Geotechnical properties of peat soil stabilised with shredded waste tyre chips

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SUMMARY

To accommodate major civil engineering projects in or in the vicinity of peatlands, it is essential to stabilise peat deposits. On the other hand, the accumulation of waste tyres in recent decades has caused environmental problems around the world. An effective remedy for both issues is to use scrap tyre material to stabilise problematic peat soils. This article reports an experimental investigation of the effects of adding shredded tyre chips on the stability and bearing capacity of peat soil. Peat soil samples from the Chaghakhor Wetland (Chaharmahal and Bakhtiari Province, Iran) were mixed with sand at a constant dosage of 400 kg m^{-3} and different percentages (0 %, 5 %, 10 %, 15 % and 20 % by weight) of shredded tyre chips. The unconfined compressive strength, effective cohesion, angle of internal friction and coefficient of permeability were measured for all of these mixtures. The results showed that adding shredded tyre chips significantly improved the geotechnical properties of the peat soil. The mixture with 10 % shredded tyre chips showed the highest unconfined compressive strength; the one with 15 % tyre chips exhibited the highest ductility; and adding 20 % shredded tyre chips provided the highest values for angle of internal friction, effective cohesion and coefficient of permeability. Scanning Electron Micrographs (SEM) showed that the pore spaces in the stabilised peat were mostly filled with sand.

KEY WORDS: Chaghakhor Wetland, direct shear strength, Iran, rubber, unconfined compressive strength.

INTRODUCTION

Peat deposits are formed when organic matter accumulates more rapidly than it decays. This usually occurs when dead vegetation is preserved below a high water table, as in swamps or wetlands (Jarret 1997, Warburton *et al*. 2004, Youventharan *et al*. 2007a, Xintu 2008, Kalantari 2013). In geotechnical terms, peat soil has high permeability, porosity ratio, compressibility and consolidation settlement; low pH, bulk density, bearing capacity and shear strength; and relatively low plasticity. Also, its particle-size distribution is different from that of inorganic soils. All of these peculiarities arise from the high natural water content (> 200 %) and high organic content (> 75 %) of peat (Andriesse 1988, Huat 2004, Youventharan *et al*. 2007b, Hashim & Islam 2008, Wong *et al*. 2008, Zainorabidin & Wijeyesekeram 2008). Reported values for the undrained shear strength of peat determined by *in-situ* vane testing are in the range 3–15 kPa; and it is very weak, with a cone end resistance (q_t) of 0.1–0.5 MPa as determined using the Cone Penetration Test (CPTU) (Adams 1961, Adams 1965, Coutinho & Lacerda 1989, Hanzwa *et al*. 1994, Przystanski 1994, De Haan 1997, Mitachi 1998, Carlsten 2000, Edil 2001, Rahadian 2001, Long 2005, Long & Boylan 2012).

In the context of civil engineering, peat is a problematic deposit. If it is subjected to compressive stress, for example due to additional foundation load, this will lead to excessive settlement. Partly elastic immediate settlement is followed by primary and secondary consolidation, with the latter often contributing the greatest portion of total settlement. Excessive settlement is a serious problem for any structure, even when loading is moderate. Therefore, it is essential to stabilise peaty ground that is to support any structure and/or infrastructure (Jarret 1995, Ahnberg 2002, Edil 2003, Hayashi & Nishimoto 2005, Tang *et al*. 2011). The main purposes of soil stabilisation are to improve stability, increase bearing capacity, and reduce settlement and lateral deformation (Hashim & Islam 2008, Wong *et al*. 2008, Hashim & Islam 2009, Wong *et al*. 2013). Depending on the thickness of the peat layer, several stabilising methods are available including stabilisation with chemical additives, pre-loading, removal and replacement of the problematic deposit, compaction control, stone columns, lightweight fills and surface mattresses, surcharge loading, and thermal methods (Chen 1988, Zainorabidin & Wijeyesekeram 2007). Some of these methods have been criticised on the basis of high cost and/or ineffectiveness. For example, according to Puppala &

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Musenda (2002), removal and replacement, compaction control, stone columns and surcharge loading are rather expensive; and the addition of gypsum is somewhat ineffective. Therefore, new ideas for increasing the strength and reducing the swelling behaviour of expansive soils are being developed. One new method which is considered to be inexpensive, accessible and environmentally friendly involves the use of waste materials such as scrap tyres.

Solid waste management is a major environmental concern worldwide. To alleviate environmental problems, waste materials are increasingly being recycled and civil engineering projects are among the popular destinations (Hong & Shahin 2010). Scrap tyres are generated and accumulated in large quantities (Hambirao & Rakaraddi 2014), and can be shredded and chipped for use as an engineering fill. Tyre chips possess low density, high durability, high thermal insulation and in many cases least cost compared to other fill materials, and Humphrey (1999) commended their use in civil engineering applications. Cetin *et al*. (2006), Akbulut *et al*. (2007), Zolfeghari Far *et al*. (2013) and Hambirao & Rakaraddi (2014) reported an increase in the unconfined compressive strength, ductility and toughness of soft (also weak) clayey soil samples when they were mixed with waste rubber. Therefore, especially because it may not be possible to stabilise peat soil in all situations using conventional methods (due to its high organic content and high pH), it is reasonable to extend the application of waste tyre materials to the stabilisation of peat soils. Although we might expect that tyre powders (as opposed to shredded tyre chips) would reduce the coefficient of permeability of clay soils, Cetin *et al*. (2006) showed that the permeability coefficient was increased by adding either powder or chips. Also, both additives have been shown to increase the damping ratio, shear modulus and unconfined compressive strength (UCS) of the soil, but shredded tyre chips provide more effective reinforcement than tyre powders (Akbulut *et al*. 2007). On this basis we chose shredded tyre chips for trial on peat soil. To limit the increase in coefficient of permeability that would arise from adding shredded tyre chips to peat soil, we also added sand.

The aim of the research reported here was to experimentally study the effect of adding different percentages of shredded tyre chips to peat soil, along with sand as a filler, and ultimately determine the optimal percentage of tyre chips in terms of highest unconfined compressive strength. Shear strength parameters (c, φ) and the coefficient of permeability of the stabilised peat soil (k) are also reported.

METHODS

Collection of peat samples

The peat soil that was tested in this study was collected from a fen peatland within the 2,300 ha Chaghakhor Wetland (Figure 1), located at 3,830 m a.s.l. in Chaharmahal and Bakhtiari Province, 160 km south-west of Isfahan (Esfahan), Iran. The peat layer ranges in thickness from 0.5 m to 4 m, and is a

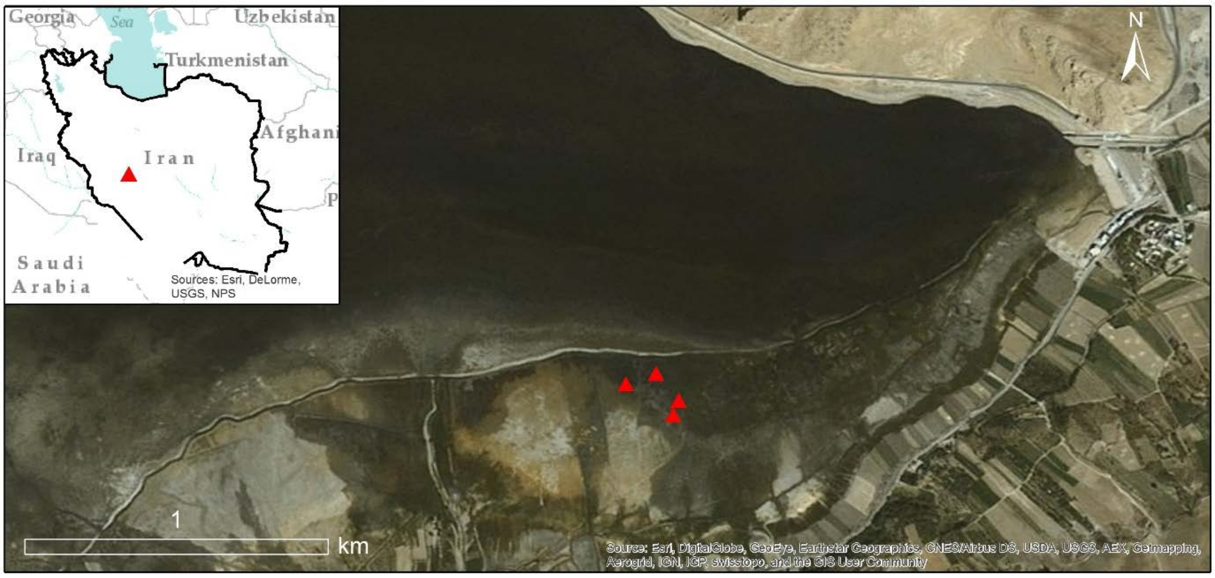

Figure 1. Main panel: peat sampling locations (red triangles) superposed on ESRI World Imagery of the eastern end of Chaghakhor Wetland. Inset: location of Chaghakhor Wetland (red triangle) within Iran; basemap from ESRI World Reference Overlay, country boundary from MapCruzin 'Iran administrative' data (Creative Commons Attribution Share-Alike 2.0, www.openstreetmap.org and www.mapcruzin.com).

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potential hazard for a proposed development of ecotourism facilities. The site, sampling procedure and peat characteristics are described by Rahgozar & Saberian (2015). Peat samples were collected from the floors of four incrementally excavated pumped pits when they reached depths of 0.6, 1.2, 1.8, 2.4 and 3.0 m (total peat depth at the sampling locations ranged from 3.4 m to 4.0 m, Table 1). Each sample was augered out from an area approximately 30 cm in diameter, to a depth of ~20 cm. The locations of the sampling sites are given in Table 1 and basic properties of the peat are summarised in Table 2.

Preparation of specimens

The procedures for making the stabilised soil admixtures and preparing test specimens followed Hebib & Farrell (2003). The admixtures contained peat, sand and shredded (rubber) tyre chips. From an engineering point of view, there were no significant differences in the properties of peat collected from different depths or sampling locations (Rahgozar & Saberian 2015). Therefore, peat taken from the five different depths in all four field sampling pits was evenly mixed to produce a single composite sample. Still at its natural moisture content (446–593 %), the peat was then was then pushed through a 2 mm sieve (using a gloved hand) to homogenise it and remove coarse particles. The particle size distribution of the well-graded sand (from soil mechanics laboratory stock) was in accordance with ASTM F2396-11 (Figure 2). The dimensions of the shredded tyre

Table 1. Chaghakhor peat sampling locations and total peat thickness (adapted from Rahgozar & Saberian 2015).

Core	Latitude (N)	Longitude (E)	Thickness of peat (m)
1	31° 54' 50.03"	50° 55' 26.47"	3.6
2	31° 54' 51.56"	50° 55' 27.04"	3.8
3	31° 54' 54.44"	50° 55' 24.60"	3.4
4	31° 54' 53.33"	50° 55' 21.37"	4.0

Table 2. Basic properties of Chaghakhor peat (adapted from Rahgozar & Saberian 2015).

Basic soil property	Range of values	Method
Natural moisture content (%)	446–593	ASTM D2974-87
Initial void ratio	7.28–7.48	ASTM D2435
von Post humification	H2–H4	Landva & Pheeney (1980)
Linear shrinkage (%)	53–57	ASTM D427
Density of solids	1.43–1.56	ASTM D854
Organic content (%)	82–89	ASTM D2974-87
Ash content (%)	11–15	ASTM D2974-87
Fibre content (%)	80–83	ASTM 1997-91
Bulk density (Mg m^{-3})	0.88–0.94	ASTM D2937-00
Dry density (Mg m^{-3})	0.16–0.21	Den Haan (1997)*
Liquid limit, LL (%)	334–380	ASTM D4318-00†
pH of peat	4	BS 1377:1990 Test 11 (A)
pH of groundwater	4.5	BS 1377:1990 Test 11 (A)

*$\gamma_d = 35.075\omega^{-0.856}$, where ω is natural moisture content (%). †using water collected at sampling location.

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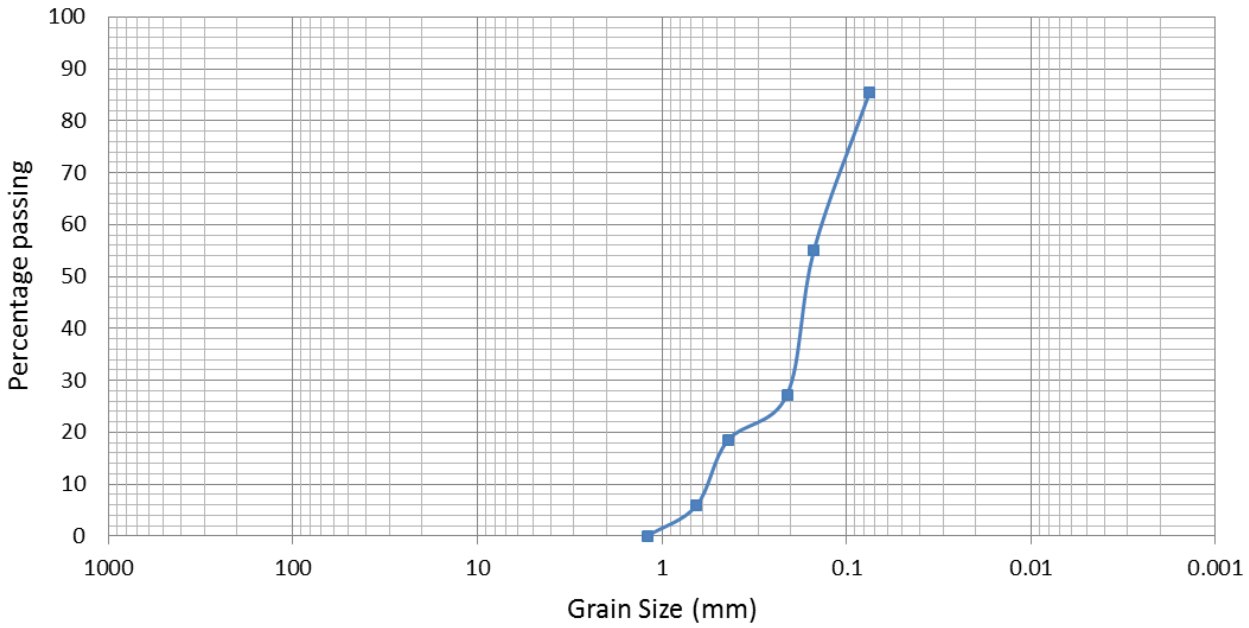

Figure 2. Particle size of distribution of the well-graded sand used as a filler. The underlying data are also provided (on the right).

Sieve size (mm)	Weight retained (%)
1.180	5.86
0.600	12.56
0.425	8.79
0.212	27.91
0.150	30.31
0.075	14.57

chips, sourced from a local recycling facility in Isfahan, were 20 × 15 × 0.5 mm (Figure 3).

Four stock mixtures of peat, sand and shredded tyre chips were prepared. All of them contained 16.25 kg of peat (~ 920 kg m^{-3}) and 8.06 kg of sand (400 kg m^{-3}), but they differed in the dosage of shredded tyre chips added (5 %, 10 %, 15 % or 20 % of the weight of peat). To produce each stabilised soil admixture, the sieved peat was intimately mixed with the shredded tyre chips and sand by agitating with a gloved hand for ten minutes (Wong *et al*. 2013).

Test specimens for unconfined compression, direct shear and falling head permeability tests were prepared by packing the stabilised soil admixture into moulds of different sizes. Specimen sizes are given in Table 3. The moulds used for the unconfined compression test were plastic tubes (50 mm internal diameter, 250 mm long). For direct shear tests, the internal dimensions of each mould were 60 × 60 × 25 mm. For falling head tests, the moulds (lower chamber sections for the permeameter) were cylindrical (100 mm internal diameter × 250 mm tall). The test material was packed into the moulds in layers and compacted using a tamping device.

Figure 3. Shredded tyre chips. The dimensions of each chip are 20 × 15 × 0.5 mm.

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Table 3. Sizes of soil specimens for unconfined compression, direct shear and falling head permeability tests.

Test	Dimensions of soil specimens
Unconfined compression	50 mm diameter ×150 mm height
Direct shear	60 mm × 60 mm cross-section × 20 mm height
Falling head	100 mm diameter × 130 mm height

Geotechnical tests

Unconfined compression (ASTM D2166-06), direct shear (ASTM D3080-04) and falling head permeability (ASTM D5084-03) tests were performed to quantify the mechanical properties of the test specimens. The direct shear tests were drained. All laboratory testing methods followed the manual of soil laboratory testing developed by Head (2006) according to US (ASTM) Standards, and are described in more detail by Rahgozar & Saberian (2015). Each test was replicated three times (on three different specimens) and a mean result computed.

The unconfined compression test was conducted by placing the prepared specimen in the compression device and applying load so that the device produced axial strain at a rate of 1 % per minute, then the dial readings for load and deformation were manually recorded at 30-division increments of deformation.

For each peat admixture, a series of direct shear tests was carried out using different specimens, with three normal stresses of 55.5, 111 and 222 kPa. Although an untreated peat soil may not experience (or be capable of withstanding) normal stress of such magnitudes, this stress range is realistic when the peat has been stabilised for construction purposes. To obtain the values of cohesion (c) and angle of internal friction (φ) parameters for each stock mixture, the data were plotted and a Mohr-Coulomb line was fitted.

The falling head tests were conducted using a laboratory permeameter. The time taken for a measured quantity of water to flow through the specimen was recorded, and the coefficient of permeability (m s^{-1}) was calculated using a standard formula.

Controls

To evaluate the degree of improvement in the mechanical properties of the test specimens and to attribute it between the different additives, the measured properties of the stabilised soil must be compared with those of (a) untreated peat and (b) peat with sand (only) as an additive. Therefore, unconfined compression, direct shear and falling head tests were also carried out on three replicate specimens prepared from the composite (mixed) sample of peat from the Chaghakhor site without any additives, and on three replicate specimens taken from an additional stock mixture prepared by mixing Chaghakhor peat with sand (only) at a dosage of 400 kg m^{-3}.

Electron micrographs

The microstructure of the untreated and stabilised peat was examined on scanning electron micrographs obtained using VEGA3 TESCAN apparatus (TESCAN USA Inc.).

RESULTS

Geotechnical properties of stabilised peat soil

Figure 4 shows the relationships between unconfined compressive stress and normal strain for untreated Chaghakhor peat, the peat/sand mixture and the four admixtures with sand and tyre chips. Figure 5 shows how the unconfined compressive strength varied with the percentage of shredded tyre chips added. The admixture with 10 % shredded tyre chips had the highest unconfined compressive strength (405 kPa).

The results of the direct shear tests, with Mohr-Coulomb lines fitted, are shown in Figure 6. All of the (stabilised) admixtures had much higher cohesion and friction angle values than untreated peat. For admixtures containing shredded tyre chips, the Mohr-Coulomb lines for specimens with different percentages (5 %, 10 %, 15 % and 20 %) of tyre chips are more or less parallel, indicating that friction angle is independent of the dosage of tyre chips.

Table 4 lists direct shear and permeability parameters for example specimens of stabilised peat with different percentages of shredded tyre chips, as well as those for the controls. This Table also shows the percentage improvement (increase) in the c and φ parameters, coefficient of permeability (*k*) and UCS relative to untreated soil. For each test mixture the results for the three replicate samples are shown and the improvements indicated are calculated using the mean test results for these three samples.

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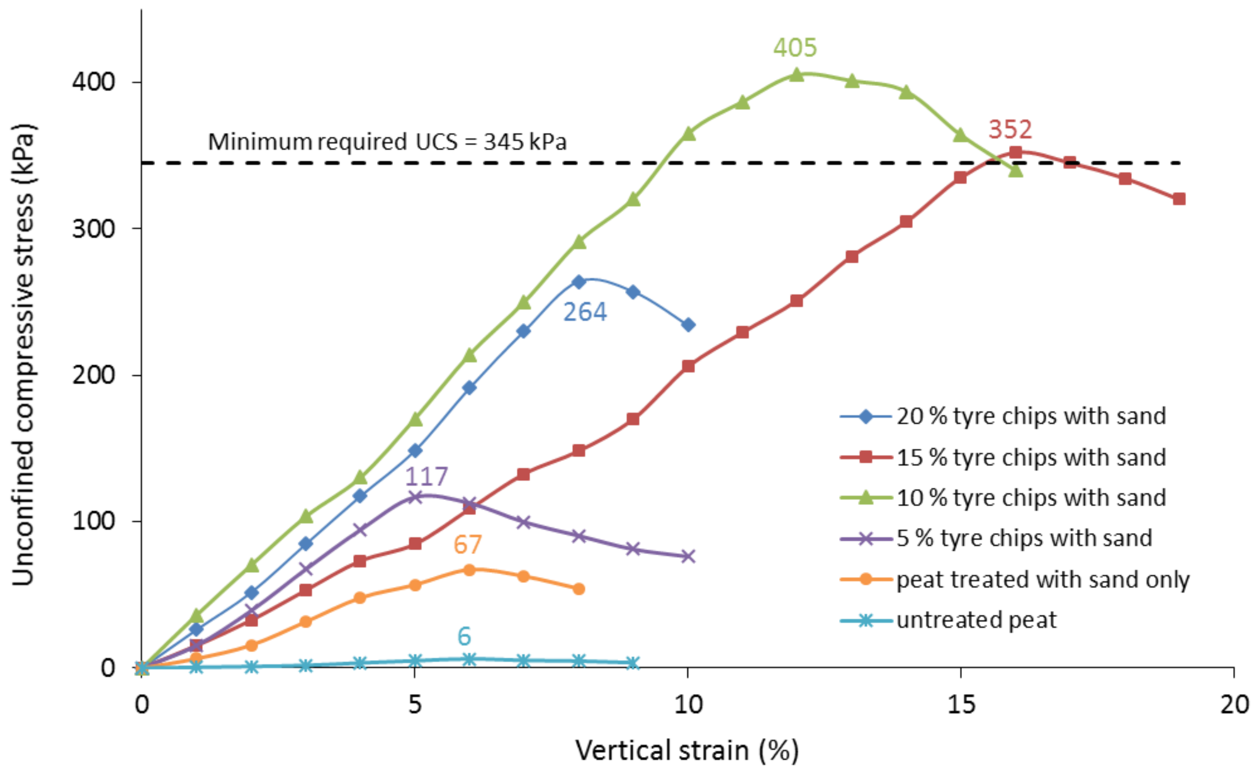

Figure 4. Results of unconfined compression testing for different soil specimens. In each case, unconfined compressive strength (UCS) is equal to stress (the label value) at the peak of the stress-strain curve.

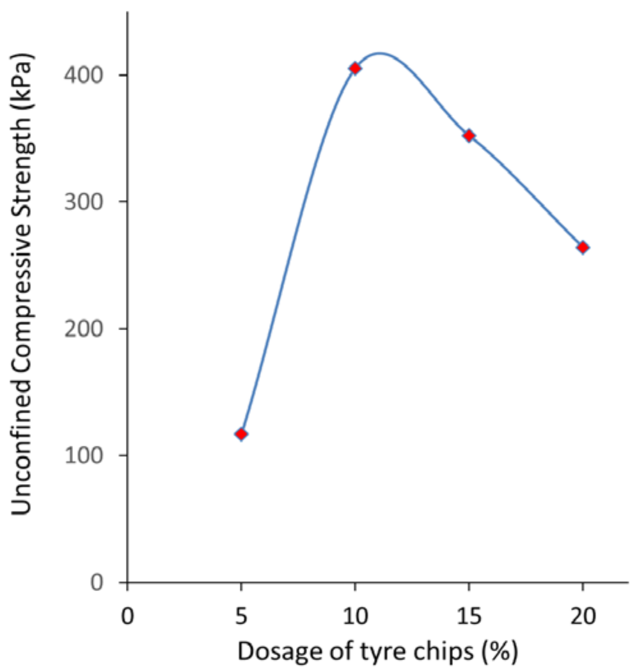

Figure 5. Effect of shredded tyre chips at dosages ranging from 5 % to 20 % on the unconfined compressive strength (UCS) of stabilised peat. The values of UCS are derived from Figure 4.

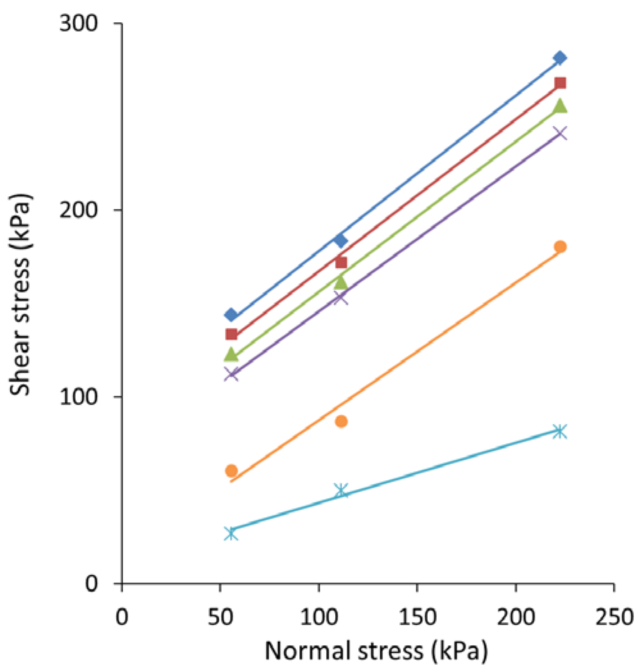

Figure 6. Results of direct shear tests for different soil specimens, with Mohr-Coulomb lines fitted. In each case, cohesion (c) is given by the y-intercept and angle of internal friction (φ) by the slope of the line. For the key to specimen treatments, see Figure 4.

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Table 4. Experimentally measured shear strength parameters cohesion (c) and angle of internal friction (φ), coefficient of permeability *k* (at 20 °C), and unconfined compressive strength (UCS), of stabilised Chaghakhor peat specimens and controls.

Dosage of sand (kg m^{-3})	Dosage of tyre chips (%)	c (kPa)			φ (degrees)			k (m s^{-1})			UCS (kPa)		
		Test results	Mean value	Increase (%)	Test results	Mean value	Increase (%)	Test results	Mean value	Increase (%)	Test results	Mean value	Increase (%)
0	0	10.4 11.1 11.2	11.2	0	17.6 17.8 17.8	17.8	0	6.2×10^{-5} 6.9×10^{-5} 7.1×10^{-5}	6.7×10^{-5}	0	5.9 6.5 6.5	6.3	0
400	0	13.1 16.0 12.9	14.0	25	38.5 35.2 35.5	36.4	104	5.1×10^{-9} 5.0×10^{-9} 6.2×10^{-9}	5.4×10^{-9}	-1,240,740	65.3 67.5 68.7	67.2	966
400	5	66.9 68.5 69.5	68.3	508	36.8 37.4 39.0	37.7	112	6.5×10^{-8} 6.8×10^{-8} 7.9×10^{-8}	7.1×10^{-8}	-94,366	114.2 116.7 119.5	116.8	1,753
400	10	74.3 75.9 77.1	75.8	574	37.6 39.7 39.1	38.8	118	3.9×10^{-8} 3.8×10^{-8} 5.2×10^{-8}	4.3×10^{-8}	-155,813	402.4 405.7 408.1	405.4	6,334
400	15	83.7 87.1 86.2	85.7	663	38.0 38.4 40.9	39.1	120	5.0×10^{-7} 5.2×10^{-7} 6.2×10^{-7}	5.6×10^{-7}	-11,964	348.6 351.4 356.9	352.3	5,492
400	20	92.6 96.6 95.1	94.8	744	38.2 40.1 41.0	39.8	123	5.9×10^{-6} 6.2×10^{-6} 7.1×10^{-6}	6.4×10^{-6}	-1,046	260.8 264.3 267.5	264.2	4,093

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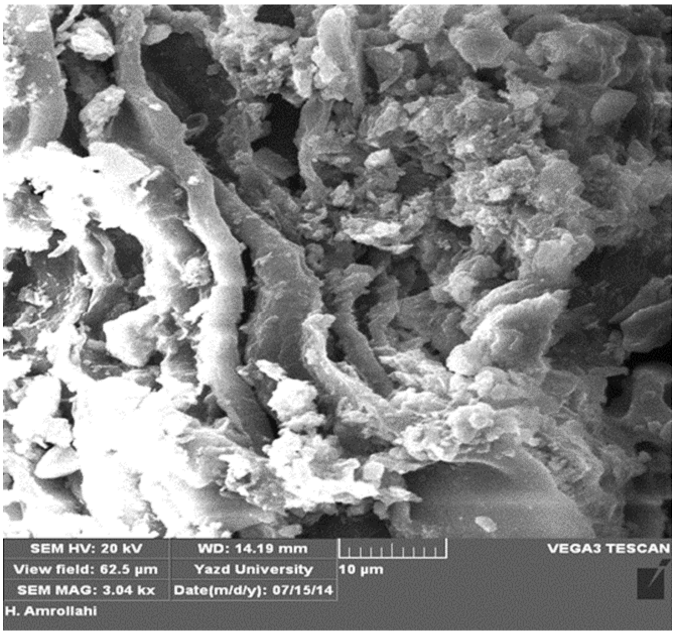
Electron micrographs

Figure 7 shows scanning electron micrographs (SEM) of air-dried samples of untreated and treated (10 % shredded tyre chips) Chaghakhor peat. The tyre chips themselves were too large to be included in the specimens prepared for electron microscopy. It is clear that the untreated peat is loosely composed of fibres and coarse organic particles in random order. Each coarse organic particle contains inner pores which render the soil capable of retaining a considerable amount of water when fully saturated. Hence, it can be stated that the soil is characterised by inner pores within the coarse organic particles and outer pores between soil particles and fibres. This description of the microstructure of untreated peat conforms with the finding of Kogure *et al*. (1993) that a physical peat soil model may be developed in which the soil can be divided into two major components, namely organic bodies and organic spaces. The organic bodies consist of organic particles with their inner voids filled with water, while the organic spaces are the outer voids between soil particles, which may or may not also be filled with water (Gofar 2006, Wong *et al*. 2009).



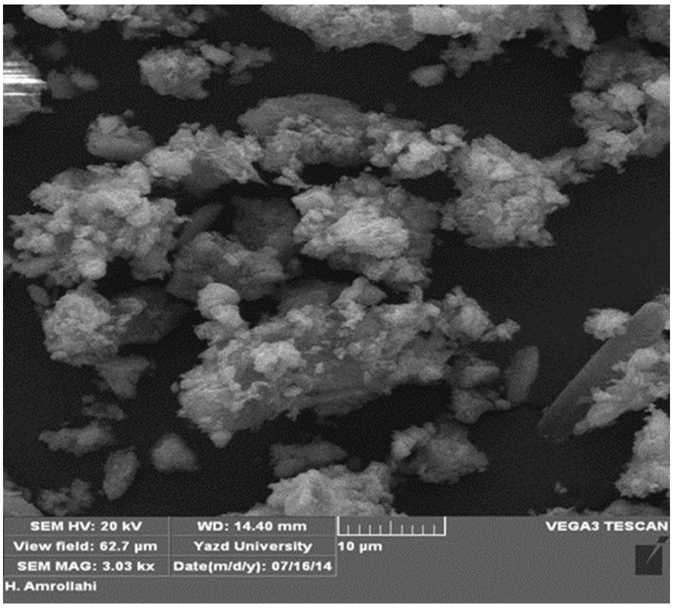


Figure 7. Scanning electron micrographs of (above) the untreated peat (from Rahgozar & Saberian 2015), and (below) the peat stabilised with 10 % shredded tyre chips and sand (no tyre chips in SEM specimen).

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DISCUSSION

In previous trials of a variety of potential stabilising additives for peat soils, sand has often been included at dosages of 300–600 kg m^{-3}, either as a filler or to bond with other ingredients such as cement or lime (Wong *et al*. 2008, Wong *et al*. 2013). The addition of sand has no adverse chemical effects, causes a reduction in void ratio of the soil, and increases the number of soil particles. Filling the pore spaces with sand strengthens the structural matrix of the soil, reducing compressibility and providing additional shear strength (Wong & Hashim 2008). Perhaps for this reason, sand has invariably been included in the admixtures tested within previous studies on stabilising weak soils (such as clay) with shredded tyre chips. In our study to determine the optimum percentage of shredded tyre chips for stabilising Chaghakhor peat, we followed other authors by including sand in our stock mixtures at a constant dosage (400 kg m^{-3}) chosen as the average of concentrations used in previous research. However, we also evaluated the effect of adding sand only (at the same dosage) to the peat.

The role of shredded tyre chips in stabilised soil admixtures is similar to that of the fibres in reinforced concrete, in that they reduce the formation of cracks and limit widening of any cracks that do form. The chips considered by Zornberg *et al*. (2004) for stabilising a sandy soil measured 12.7 × 25.4 mm, while Singh & Vinot (2011) used three chip sizes (10 × 10 mm, 10 × 20 mm and 10 × 30 mm) for stabilising silty clay and sand. These authors found that sand reinforced with tyre chips had greater shearing resistance than unreinforced sand, and reported optimum tyre chip contents of up to 30 % for highest shear strength. The inclusion of tyre chips also led to a reduction in loss of post-peak ultimate strength. Since previous researchers did not indicate any preferred chip dimensions, for our trials on peat soils we chose chips that were around the average size used in previous studies on other soil types (20 × 15 × 5 mm).

ASTM D4609 (Standard guide for evaluating effectiveness of admixture for soil stabilisation) specifies that, in order for a soil stabilisation treatment to be considered effective, the resulting unconfined compressive strength must be 345 kPa (50 psi) or more (Sariosseiri & Muhunthan 2009). Adding sand (alone) to Chaghakhor peat increased soil strength to 67 kPa, which is well below the ASTM requirement (Figure 4). With tyre chip dosages of 10 % and 15 %, the unconfined compressive strength exceeded the threshold of 345 kPa (Figures 4 and 5). It can be observed from Figure 4 that the test specimen with 10 % shredded tyre chips had the highest unconfined compressive strength which, at 405 kPa, was around 64 times that of untreated peat (6 kPa). Hong & Shahin (2010) and Zolfeghari *et al*. (2013) reported a similar trend of increase in the unconfined compressive strength of clayey and tropical soils when they were stabilised with shredded tyre chips.

In the unconfined compressive strength tests, the stabilised peat specimens generally showed an initial (rather) linear elastic curve followed by plastic deformation and energy absorption before fracture, indicating ductile (as opposed to brittle) behaviour (Whitlow 2001). A brittle material (e.g. cast iron, concrete, soil) is characterised by a steep linear elastic curve followed almost immediately by the breaking point, with no apparent plastic deformation and energy absorption before fracture. For a ductile material, after a linear elastic curve, the material yields, showing extensive plastic deformation and energy absorption with a small increase in stress ("toughness") before fracture. Materials that are capable of sustaining more plastic deformation before failure are considered more ductile. In our tests, the sample with 10 % shredded tyre chips had the highest modulus of elasticity (stress ÷ strain) of 3.5 MPa and the highest unconfined compressive strength of 405.41 kPa at 12 % vertical strain (Figure 4), although this admixture started to yield at around 10 % vertical strain. The sample with 15 % shredded tyre chips had a lower modulus of elasticity and could sustain a vertical strain of 16 % before failure, although its maximum unconfined compressive strength (352 MPa) was only just above the required threshold (Figure 4).

According to Figure 4, both the strength and the ductility of the stabilised peat soil increases with the percentage of shredded tyre chips added. This is expected because highly organic soil such as peat tends to have very poor mechanical properties. The sample with 10 % tyre chips showed the highest strength and stiffness and considerably improved ductility, although the ductility of the sample with 15 % tyre chips was slightly higher than that of the sample with 10 % tyre chips. This increased strength and ductility may prevent the soil from cracking and/or failing under load. The reason for the decline in strength and stiffness at tyre chip concentrations above 10 % is the reduction in bonding between chips and soil caused by the reduction in homogeneity and consistency of the peat. Similar effects have been observed by Turatsinze *et al*. (2005), who studied electron micrographs of bonding between rubber shreds and cement paste; and by Akbulut *et al*. (2007) and Hong & Shahin (2010) when experimenting on

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the utilisation of shredded tyre chips with soft clays.

From Figure 4 and Table 4 it can be seen that mixing sand (alone) with the peat improved cohesion (c) and angle of internal friction (φ) by 25 % and 104 %, respectively. The mixture with 20 % shredded tyre chips exhibited the highest values of c and φ, with cohesion 8.4 times and angle of internal friction 2.2 times the corresponding values for untreated peat; whereas for the mixture with 5 % tyre chips the c value was only 6.08 times and the φ value 2.1 times that of untreated soil. These findings are consistent with the results of research by Cetin (2006) and Akbulut (2007) on the effect of shredded tyre chips on engineering properties of clayey soil. They also indicate that, whereas adding tyre chips at dosages increasing from 5 % continues to enhance the improvement in cohesion achieved by adding only sand to the peat, there is little further effect on φ.

At a standard temperature of 20 °C, the coefficient of permeability of the Chaghakhor peat soil was found to be comparable to that of very fine silty sand (Table 4), and thus in agreement with the findings of Colley (1950), Miyakawa (1960), Berry & Vickers (1975) and Wong *et al*. (2013) that the coefficient of permeability of fibrous peat is between 10^{-6} and 10^{-5} m s^{-1}. Thus, in its initial untreated condition, the peat had moderate permeability and good drainage capability. Adding sand reduced the coefficient of permeability significantly (by 1.24×10^{6} %), to 5.4×10^{-9} m s^{-1}. When tyre chips were also added, the volume of voids in the sample increased, giving a higher permeability coefficient. However, the coefficient of permeability of the mixture with 5 % tyre chips (7.1×10^{-8} m s^{-1}) was still reduced by 9.5×10^{2} times in comparison with untreated peat. As expected, the permeability coefficient increased as the percentage of tyre chips increased, and was highest (6.47×10^{-6} m s^{-1}) for the mixture with 20 % tyre chips.

Thus, although the friction angle was not very sensitive to tyre chip dosage above 5 %, both the cohesion and the coefficient of permeability of the stabilised peat were quite strongly affected by the percentage of tyre chips added.

From the microscopic appearance of the stabilised peat (Figure 7b), it can be concluded that the stabilised soil is characterised by a well-structured matrix with very small pores, due to sand filling a large proportion of the voids. This causes the stabilised soil to retain less pore water and, therefore, increases its compressive bearing strength.

Thus, we can conclude from this case study that the stabilisation of Chaghakhor peat soil with waste tyre chips and sand is capable of improving its foundation characteristics to a level that is suitable for major civil engineering projects. Of the different dosages of shredded tyre chips (dimensions 20 × 15 × 0.5 mm) tested (in combination with 400 kg m^{-3} of sand), the optimal percentage of tyre chips has been found to be about 10 % of the weight of peat in the mix. There are other additives (e.g. pozzolanic binders such as cement, lime and gypsum) that may be applied along with tyre chips and sand, which can be expected to additionally enhance the strength of peat soil. Further research is needed to explore the effects of these other potential additives.

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