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INVESTIGATION OF THE USE OF SCRAP TYRES AS SOIL REINFORCEMENT

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ABSTRACT

Waste tyres, which are produced in every society in numbers that are increasing annually, are impacting the environment and causing serious problems. These materials possess exceptional properties that can be reused as reinforcement materials in the geotechnical engineering industry. This study investigated the effects of tyre shreds that were randomly mixed with sand and clay to enhance their engineering properties. An Atterberg limits analysis, as well as compaction and odometer tests, were performed on china clay with scrap tyres of varying weights (10, 20, 30 and 40%). The results show that the Atterberg limits of clay decrease in proportion to increases in the volume of tyre shreds. The compaction characteristics of clay decreased with increased tyre-shred contents of 2–6 mm and 12 mesh. Compression and recompression indexes increased gradually with the tyre-shred content of 12 mesh. A series of direct shear strength tests were performed on the sand-shredded tyre mixtures of Levenseat sand and concrete sand using a direct shear box of 10 cm x 10 cm. Two relative sizes of shredded tyres, 12 mesh and 2–6 mm, were mixed with sand of different weight percentages. The results showed a general increase in the shear strength parameters of both types of sand with the addition of the shredded tyres. The maximum shear strength was obtained at optimum shredded tyre content, approximately 20% for the 2–6 mm shreds and 15% for the 12-mesh shreds. The results showed that it is possible to use shredded tyres in geotechnical applications.

KEYWORDS: Shredded tyre; Sand; Clay; Consistency; Shear strength; Compressibility

1. INTRODUCTION

Population growth, accompanied by a vast range of industrial and human activities, has resulted in large volumes of solid waste being generated globally. A large quantity of these waste materials are not reused but are rather disposed of in the limited number of available disposal sites, which may be exhausted in the near future. Millions of tons of waste tyres are generated annually due to the increasing number of cars being driven by people all over the world. This has led to significant concerns about environmental problems posed by municipal solid waste that contains an ever-growing proportion of waste tyres. According to the Council for Development and Reconstruction (CDR), in Lebanon in 2012 the rate of owning a car is one in 2.7, which is similar to advanced industrial counties (Mrad and El-Samra, 2020). In Lebanon the number of passenger cars is expected to be more than 6 million by the year 2020 and will reach 9 million by the year 2035 (Mrad and El-Samra, 2020). Consequently, the local waste tyre production is subjecting to increase with the increasing

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number of cars. As maintained by Dickson *et al.* (2001), the United States generates around 270 million waste tyres each year. According to Hird *et al.* (2002), in England and Wales, for instance, there are approximately 38 stockpiles of nearly 14 million tyres, a quantity that is essential for finding beneficial ways of recycling and reusing tyres. The European Tyre Recycler Association ETRA (1998) reported that there were 250 million used tyres in the European Union; a noticeable number of tyres are stockpiled in other countries, resulting in an accumulation of more than a billion used tyres per annum throughout the world. Discarded waste tyres deposited in open spaces cause major environmental and human health problems.

Some studies have shown that the use of scrap tyres is beneficial in civil engineering applications, particularly in the field of geotechnical engineering. The use of tyre shreds in construction conserves natural aggregate resources, eliminates their disposal cost, reduces stockpiles of waste tyres, which are prone to fire and health hazards, and eliminates damage to structures made of tyre shred soil mixtures (Yoon *et al.*, 2006).

Increasing efforts have been made to find applications for such materials in the field of civil engineering. For example, waste tyres are used

- for reinforcing soft soil in road construction;
- as lightweight material for backfilling in retaining structures;
- for stabilising slopes;
- for controlling ground erosion;
- as sound barriers;
- as aggregates in leach beds of landfills;
- as sources for creating heat;
- for limiting freezing depth;
- as an additive material with asphalt;
- for vibration isolation;
- as a fuel supplement in coal-fired boilers;
- as cushioning foams;
- for low-strength but ductile concrete (Ghazavi, 2004).

On the other hand, the disadvantages of using shredded tyres alone as fill material include self-heating mechanisms, compaction problems and high deformation (Youwai and Bergado, 2003). It is also important to consider any possible environmental implications before using tyre shreds in geotechnical applications. Such implications include potential groundwater contamination (Lee *et al.*, 1999). Edil and Bosscher (1992) indicated that shredded tyres do not illustrate any possibility of becoming a dangerous waste material or of having adverse effects on the quality of groundwater. Degradation of tyre shreds can be due to microbial action and ultra-violet light (Yoon *et al.*, 2006). Some study indicates that the effect of micro-organisms on scrap tyres is not well understood and Carbon black present in tyres blocks the damaging ultra-violet component of sunlight (Yoon *et al*., 2006). Further research into the degradation of tyre shreds is required.

Studies by Ahmed (1993) and Ahmed and Lovell (1993) revealed that the shear strength increased as the tyre chip content increased in the sand-tyre chip mixtures with optimum content of 30% tyre chips by volume. Edil and Bosscher (1994) report that the addition of 25% tyre chips (20 to 80 mm) increased the shear strength of the sand at low normal stresses. Foose *et al.* (1996), Tatlisoz *et al.* (1998) and Youwai and Bergado (2003) conducted large-scale direct shear tests to study the mechanical effect of using shredded waste tyres to reinforce sand. They investigated six factors that affect the shear strength of mixtures of sand and tyre shreds: normal stress, shred content, soil matrix, unit weight of a mixture, shred length and shred orientation. They found that sand matrix and shred content are the most important characteristics affecting the shear strength of the mixture. Lee *et al.* (1999) studied the behaviour of sand and tyre chips to determine the stress-strain relationship of the mixture and

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observed the dilatancy behaviour of rubber sand between pure chips and pure sand. Ghazavi and Sakhi (2005) conducted large shear box tests on sand reinforced with shredded waste tyres and studied the usefulness of optimising the size of waste tyre shreds on shear strength parameters. Attom's (2006) direct shear tests of mixtures of sand and shredded tyres showed that the shear strength and angle of internal friction improved with the addition of shredded waste tyres. Bali *et al.* (2016) investigated that the shear strength properties of sand-tyre chips mixture increased as the tyre chip of 20×10 mm content increased, the optimum percentage of the shredded tyre is in the range of 30–40% by weight. A study by Ghazavi *et al.* (2011) demonstrated that the shear strength and friction angle decreased for tyre-shred contents beyond 20% by weight. Mashiri *et al.* (2015) observed that shredded tyre chips significantly improve the shear strength properties and the reduction in dilatancy behaviour of sand–tyre chip mixtures. Sand-tyre shred mixtures showed an increase in shear strength up to 30% by weight and were then reduced by direct shear tests (Bałachowski and Gotteland, 2007; Singh and Vinot, 2011, 2013).

Other geotechnical properties were also studied, such as Atterberg limits and compaction and compressibility. Cetin *et al.* (2006) and Oikonomou and Mavridou (2009) observe that Atterberg's limits decreased as the percentage of the tyre shreds increased or the clay content decreased. Foose *et al.* (1996) and Cetin *et al.* (2006) agree that the addition of tyre shreds lowers the maximum dry unit weight. The dry densities of clay mixed with tyre shreds were reduced as the percentages of shreds increased, and there was not a distinct relationship between the size of the shredded tyre and the unit weight that was achieved (Cetin *et al.*, 2006; Daud *et al.*, 2015). For reinforcing expansive soils the coarser tyre shreds slightly outperformed the finer tyre shreds and the 10% tyre shreds were found to be the optimum choice (Soltani *et al.*, 2019). The compressibility of soil mixed with tyre material was increased significantly (Edil *et al.*, 1990; Srivastava *et al.*, 2014).

However, the California bearing ratio (CBR) for clay increased with the addition of shredded tyre (Daud *et al.*, 2015; Kolhe and Langote, 2018). The crumb rubber–sand mixture with the crumb rubber of 30% by weight was observed to be the most appropriate filler material which resulted in a better performance in the wall compared to the other mixing ratios (Tajabadipour and Marandi, 2017). Chenari *et al.* (2017) found that the inclusion of shredded tyre to sand decreases settlement reduction factor and increases bearing capacity ratio. Rahgozar and Saberian (2016) discovered that tyre shred significantly enhanced the peat soil geotechnical properties, the mixture showed the highest unconfined compressive strength with the inclusion of 10% tyre shred. It has also noticed that the addition of small pieces rubber up to 5% in the clayey soil improves the California bearing ratio, and increase the split tensile strength and unconfined compressive strength (Yadav and Tiwari, 2018). The coefficient of permeability for clay increases with an increase in the percentage of the tyre shreds.

The aim of this study was to investigate the engineering effect of using shredded waste tyres as soil reinforcement material by examining the effects of these tyres on shear strength, compaction and Atterberg limits parameters and compressibility when the tyre shreds are randomly mixed with sand and clay. The effects of varying tyre-shred content and tyre sizes on soil characteristics were also evaluated.

2. MATERIALS

2.1 Sandy soils

The sands used in the study were Levenseat sand and concrete sand, as shown in Figure 1. Levenseat sand, fine-grained and light in colour, consists of sub-angular particles and features a high silica content, while concrete sand is

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coarse-grained, tan to light brown in colour, with particles that are sub-angular to round in shape. The soil properties of both sands are shown in Table 1.

Table (1): Properties of concrete sand and Levenseat sand

Property	Concrete Sand	Levenseat Sand
Specific gravity, Gs	2.61	2.69
Particle size range (mm)	0.075–4.75	0.05–1.18
Bulk density (t/m^3)	1.60	1.38
Angle of friction (°)	40.3	42.9
Absorption (%)	1.2	1.5
pH	6.7	7.0

2.2 Clay soil

China clay, a commercial clay that is primarily manufactured from the hydrated aluminosilicate clay mineral kaolinite, was used in the study (Figure 1). This clay features a fine particle-size distribution; its particles are flat in shape and soft in texture. Particle-size distribution has an influence on the colour, dispersion, plasticity and strength of soil. The soil properties of china clay are shown in Table 2.

Table (2): Properties of china clay

Specific Gravity (Gs)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Linear Shrinkage (%)	MDD (kg/m^3)	OMC (%)
2.65	55	29	26	2.86	1478	28.2

2.3 Tyre shreds

Three sizes of chip types were used in this experimental investigation: 2–6 mm, 12 mesh (1.6–0.5 mm) and 50 mesh, as shown in Figure 1. It was difficult to obtain a single size of tyre shreds to use in this investigation; the small tyre pieces were used because of the limited testing facilities. Additionally, as is consistent with many studies described in the literature, the majority of the tests were carried out on waste tyre shreds longer than 10 mm. All the chip types mixed with the soils were free of steel and wires. Some properties of tyre shreds are as follows: specific gravity 1.13–1.36 (Youwai and Bergado, 2003), density 500–600 kg/m^3 (Wu *et al.*, 1997) and absorption 1–2.5% (Lee *et al.*, 1999).

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Fig. (1): Top: China clay (left), Levenseat sand (middle), concrete sand (right).
Bottom: shredded tyre 2–6 mm (left), 12 mesh (middle), 50 mesh (right)

3. METHODOLOGY

Atterberg limits tests, in accordance with British Standard (BS) 1377-2:1990, were undertaken to investigate the effects of tyre shred material on the liquid limit, plastic limit and plasticity index of china clay. Samples were prepared by mixing china clay with different percentages of tyre shreds of 50 mesh by weight. The liquid limit test was performed by measuring the penetration into the soil specimen via the cone pedometer method. The liquid limit was determined at the cone penetration of 20 mm. The plastic limit is the water content at which soil begins to behave as a plastic material by rolling into 3 mm diameter threads without crumbling.

The compaction test for specimens was conducted in accordance with BS 1377-4: 1990. This test gave the maximum dry density (MDD) and optimum moisture content (OMC) for mixing china clay with tyre shreds of 12 mesh and 2–6 mm at ratios 0:100, 10:90, 20:80, 30:70 and 40:60 by weight. The tests were performed on specimens via the BS light compaction test method (2.5 kg rammer) standard protect. The specimens were prepared according to the above ratios and were then stirred together with water in a mixing bowl for 5 minutes. The sample was compacted in a BS one-litre compaction mould in three layers, with tamping at 27 blows per layer and falling at a height of 300 mm.

Loading and unloading odometer tests, in accordance with BS 1377-5: 1990, were carried out on the china clay containing 0, 10, 20, 30, and 40% tyre shreds by dry weight. A tyre shred size of 12 mesh was used in this component of the study. The samples were prepared with results obtained in the compaction test and placed in the odometer ring with a diameter of 75 mm; the initial height of each of the specimens was 19 mm. The specimens were incrementally consolidated to normal stresses of 50, 100, 200, 400 and 800 kPa and gradually rebounded to a normal stress of 200 kPa. The compression index (Cc) and the recompression (swell) index (Cr) were determined for china clay and clay-tyre shred mixtures.

A direct shear box test (10 cm x 10 cm), in accordance with BS 1377-7: 1990, was conducted on the Levenseat sand and concrete sand mixed with four different concentrations of 10%, 20%, 30% and 40% tyre shreds by weight for both shred sizes of 2–6 mm and 12 mesh.

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The mixed materials were carefully placed into the shear box to avoid the segregation of shredded tyres from the sand and were slightly compacted by a small hand tamper. The direct shear testing involved shearing a laterally restrained square soil sample along a horizontal plane. The failure occurred when the shearing resistance reached the maximum value the sample could sustain. The samples were tested under three different normal pressures: 10, 30 and 50 kPa. The box was horizontally divided into two halves which could be adequately fixed together by screws that passed vertically through the walls of the upper half and screwed into the lower half. The constant rate of shear stress or displacement rate of 1 mm per minute was applied in this test.

4. RESULTS AND DISCUSSION

4.1 Atterberg Limits

The liquid limit and plastic limit for china clay were 55% and 29%, respectively. With the addition of tyre shreds, the clay content decreased, and, accordingly, the Atterberg limits decreased, as expected. In general, the results for the clayey soil-tyre shred mixture (Figure 2), showed that as the tyre shreds increased, the liquid limit decreased up to 20% content of tyre shreds, remained constant up to 30% and then decreased by up to 40%.

The plastic limit remained almost constant up to 20%, at which point it began to increase up to 30% and then decreased by up to 40%. According to the results, the effect of tyre shreds on the plastic limits compared to the liquid limit is insignificant. Also, the plasticity index was reduced by increasing the tyre-shred content in the mixture. These results are generally consistent with those obtained by Cetin *et al.* (2006) and Oikonomou and Mavridou (2009).

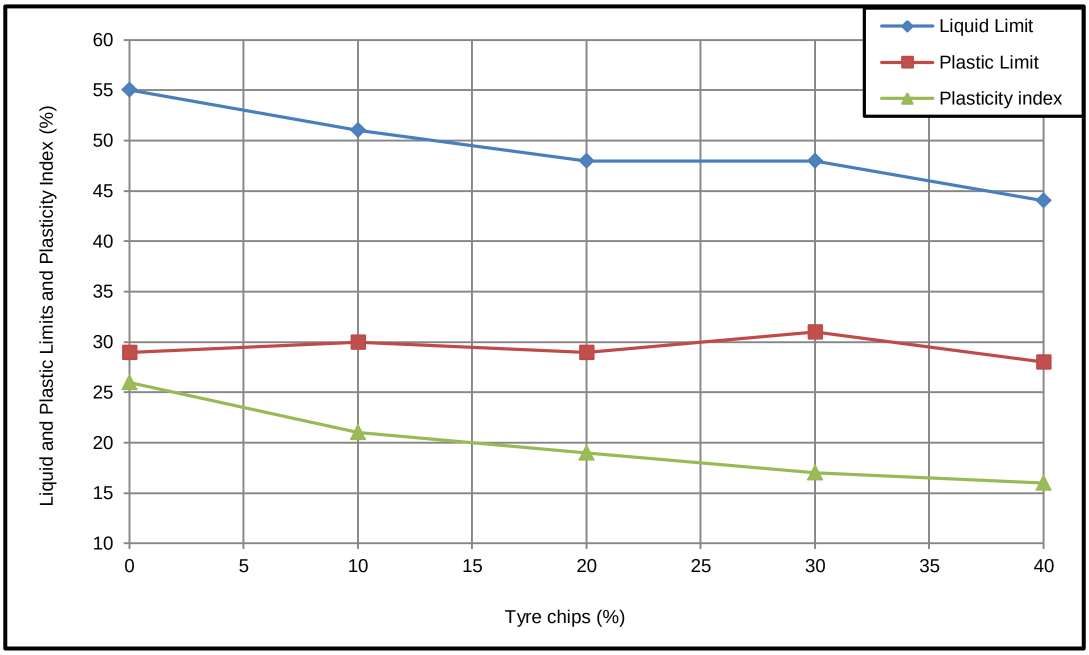

Fig. (2): Variation of liquid and plastic limits and plasticity index for clay as tyre chip increases

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4.2 Compaction Test

The Proctor curves (Figure 3) clearly demonstrate that the MDD and OMC were higher only for the clayey soil and decreased as the percentage of tyre shreds increased, both for the 2–6 mm and the 12-mesh tyre shred soil mixtures. This result, which is similar to that reported by Tatlisoz *et al.* (1997) and Kolhe and Langote (2018), may be due to the lower specific gravity of the shredded tyre and to changes in the particle size distribution and organic content. In addition, a reduction in the OMC may be due to a lower absorption of tyre shreds compared to that occurring in china clay. The reduction in the OMC is in contrast to the result reported by Daud *et al.* (2015) which OMC is increased with the increase of tyre shred (1-5 mm) to clayey soil.

The curves demonstrate that the maximum dry unit weight systematically decreased as shred content increased (Ahmed and Lovell, 1993). These results, which are similar to that obtained by Cetin *et al.* (2006) and Oikonomou and Mavridou (2009), show good potential for using scrap tyres as lightweight fill material. However, the use of finer-size tyre shreds decreased the MDD of china clay relatively more significantly when compared to the corresponding values of MDD obtained with coarser-size tyre shreds. This was due to the density of the 2–6 mm tyre, which is slightly higher than the 12-mesh size.

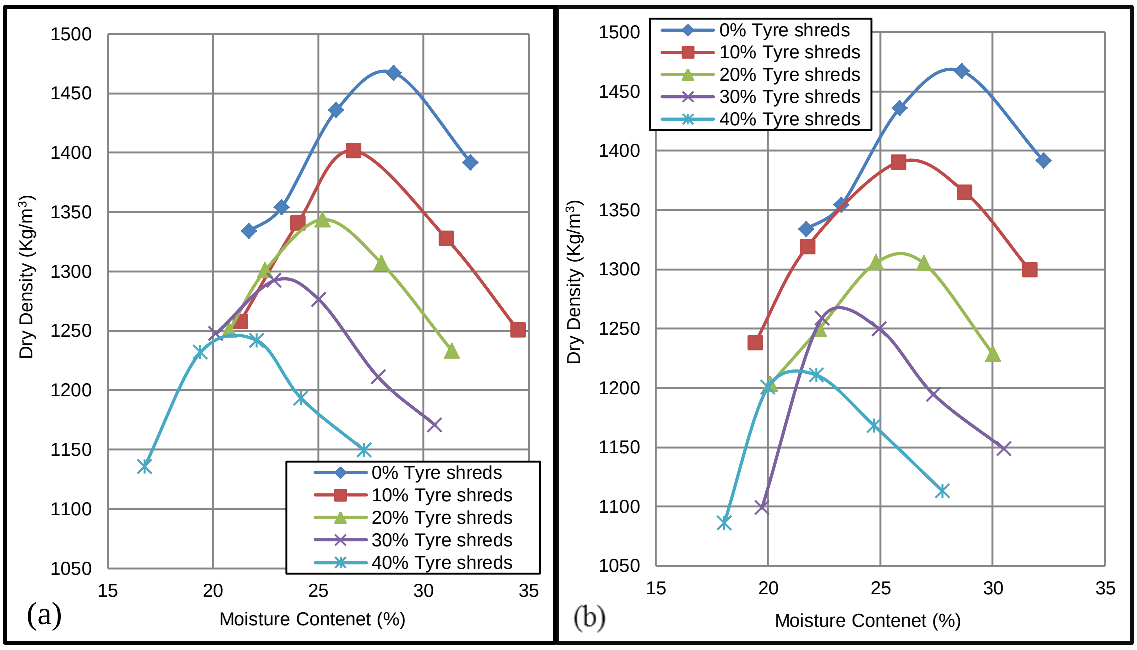

Fig. (3): Compaction curve for 2–6 mm (a) and 12 mesh (b) tyre shred-china clay mixtures

4.3 Loading–Unloading Odometer Tests

A complementary test program under odometer conditions was also performed because the compressibility of tyre materials is high, and its specific weight is approximately less than half that of the clay. The purpose of the test was to obtain additional information on the mechanical behaviour of clay with tyre shreds. According to the logarithm pressure and void ratio curve (e-log p), the addition of tyre shreds caused a reduction in the void ratio, which resulted in a stronger material. The slope of the linear portion of the pressure void ratio curve on a semi-log plot is represented by the Cc. The Cc of china clay increases gradually with the inclusion of tyre-shred content, as shown in Figure 4. The Cr is the slope of the (e-log p) plot during decompression or unloading. For all

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tested samples, the Cr was smaller than the Cc and increased with the inclusion of tyre-shred content (Figure 4), results which are in agreement with Srivastava *et al.* (2014). The compressibility of soil mixed with tyre shreds was found to increase significantly for tyre percentages of more than 30% by weight (Edil *et al.*, 1990). Edil and Bosscher (1994) suggested that the use of backfill comprising soil mixed with tyre shreds may be less compressible than those consisting of pure tyre chips.

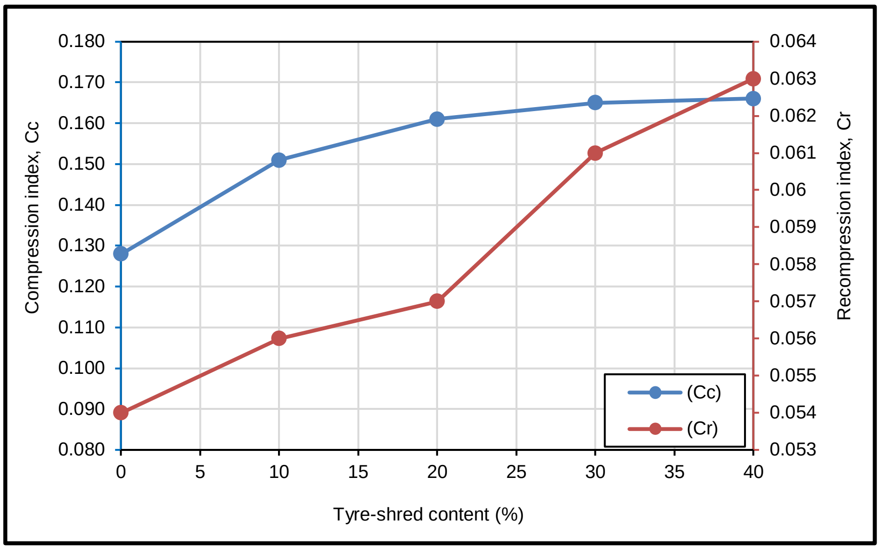

Fig. (4): Effects of shredded tyre content on compression and recompression indexes of clay

4.4 Direct Shear Test

4.4.1 Peak Shear Stresses

Maximum shear stresses were achieved by using load displacement curves at different applied normal stresses of 10, 30 and 50 kPa (Table 3). The failure was taken to correspond to 15% shear strain. The increment of shreds to Levenseat sand and concrete sand enhanced their peak shear stresses to an optimum amount, after which they reduced. It should be noted that a high shear displacement was required to mobilise the peak shear stress with an increased shredded-tyre content in the composite. In the tyre shred-sand mixture, the shear stress development for long tyre shreds (2–6 mm) was higher compared to that of the small-size tyre shreds (12 mesh). This difference could be attributed to the larger tyre shred size having a larger contact area with the sand: when randomly distributed in sand, the larger shreds acted as anchors in the shear zone and thus increased the shear resistance compared to that of the smaller-size shred. Gray and Al-Refeai (1986) explain that the random inclusion of tyre shreds in sand, variously positioned in the shear zone such as inclined and vertical, contribute to the shear reinforcement mechanism and thus increase the maximum resistance of sand during shear testing.

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Table (3): Peak shear stresses for sand-tyre shred mixtures

Tyre Shreds %	Peak Shear Stresses (kPa)											
	Concrete Sand						Levenseat Sand					
	Applied Normal Stresses (kPa)						Applied Normal Stresses (kPa)					
	10		30		50		10		30		50	
	Shred size						Shred size					
	12 mesh	2–6 mm	12 mesh	2–6 mm	12 mesh	2–6 mm	12 mesh	2–6 mm	12 mesh	2–6 mm	12 mesh	2–6 mm
0%	12.18	12.18	24.94	24.94	46.11	46.11	10.73	10.73	26.10	26.10	47.85	47.85
10%	12.47	12.18	27.84	25.81	47.85	47.85	13.63	13.63	31.61	31.61	50.46	50.46
20%	12.49	15.08	27.84	31.32	47.50	53.65	12.47	15.95	30.16	34.22	50.17	55.10
30%	11.31	13.63	26.10	29.58	41.18	46.11	11.02	13.34	28.71	33.93	45.82	53.65
40%	9.28	9.57	23.20	23.20	34.80	40.89	10.15	13.92	24.07	30.45	40.60	52.49

However, some samples of concrete sand-tyre shred (2–6 mm) mixtures were placed into the shear box in three layers, and each layer was compacted using a hand tamper to observe the effects of compaction on shear strength by comparing peak shear stresses to those of the specimens placed into the shear box in one layer. As shown in Table 4, the peak shear stresses for samples placed into the shear box in three layers are higher than those for the samples placed in one layer; this was clearly shown in high normal stresses. The effects of compaction on shear strength might be more apparent with the use of a large direct shear box test.

Table (4): Peak shear stresses for concrete sand-tyre shred (2–6 mm) mixtures

Tyre Shreds %	One Layer			Three Layers		
	Applied Normal Stresses (kPa)			Applied Normal Stresses (kPa)		
	10	30	50	10	30	50
0%	12.18	24.94	46.11	10.73	26.10	47.85
10%	12.18	25.81	47.85	12.47	33.64	52.78
20%	15.08	31.32	53.65	15.08	34.22	55.39
30%	13.63	29.58	46.11	13.92	31.61	47.56
40%	9.57	23.20	40.89	10.15	24.07	42.60

4.4.2 Mohr-Coulomb Failure Envelopes

Coulomb failure envelopes were generated by using the peak shear stresses at different applied normal stresses of 10, 30 and 50 kPa. The intercept of the failure envelopes on the vertical axis represented the apparent cohesion (c’) of the composite, while the inclination to the horizontal axis was the angle of internal friction (φ’). The nonlinear variation of maximum shear stress at failure led to the appearance of cohesion for the different concentrations of sand-tyre shred mixture (Foose *et al.*, 1996). The friction angle increased at 20% tyre-shred content and decreased with higher concentrations (Figures 5).

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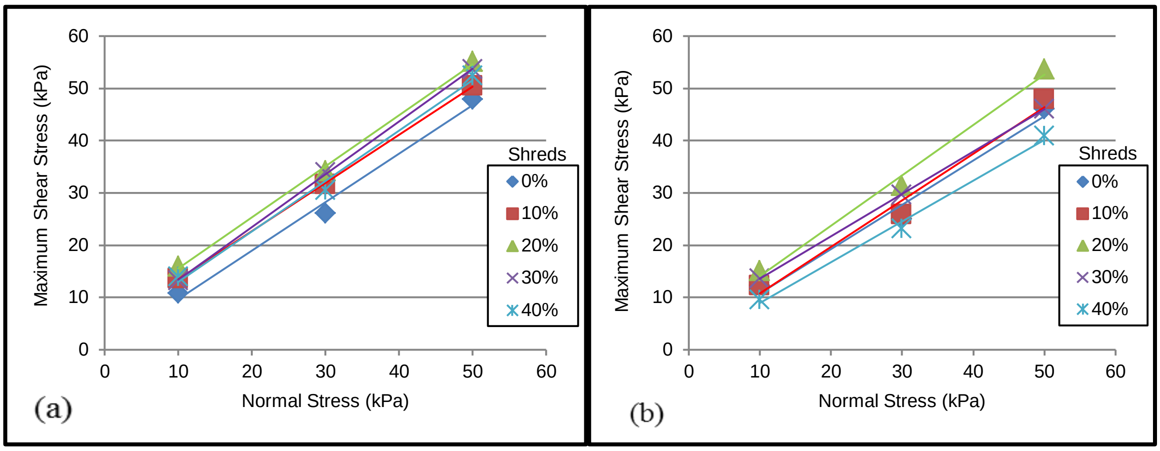

Fig. (5): Mohr-Coulomb failure envelopes for (a) Levenseat sand and (b) concrete sand with inclusion of 2–6 mm tyre shreds

4.4.3 Effects of Tyre Shreds on Friction Angle and Cohesion of Sand

The Levenseat sand-tyre shred (2–6 mm) composite showed a better improvement in friction angle and cohesion compared to the other mixtures (Figure 6). The different values of friction angles obtained from all sand-tyre shred mixtures were 44.4° for Levenseat sand with the addition of the 12-mesh tyre shreds and 51.7° for the 2–6 mm shreds. On the other hand, the concrete sand exhibited lower friction angles when mixed with the 12-mesh tyre shreds were 43.1°, but the inclusion of the longer 2–6 mm shreds achieved a maximum friction angle of 45° (Figure 6a). All the higher values were obtained at a shredded tyre percentage of 20%, which was consistent with studies by Ahmed (1993) and Ghazavi *et al.* (2011) and in contrast to the concentration of 10% reported by Singh and Vinot (2013). There is small improvement in the cohesion values for Levenseat sand and concrete sand when mixed with tyre shreds. Also, a study by Rahgozar and Saberian (2016) indicated that adding 20% tyre shred provided the greatest values for the internal friction angle and effective cohesion. The longer 2–6 mm tyre shreds gave the mixture a higher cohesion than the shorter 12-mesh shreds (Figure 6b). The increased friction angle and small increase in cohesion for this particular size of tyre shreds can be attributed to the interlocking effects between tyre shreds and sand particles. Additionally, the long 2–6 mm tyre shreds had a better reinforcing effect in the shear zone, which contributed to the significant increase in shear resistance of sand compared to the 12-mesh shred size.

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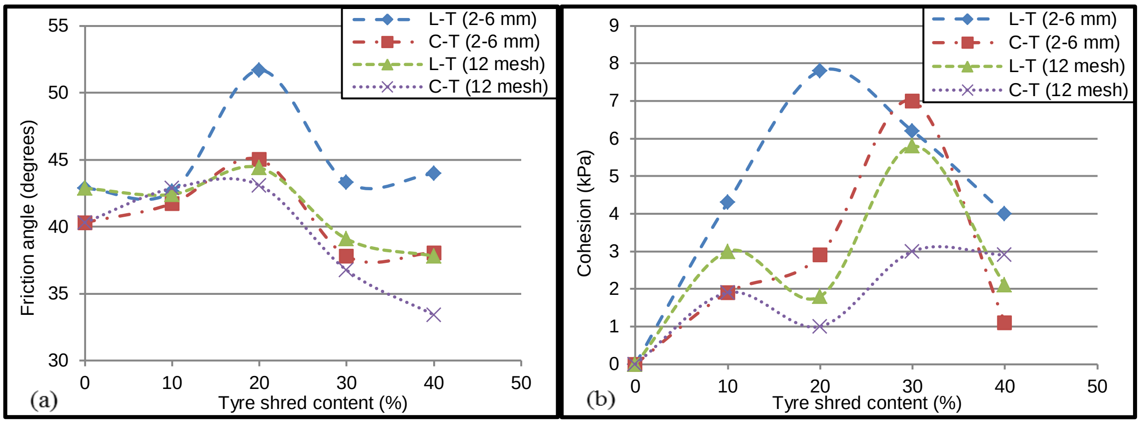

Fig. (6): Effect of tyre-shred content on (a) friction angle and (b) cohesion of Levenseat sand (L-T) and concrete sand (C-T)

4.4.4 Vertical Deformation and Horizontal Displacement Relationship

For unreinforced sand, the amount of dilation and contraction depended only on applied normal pressure. The contraction increased as the vertical confining pressure increased, which reduced the sample dilation. For the sand-tyre shred mixture, the vertical deformation depended on both the dosage of tyre shreds in the mixture and on the applied normal pressure. The increased normal pressure and tyre-shred content reduced the dilatant behaviour and increased the contractive behaviour of the test specimen (Figure 7). In Baleshwar and Vianot's (2011) explanation of the reduced dilatant behaviour and increased contractive behaviour during shear strength tests, the authors state that the addition of shredded tyres to sand, as well as the movement of sand particles around the shredded tyres due to the increase in vertical pressure during the shear phase, leads to a dilatancy effect that is less than that which occurs in sand alone, thus increasing the contraction of the composite. These results generally agree with other research, such as that by Lee *et al.* (1999), Ghazavi (2004), Gotteland *et al.* (2005) and Mashiri *et al.* (2015). It can be noted that anomalies in vertical deformation in one test achieved high dilation at high normal pressure compared to that at lower pressure. Figure 7b shows almost identical behaviour at both 0% with 10% tyre shreds tyre and at 20% with 30% tyre shreds.

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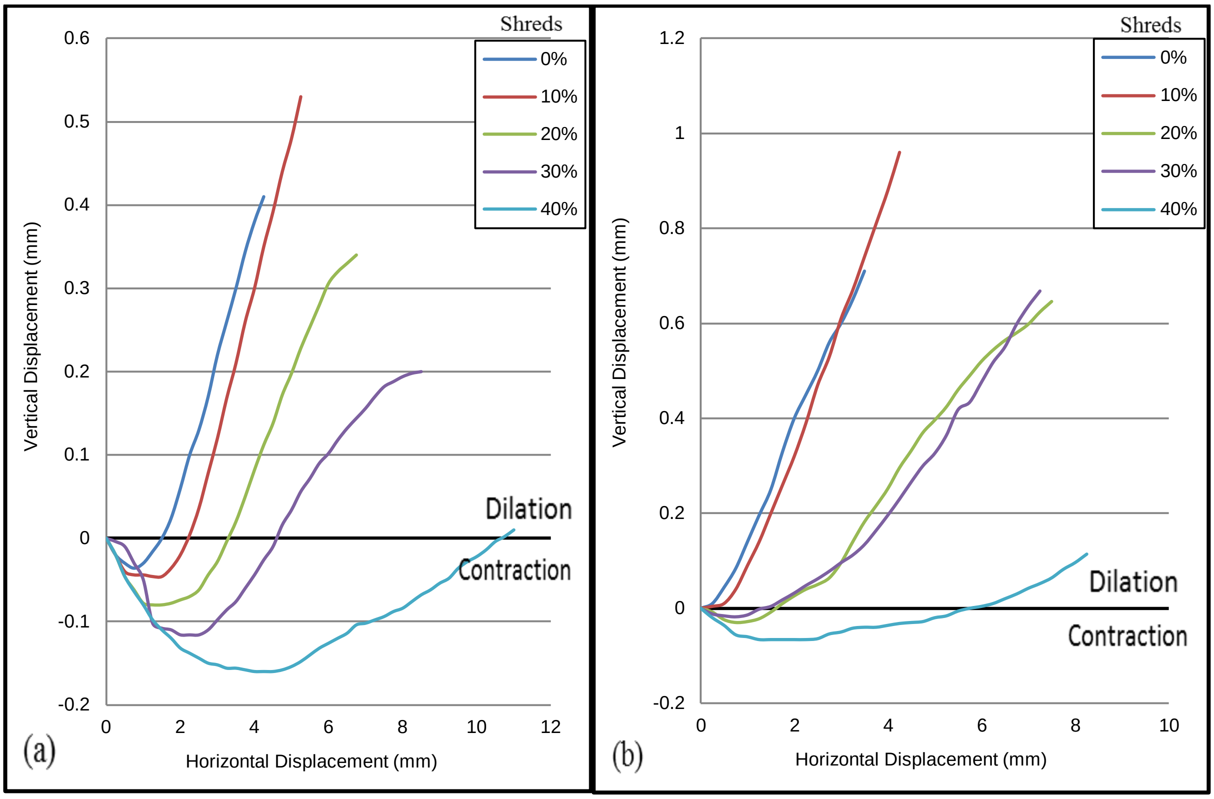

Fig. (7): Variation of vertical displacement with horizontal displacement for concrete sand-tyre shred mixture at normal stresses of (a) 50 kN/m^2 and (b) 10 kN/m^2

4.4.5 Effects of Tyre Shreds on Shear Strength of Sand

A significant improvement of shear strength was observed in both Levenseat sand and concrete sand: with random inclusion with the tyre shreds, the highest values were obtained at a tyre-shred content of 20% for the 2–6 mm size, as shown in Figure 8. This value were reported similarly by Ahmed (1993), Ahmed and Lovell (1993), Edil and Bosscher (1994) and Tatlisoz *et al.* (1998). This result is in contrast to the percentage content reported by Tanchaisawat *et al.* (2010) and Singh and Vinot (2011), Bali *et al.* (2016), which is 30% by weight. Beyond the 20% optimum percentage for 2–6 mm tyre shreds and 15% for 12-mesh tyre shreds, there was a reduction in the shear strength. The reduction in the shear strength of mixture beyond the optimum percentage of tyre shreds might be due to decreasing cohesion between particles of sand and tyre shreds, increasing of voids in the mixture and decreasing density of the mixture. In addition, the large tyre shreds appeared to provide a better improvement compared to the smaller size. Moreover, the differences in optimum concentrations of the two sizes might be due to the higher density and better particle correlation of the 2–6 mm tyre shreds when compared to the 12-mesh tyre shreds, as well as to the larger contact surface area between the sand and the large shreds. For the tyre shred dosage of 20% in the concrete sand, the shear strength obtained increased from 24.94 kPa to 31.32 kPa for the 2–6 mm size tyre shreds at an applied normal stress of 30 kPa, which is an increase of about 25.6% (Figure 8a). For Levenseat sand, at the 20% tyre shreds of the 2–6 mm size, the shear strength increased from 10.73 kPa to 15.95 kPa at an applied normal stress of 10 kPa, which is an increase of about 48.7% (Figure 8b).

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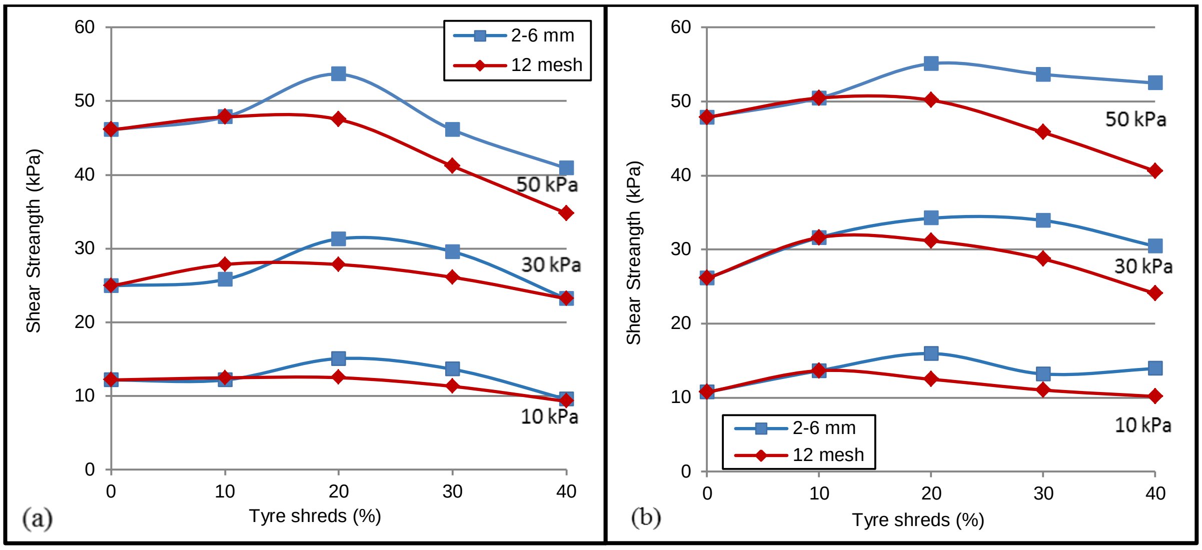

Fig. (8): Shear strength variation with the two tyre shred sizes and applied normal pressures of 10, 30 and 50 kPa for (a) concrete sand and (b) Levenseat sand

5. CONCLUSIONS

In this study, the effects of scrap tyre on the geotechnical characteristics of china clay and Levenseat sand and concrete sand were investigated, and the following conclusions were drawn:

- Atterberg limits characteristics mostly decrease with an increased volume of tyre shreds in clay; with the addition of tyre shreds, the clay content decreases.
- The MDD and the OMC decrease with an increasing volume of tyre shreds in clay; this is due to the lower specific gravity and absorption of the tyre material.
- Compression and recompression indexes increased gradually with the shredded tyre content for the clay.
- The inclusion of shredded tyres to the sand generally increased its shear strength parameters and friction angles. The maximum friction angles were achieved at 20% shred content for both sizes of tyre shreds, while the highest overall shear strength was observed at a concentration of 20% and 15% for 2–6 mm and 12-mesh tyre shred sizes, respectively.
- The longer shredded tyre particles may be desirable as reinforcement material because they achieve a relatively higher shear strength than the shorter tyre shreds, and the shredding has fewer energy requirements.
- The strength parameters of the sand-shredded tyre mixture improved due to the mobilisation of the tensile resistance of the shredded tyres during the shear, which caused the reinforcement of the sand by absorbing the shear load.
- Testing large and undisturbed samples in large direct shear box test are recommended to evaluate its strength and performance. It may be more accurate to determine the results and fairly represented the site.
- The use of shredded tyres may be effective in geotechnical applications as reinforcement material and lightweight fill but with percentages that do not significantly affect compressibility.

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List of Symbols

The following symbols used in this paper:

Symbol	Description	Symbol	Description
φ’	Angle of internal friction	kg/m^3	Kilogram per cubic metre
°	Degree	mm	Millimetre
c’	Cohesion	t/m^3	Ton per cubic meter
MDD	Maximum dry density	%	Percent
OMC	Optimum moisture content	pH	Power of hydrogen
CBR	California bearing ratio	Gs	Specific gravity
Cc	Compression index	kg	Kilogram
Cr	Recompression (swell) index	cm	Centimetre
BS	British Standard	kPa	Kilopascal
log p	Logarithm pressure	kN/m^2	Kilonewton per square meter
e	Void ratio	ETRA	European Tyre Recycler Association
L-T	Levenseat sand-Tyre shreds	CDR	Council for Development and Reconstruction
C-T	concrete sand-Tyre shreds	*et al.*	et alia

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