resistance of 57.8 kPa from the composite containing 20% tyre shreds in the Cape Flats sand tested at the applied normal pressure of 50 kPa compared to that from 10% which was 53.2 kPa at the same normal pressure. It can be noted by increasing the tyre shreds content in the mixture, a high shear displacement was required to mobilize the peak shear stress. In all concentrations of tyre shred, the optimum tyre shred content for all applied normal pressures attaining the maximum shear stress was 30%. A similar trend was observed for tyre shred-Klipheuwel sand composite in which the optimum tyre shred content was also 30%. The higher tyre shred content and normal loading enhanced the degree of interlock within the sample which contributed to the improved peak shear stress of the sand-tyre shred composite. Furthermore, the shear stress development for long tyre shreds (50-60 mm) was observed to be higher compared to that of the small size tyre shreds (10-15mm) sand composites. The difference in improvement could be attributed to the long tyre shreds having a larger contact area with sand. These long randomly distributed tyre shreds in sand acted as anchors in the shear zone and thus increased the shear resistance compared to smaller size tyre shreds. In all tyre shreds sand composite comprising either 10-15 mm or 50-60 mm tyre shreds, it was thought that the random inclusion of tyre shreds in sand positioned in the shear zone either as vertically and inclined at an angle contributed to shear reinforcement mechanism, thus increasing the maximum resistance of sand during shear.

Table 2: Peak Shear Stresses attained during direct shear testing

Peak Shear Stresses (kPa)												
Tyre Shred Content	Cape Flats Sand						Klipheuwel Sand					
	Applied Normal Stresses						Applied Normal Stresses					
	50 kPa		100 kPa		200 kPa		50 kPa		100 kPa		200 kPa	
Shred	10-15	50-60	10-15	50-60	10-15	50-60	10-15	50-60	10-15	50-60	10-15	50-60
0%	49.9	49.9	88.5	88.5	177.8	177.8	59	59.1	96	96	204.7	204.7
10%	53.2	55.6	98.9	104.1	182.6	202.8	62.9	61.9	109.8	110	221.8	227.7
20%	57.8	60.8	100.8	117	181.8	199.6	63.1	63.9	111.7	109.6	216.1	226.2
30%	61.1	77.9	101.9	125.8	185.9	208.9	64.7	77.6	117	135.3	220.7	230
40%	60.8	65.2	102.6	133.6	183	205.9	65.1	81.8	108.2	126.4	205.7	229.9
50%	55.3	62.5	94.5	127.2	174.9	198.6	57.9	72	98.8	121.2	179.2	219
100%	33.1	43.9	54.8	64.1	94.4	112.9	33.1	43.9	54.8	64.1	94.4	112.9

4.2 Mohr-Coulomb Failure Envelopes

The peak shear stresses at different applied vertical pressures (normal stresses) of 50 kPa, 100 kPa and 200 kPa were used to generate coulomb failure envelopes shown in the graphs in Figures 7 and 8. The inclination of the failure envelopes to the horizontal axis represented the angle of internal friction (φ') of the composite while the intercept on the vertical axis was the apparent cohesion (c'). The cohesion observed was due to the nonlinear variation of maximum shear stress at failure for the different concentrations of tyre shred-sand composites (Foose et al., 1996, Ahmed, 2004). Klipheuwel sand had a higher angle of internal friction (44.6°) than that of Cape Flats sand (40.6°)owing to the angular shape and a high coefficient of uniformity Klipheuwel sand particles (Cu = 7) resulting in better interlocking as compared to Cape Flats sand with Cu = 1.7. Tests on pure tyre shreds of size 10 -15 mm yielded a friction angle of 22.1° and a cohesion of 13.3 kPa while 50-60 mm tyre shreds achieved values of 24.9° and 19.4 kPa respectively. The friction angle increased from 44.6° for unreinforced Klipheuwel sand to 46.9° for 10-15mm tyre shred-sand mixture at 10% tyre shreds content and decreasing with higher concentrations. On addition of the 50-60 mm tyre shreds, the friction angle was enhanced at dosages of 40% for Klipheuwel beyond which lower values were observed. The maximum value was obtained at a tyre shred concentration of 10%. In general the friction angle was enhanced upon adding tyre shreds to the two sands and a maximum value of friction angle was attained at 10% shred content giving values of 44. 5° and 48.1° compared to 40.6° and 44.6° from unreinforced Cape Flats and Klipheuwel sands respectively.
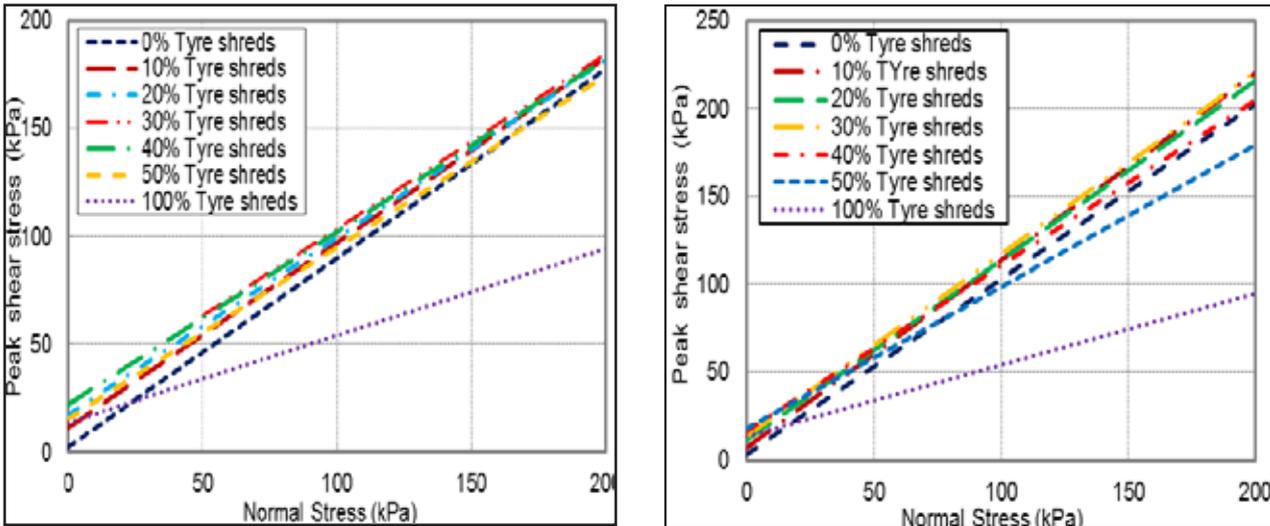
Figure 5: Mohr-Coulomb Failure Envelopes for a) Cape Flats sand and b) Klipheuwel sand on inclusion of 10-15 mm tyre shreds
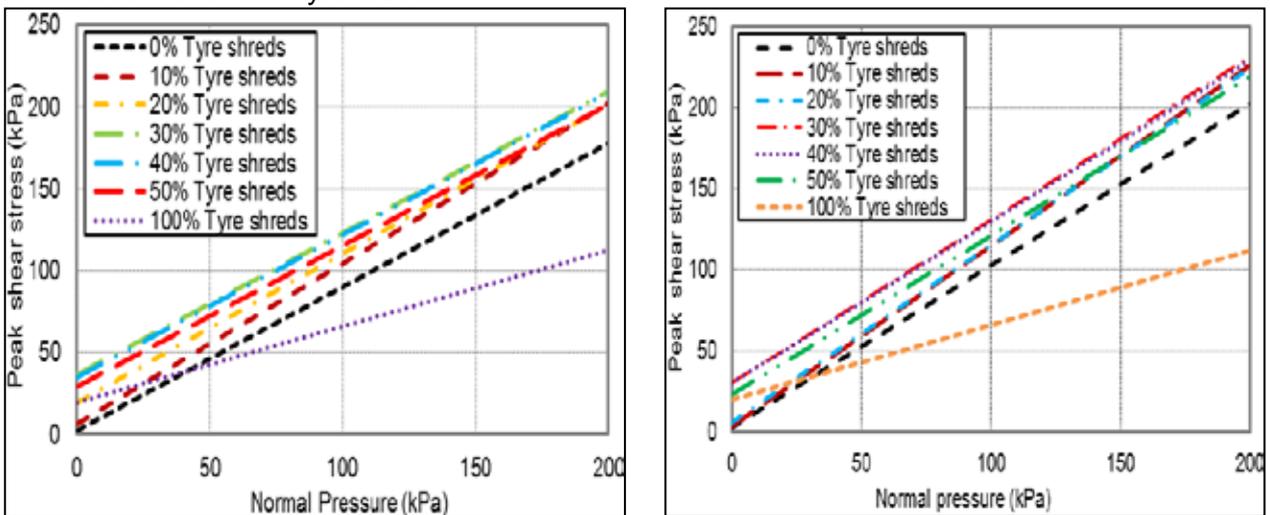

Figure 6: Mohr-Coulomb Failure Envelopes for a) Cape Flats sand and b) Klipheuwel sand on inclusion of 50 -60 mm tyre shreds

4.3 Effect of tyre shreds on friction angle and cohesion of sand

An analysis of the shear strength parameters of friction angle and cohesion of the specimens tested determined from the failure envelopes shown in Figures 5 and 6 was undertaken to evaluate the variation of the parameters on inclusion of the tyre sheds at different concentrations. The Cape Flats sand-tyre shred composite showed a better improvement in cohesion compared to Klipheuwel sand-tyre shred mixtures which achieved higher values of friction angle (Figure 7). As shown in Figure 7a, the 10-15 mm shred size the concentration of 35% shreds gave the maximum values of cohesion as 22.5 kPa and 12.9 kPa for Cape Flats sand and Klipheuwel sand composites respectively. For 50-60 mm shred size, the values of cohesion given by 30% shred dosage were 36.5 kPa and 30.3 kPa. The longer 50-60 mm tyre shreds gave the composite a higher cohesion than the shorter 10-15 mm shreds. Figure 7b shows the various values of friction angles obtained from all tyre shreds sand composites which were 46.9° for Klipheuwel sand with addition of the 10-15 mm size shreds and 48.1° for the 50-60mm tyre shreds. Cape Flats sand on the other hand exhibited lower friction angles when 10 -15 mm size shreds were added but the inclusion of the longer 50-60 mm shreds achieved a higher friction angle of 44.5°. All the maximum values were obtained at a tyre shred concentration of 10% which was in agreement with the percentage content reported by Black and Shakoor (1994), Mohmoud (2004), Vinot and Singh (2013). The difference in level of enhancement for the mixtures containing 10-15 mm and 50-60 mm tyre shreds could be due to the better reinforcing effect of the long shred size i.e. 50-60 mm long in shear zone which contributed to the high increase in shear resistance of sand compared to 10-15 mm shred size.
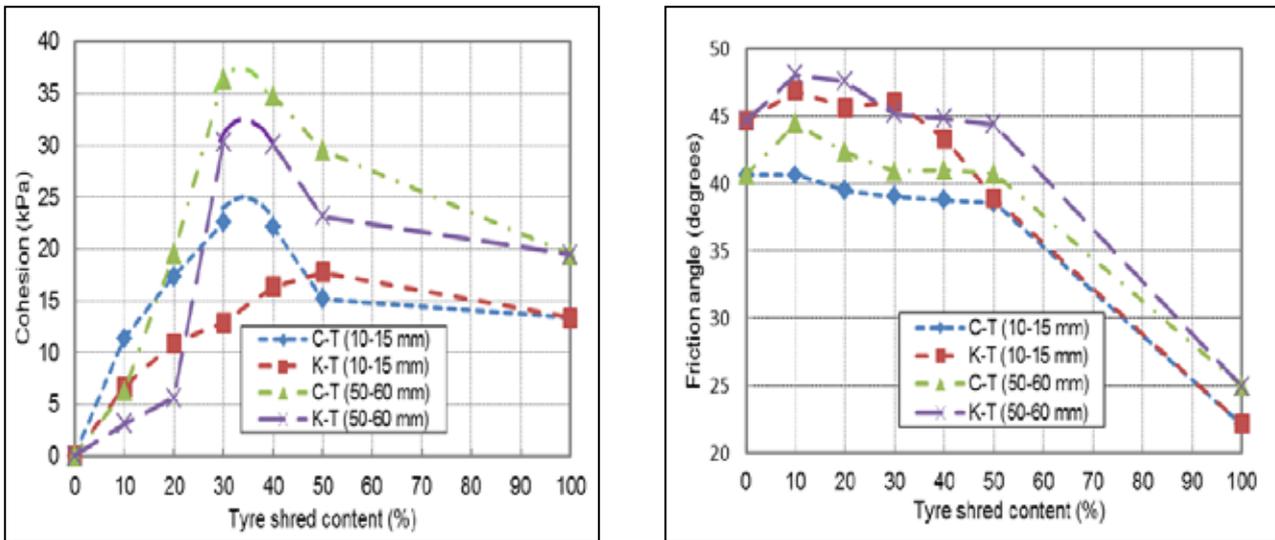
Figure 7: Effect of tyre shred content on (a) Cohesion and (b) Friction angle of Cape Flats sand (C-T) and Klipheuwel sands (K-T)

4.4 Effect of tyre shreds on shear strength of sand

The effect of the tyre-shreds on overall shear strength of the sand composite which is a mathematical combination of the friction angle and cohesion was evaluated. The results are presented the graphs in Figure 8 from which a significant improvement of shear strength was observed on the random inclusion of the tyre shreds in both Cape Flats and Klipheuwel sands with highest values obtained at a tyre shred content of 30%. This was similar to the percentage content reported by Balachowski and Gotteland (2007); Tanchaisawat et al. (2008); Singh and Vinot (2011). Beyond the 30% optimum concentration, there was a reduction in the shear strength. Furthermore, the longer tyre shred seemed to provide a better improvement compared to the smaller shreds. As shown in Figure 8a, for the tyre shred dosage of 30% in Cape Flats sand, the shear strength obtained increased from 63.1 kPa for the 10-15 mm size tyre shreds to 79.8 kPa for the 50-60 mm shred size at an applied normal stress of 50 kPa. For the normal stresses of 100 kPa, the increase was from 103.6 kPa to 123.1 kPa and for 200 kPa, the shear strength value changed from 184.7 kPa to 209.8 kPa. For Klipheuwel sand (Figure 8b), the value for a 30% tyre shreds content varied from 64.8 kPa for 10-15mm tyre shred size to 80.6 kPa for 50- 60mm shred size at 50 kPa, 116.8 kPa to 130.9 kPa at 100 kPa and 220.7 kPa to 231.5 kPa at 200 kPa. These improved values of shear strength suggest that mobilisation of tensile resistance by the tyre shreds in the sand tyres during shear resulted in reinforcement mechanism with in the soil leading to an overall increase strength of the sand-tyre shred composite.
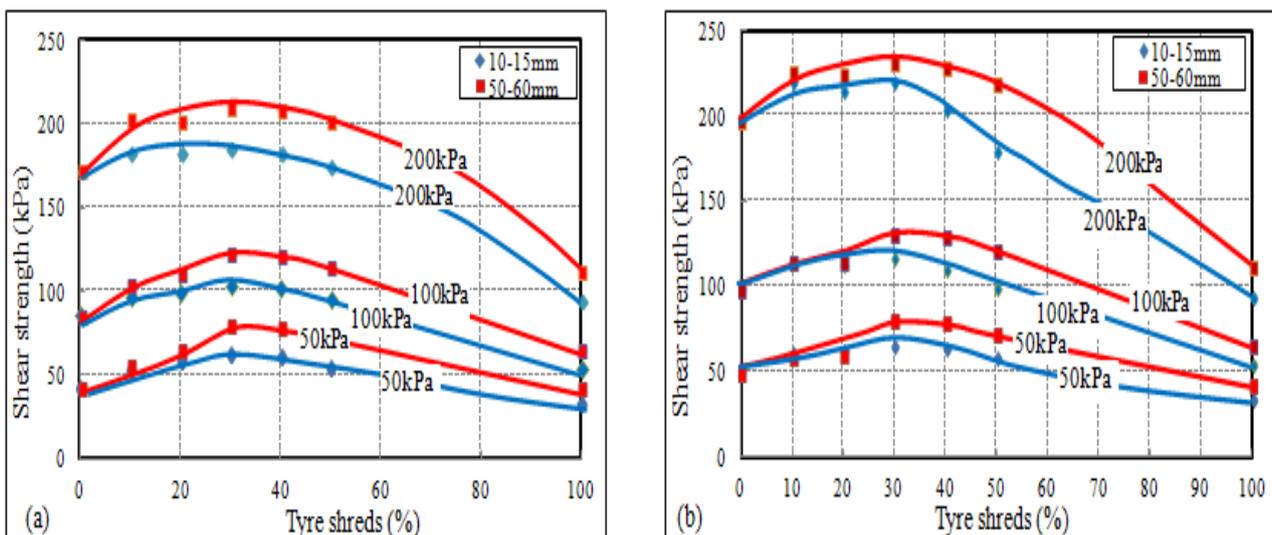

Figure 8: Shear strength variation with the two tyre shred sizes and applied normal pressures for (a) Cape Flats sand (b) Klipheuwel sand

5. CONCLUSION

The shear strength behaviour of tyre shreds mixed with typical South African sandy soils, Cape Flats sand and Klipheuwel sands was investigated in this study. Two relative sizes of tyre shreds, 10-15 mm and 50-60 mm were added to the soils at concentrations of 10%, 20%, 30%, 40% and 50% by dry mass. The various composite specimens were then tested using an automated large-scale direct shear box to obtain the shear strength of the mixture. The effect of the inclusions on the shear strength properties of the soil was examined by evaluating the strength of the composite. The results revealed that addition of tyre shreds to the sands generally increased its shear strength parameters, friction angle and cohesion and ultimately the overall shear strength which is the mathematical combination of the two different parameters. The extent of improvement was however influenced by both the relative size and concentration of tyre shreds. The maximum cohesion and friction angle were achieved at 35% and 10% shred content while the highest overall shear strength was observed at a concentration of 30% for both tyre shred sizes. However, the longer tyre shreds might be preferable as reinforcement material since they achieve relatively higher shear strength values than the shorter size shreds on inclusion in soils and the shredding has less energy requirements.

The improvement of strength parameters of the sand-tyre shred composite is attributed to the mobilisation of the tensile resistance of the tyre shred material during shear resulting in reinforcement of sand by absorbing the applied shear load. The composite material fails at higher peak stresses and can therefore take up more load than the unreinforced material. Further research in aspects such as the proper mix design of the composite and construction methodology would encourage massive re-use of tyre waste in the construction industry thereby providing an alternative means of recycling the multitudes of tyre waste generated annually.

ACKNOWLEDGEMENTS

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