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Shear Strength Characteristics of Sand-Particulate Rubber Mixture

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***Abstract*—**Waste tyres is an ongoing global problem that has a negative effect on the environment. Waste tyres are discarded in stockpiles where they provide harm to the environment in many ways. Finding applications to these materials can help in reducing this global problem. One of these applications is recycling these waste materials and using them in geotechnical engineering. Recycled waste tyre particulates can be mixed with sand to form a lightweight material with varying shear strength characteristics. This research further investigates the inclusion of particulate rubber to sand and whether it can increase or decrease the shear strength characteristics of the mixture. For the experiment, a series of direct shear tests was performed on a poorly graded sand with a mean particle size of 0.32 mm mixed with recycled poorly graded particulate rubber with a mean particle size of 0.51 mm. The shear tests were performed on four normal stresses 30, 55, 105, 200 kPa at a shear rate of 1 mm/minute. Different percentages of particulate rubber content were used in the mixture i.e., 10%, 20%, 30% and 50% of sand dry weight at three density states namely loose, slight dense, and dense state. The size ratio of the mixture, which is the mean particle size of the particulate rubber divided by the mean particle size of the sand, was 1.59. The results identified multiple parameters that can influence the shear strength of the mixture. The parameters were: normal stress, particulate rubber content, mixture gradation, mixture size ratio, and the mixture's density. The inclusion of particulate rubber to sand showed a decrease to the internal friction angle, and an increase to the apparent cohesion. Overall, the inclusion of particulate rubber did not have a significant influence on the shear strength of the mixture. For all the dense states at the low normal stresses 30, and 55 kPa, the inclusion of particulate rubber showed a slight increase in the shear strength where the peak was at 20-30% rubber content of the sand's dry weight. On the other hand, at the high normal stresses 105, and 200 kPa, there was a slight decrease in the shear strength.

***Keywords*—**Direct shear, granular material, sand-rubber mixture, shear strength, waste material.

I. Introduction

DISCARDED tyres are a worldwide problem. Every year, there are approximately one billion tyres discarded worldwide. Throughout the years, this number has increased gradually and is expected to continue increasing in years to come [1]. The increase in the need for vehicles eventually leads to an increase in the number of waste tyres. In 2009-10, there were about 48 million equivalent passenger unit (EPU) waste tyres in Australia. 66% of these tyres were discarded to landfills or dumped illegally in stockpiles, 16% were recycled domestically, and 18% were exported [2].

Waste tyres are non-biodegradable and are gathered up in stockpiles not only causing an unpleasant site to see but also causing pollution and a threat to the environment due to their flammable qualities potentially causing fire hazards. Tyre fires can cause a toxic smoke effecting the air quality, and visibility in the surrounding area as shown in Fig. 1 [3], [4].

Fig. 1 Environmental impact of burning waste tyres [4]

The usage of waste tyre rubber in engineering applications can help in reducing the global waste tyre disposal problem. Table I shows a list of possible usages of recycled rubber in Engineering applications. Rubber tyres can be processed to a variety of sizes including shreds, chips, particles or fine powder [5], [6]. Rubber tyres have existing properties that make it an appealing material to be used in engineering applications such as its high durability, high permeability, and low bulk density [7].

TABLE I
RECYCLE RUBBER USAGE IN ENGINEERING APPLICATION

Rubber Usage	Reference
lightweight material as a backfill in retaining structures	[8]-[10]
Usage in road construction to reinforce soft soil	[8], [11]
Slope stabilization	[10], [12]
Aggregates in landfill leach beds	[13]
Additive to Asphalt	[11], [13]
Freezing depth limiter	[14]
Vibration isolation	[15]
For low strength but ductile concrete	[15]

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II. Background

The granulated rubber can be defined as particulate rubber made up of non-spherical particles with dimension less than 12 mm. It is also often referred to as rubber crumbs. Recycled rubber can come in different sizes and shapes as summarized on Table II.

TABLE II
RUBBER PARTICLE SIZE NOMENCLATURE ACCORDING TO [5] AND [6]

Nomenclature	Description	Size
Tyre Shreds	Pieces of scrap tyres that have a basic geometrical shape	50 to 305 mm
Tyre Chips	Pieces of scrap tyres that have a basic geometrical shape - have most of the wire removed	12 to 50 mm
	Particulate Rubber	
Granulated Rubber	Mainly composed of non-spherical particles	Below 425 µm to 12 mm
Ground Rubber	Mainly composed of non-spherical particles	Below 425 µm to 2 mm
Powdered Rubber	Mainly composed of non-spherical particles	Below 425 µm

Studies showed that adding tyre shred to the sand until a specific percentage can increase the shear strength of the tyre shred-sand mixtures [13], [16]-[19]. Similar results were found with the rubber chips where the shear strength of the sand-chips mixture increased with rubber chips until a specific percentage [20], [21]. For the granulated rubber, contradicting results were found where some research found that the shear strength of the mixture decreased as the granulated rubber increased [22], [23], while other research found that the shear strength increased as the granulated rubber increased [24]-[26].

Many studies [22]-[26] investigated different ways of using crumb tyre rubber as reinforcements into soils and whether the addition of crumb to soils provided higher or lower shear strength. The present study aims to investigate the influence of: particulate rubber (PR) content, PR size, normal stress, and density of the mixture on the shear strength characteristic.

III. Experimental Study

A. Material

A local poorly graded sand provided by La Trobe University with a subangular shape and a Heywood Circularity Factor (HCF) of 1.10 was used in this experiment. The HCF is defined as:

$$HCF = \frac{Particle\ perimeter}{2 \times \sqrt{\pi \times Particle\ area}} \quad (1)$$

The specific gravity (G_s) of the sand was 2.57. The minimum and maximum density was 1507 kg/m^3 and 1751 kg/m^3 respectively. The maximum density was obtained using the vibratory table [27]. The mean particle size (D_{50}) was 0.32 mm.

Two different sizes of PR were provided by Tyre Cycle Company in Melbourne, Victoria. The PR was a compressible flaky angular shape with an HCF of 1.38. The specific gravity of the PR was 1.08. The D_{50} of the two PR was 0.51 mm and 1.67 mm respectively. The size ratio S_R for the two PR sizes were 1.59 and 5.22 respectively. Fig. 2 displays typical sample and SEM images of the used particulate material. It can be seen from Table III that as we add more PR to sand, the coefficient of uniformity (C_U) and the coefficient of curvature (C_C) increased while the G_S decreased. The particle size distribution curve in Fig. 3 was obtained using a sieve analysis following the Australian standard.

TABLE III
ENGINEERING PROPERTIES OF SAND AND PR

	Sand	PR-A	PR-B	SPRA10	SPRA20	SPRA30	SPRA50
D_{10} (mm)	0.17	0.19	0.93	0.18	0.18	0.18	0.18
D_{30} (mm)	0.25	0.37	1.37	0.25	0.26	0.26	0.28
D_{50} (mm)	0.32	0.51	1.67	0.33	0.34	0.35	0.39
D_{60} (mm)	0.36	0.58	1.81	0.37	0.38	0.40	0.45
C_U (mm)	2.04	3.04	1.94	2.11	2.18	2.26	2.49
C_C (mm)	0.96	1.19	1.10	0.97	0.97	0.98	0.99
G_s	2.57	0.99	1.08	2.42	2.27	2.12	1.82
S_R	-	1.59	5.22	1.59	1.59	1.59	1.59
HCF	1.10	1.38	-	-	-	-	-

*HCF calculated on the average of 50 particles

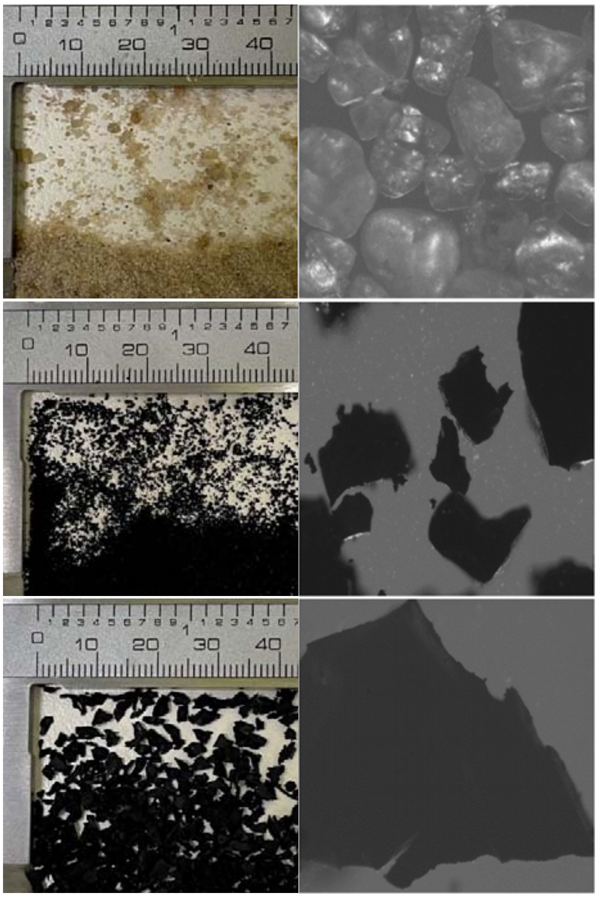

Fig. 2 Typical Sample and SEM image of the used particulate material

B. Preparation

The sample was prepared by adding rubber percentages of 10%, 20%, 30%, and 50% by dry weight of the sand. With regards to the sample density, the sample was divided into three states, the loose, slight dense, and dense states. Each state was divided into multiple layers with the same amount of sand and

PR. To avoid segregation, each layer was placed in a separate container and mixed thoroughly before pouring it in the mould as shown on Fig. 4. In the loose state, the sample was carefully placed from a very low height (0 high distance) using a spoon as a tool, while in the slight dense and dense states it was shown that the proctor compaction technique is the most suitable technique for Sand-PR mixture [28]. Hence, the sample was prepared by the dry tamping method (dynamic compaction) where each state has the input compaction energy as follows: 165 kPa for slight dense state and 825 kPa for the dense state. The compaction energy was calculated using the equation:

$$E = \frac{(No.of\ blows\ per\ layer) X (No.of\ layer) X \\ (weight\ of\ hamer) X (height\ of\ drop\ of\ hamer)}{volume\ of\ mold} \quad (2)$$

An aluminum piece was designed and assembled in the lab to compact the specimen as shown on Fig. 4.

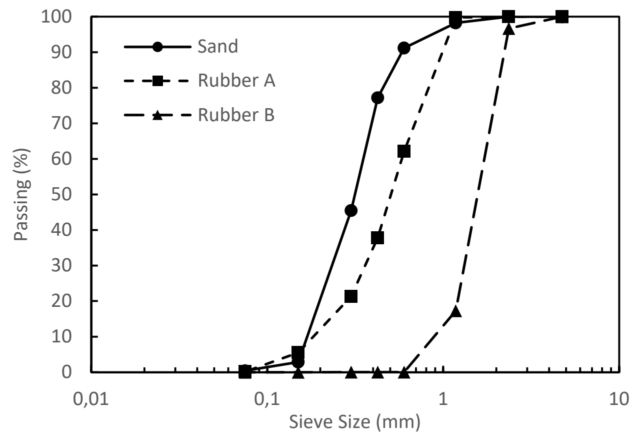

Fig. 3 Particle Size distribution curve for the granular material

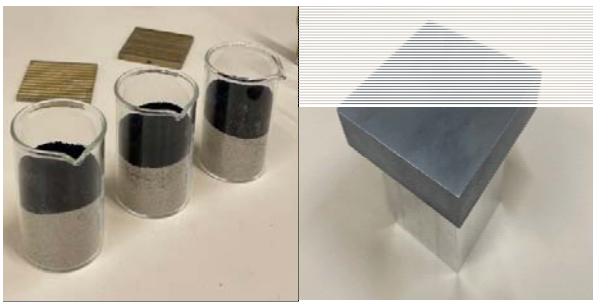

Fig. 4 Containers for each layer and an aluminum piece for compaction

C. Method

The experiment was carried out on a direct shear box (60 x 60 mm) following the Australian standard [29]. The experiment tested granular dry mixtures at a shear rate of 1 mm/min. Therefore, the pore water pressure is not relevant to our experiment. The test was conducted on four normal stresses: 30, 55, 105, 200 kPa. These stresses were kept on the specimen for 10 minutes to allow the consolidation to take place before the shear started. All shear tests have been done on a displacement of 10 mm or at the highest shear level reached. The procedure was identically repeated for each different normal stress in order to get the peak shear strength. Some tests were repeated multiple times to avoid any inaccuracies in the results. Fig. 5 displays the unit weight of the S-PR mixtures at different rubber contents.

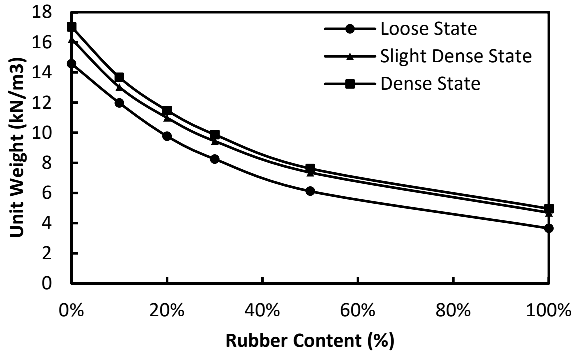

Fig. 5 Unit weight versus rubber content at loose, slight dense, and dense state

IV. Results

A. Shear Strength

Shear strength is defined as the peak parallel force divided by the sheared area. It can also be defined as the friction and interlocking of granular with each other [30]. Figs. 6-8 display the shear strength versus the rubber content at different normal stresses in loose, slight dense, and dense states.

In the loose state, it can be noticed that the inclusion of PR up to 20-30% increases the shear strength of the mixture, after which it starts to decrease. In the slight dense and dense states, it can be noticed that at the low normal stresses 33, and 55 kPa, the inclusion of PR showed a slight increase in the shear strength where the peak was at 20% to 30% rubber content of the sand's dry weight. On the other hand, at the high normal stresses 105, and 200 kPa, there was a slight decrease in the shear strength. Therefore, the optimum PR content for the highest shear strength was found to be 20-30% for the loose state and for both the slight dense and dense states at low normal stresses. Similar results were found by [25], however, Anbazhagan [25] used a PR size ranging from 12-9.5 mm, while the PR size that was used for this experiment ranged from 2.36-0.075 mm. Both size ranges are considered as PR according to [5], [6].

B. Internal Friction Angle

The internal friction angle is the sliding resistance that occurs when two particles interact due to friction [30]. Fig. 9 shows the plotted results between the rubber content and the internal friction angle of the mixture. From the figure, it is easy to notice that for all density states, there is a decrease in the internal friction angle with the initial inclusion of rubber contents. However, when rubber contents reached 20%, the three states experienced a slight increase in the internal friction angle until they reached 30% rubber content, after which the decrease of internal friction angle continued. The peak internal friction angle for the mixture in all three states was found to be at 30% rubber content by dry weight of the sand. Similar results were found by [23] but at different rubber contents. In Cablar's experiment [23], the internal friction angle for the Leighton Buzzard sand-rubber mixtures decreased with the initial inclusion of rubber content. This was so until the rubber contents reached 10% where the sand experienced a slight increase in the internal friction angle until it reached 20%. Afterwards, the internal friction angle then continued to decrease with the addition of rubber contents.

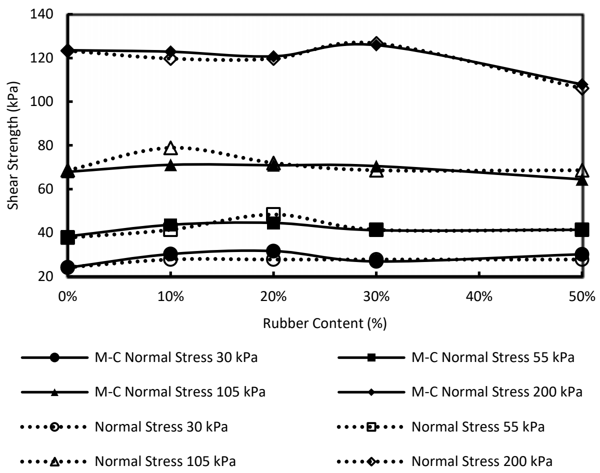

Fig. 6 Shear strength versus rubber content at loose state

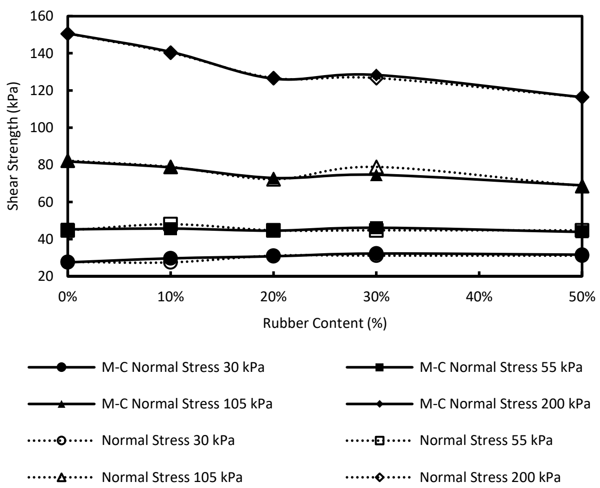

Fig. 7 Shear strength versus rubber content at slight dense state

C. Apparent Cohesion

Cohesion is the resistance provided by inter-particle forces which are affected by soil particle size, confinement, water adsorption, permeability and neutral stress [30]. According to Mohr-Coulomb's shear strength equation, cohesion could be defined as the shear strength at zero normal stress on the surface of failure. Fig. 10 displays the results with the rubber content versus the apparent cohesion value variations of the mixture. It can be observed that the mixture's apparent cohesion in the three states show a significant increase with the inclusion of rubber contents. The apparent cohesion value in 50% rubber content for the loose state increased from 6.41 kPa to 16.35 kPa, in the slight dense state it increased from 5.72 kPa to 16.64 kPa and in the dense state it increased from 3.25 kPa to 23.10 kPa. Similar results were found by [24], [25], and [31], where the apparent cohesion also significantly increased with the addition of rubber contents.

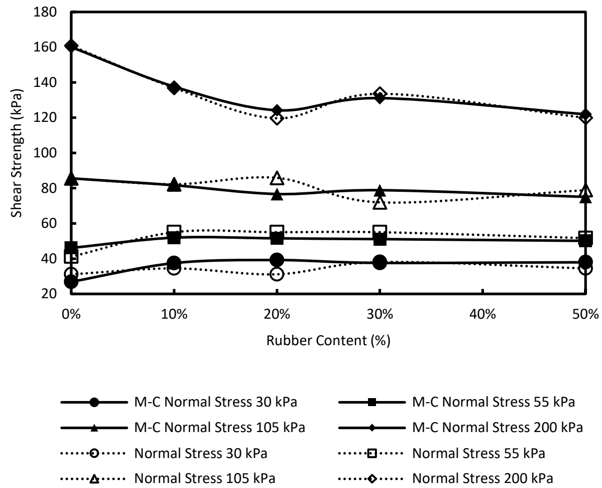

Fig. 8 Shear strength versus rubber content at dense state

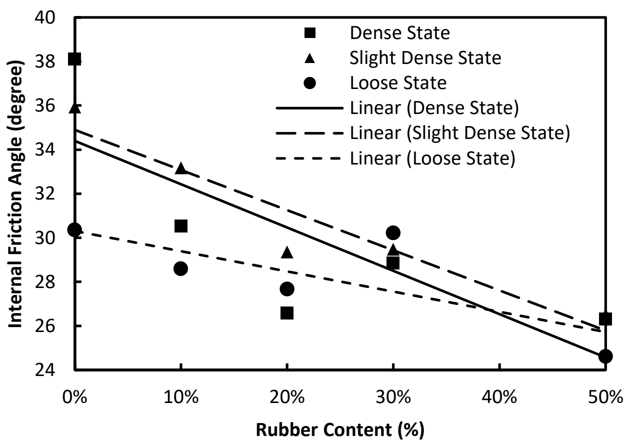

Fig. 9 Internal friction angle versus rubber content

D. Observations

The shear results identified five parameters that influenced the shear strength: normal stress, PR content, PR size, the mixture's unit weight, and the mixture's grading. The following points can be deduced from the shear experiment:

- The Mohr coulomb envelop was found to be nearly linear.
- There is a significant increase in the apparent cohesion in all density states with the inclusion of PR content in the mixture. The apparent cohesion increases in the mixture leading to higher shear strength which was approved earlier in the literature.

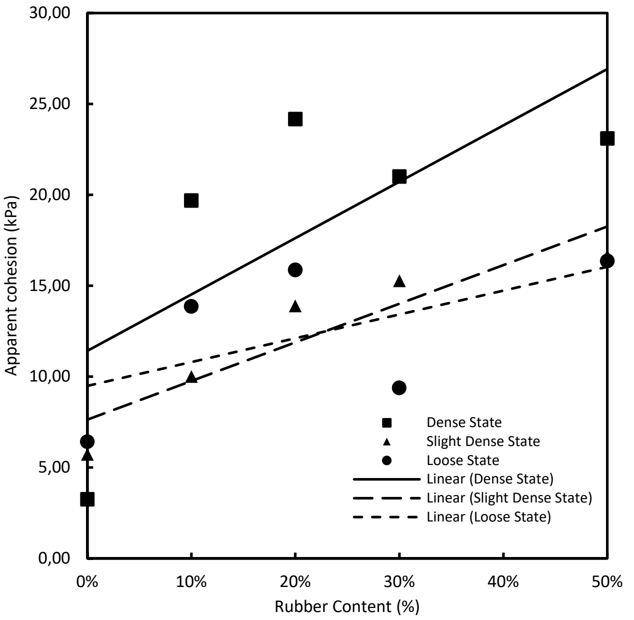

Fig. 10 Apparent cohesion versus rubber content

- The inclusion of particle rubber on sand shows an increase in shear strength on low normal stresses (30, and 55 kPa) in contrast, it shows a decrease in shear strength with the higher normal stresses (105, and 200 kPa)
- The internal friction angle in the three density states gradually decreased until they reached 20% where a slight increase took place until the rubber content reached 30%. After this, the internal friction angle continued to decrease with the inclusion of rubber content.
- The inclusion of PR on sand cannot improve the shear strength significantly. However, the optimum PR content for optimum shear strength was found to be 20 to 30% of the sand dry weight.
- The inclusion of poorly graded PR to a poorly graded sand could improve the mixture to well graded, that could have more interlocking between the particles leading to a higher shear strength.
- The inclusion of PR on sand decreases the unit weights and the lateral earth pressure which enhances the ability to use as a lightweight material in geotechnical applications.

V. Conclusion

After several studies using the direct shear, it can be concluded that the shear strength characteristics of the mixture is slightly changed and not significantly affected. The shear strength of the mixture can be affected by many parameters. These parameters can be summarized under three main categories: the loading condition parameters, environmental parameters, and sand-rubber mixture parameters. The loading condition includes the normal stress level and the shear rate. The environmental parameters include temperature and the degree of saturation. And the mixture parameters include rubber-sand size ratio, mixture gradation, mixture particle shape, mixture density, and mixture compressibility. All the aforementioned parameters could have a possible effect on the mixture's shear strength characteristics and therefore it is recommended that future studies look into gathering big data including all the mentioned parameters and applying Artificial Intelligence to predict which combination of parameter levels has the optimal effect on the shear strength of the mixture.

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