Geotechnical properties of peat soil stabilised with shredded waste tyre chips in combination with gypsum, lime or cement

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SUMMARY

Peat has a high content of water and organic substances. These weak components can cause low bearing capacity and high consolidation settlement under load, which means that peat deposits must usually be stabilised if they are to bear constructions such as buildings or roads. In this study we investigated the performance of waste tyre chips (10 % by weight) and sand (400 kg m^{-3}) supplemented with a pozzolanic binder (gypsum, lime or cement) at a range of dosages (5 %, 10 % or 15 % by weight) as a stabiliser for peat soil. Peat samples were taken from a fen peatland at Chaghakhor Wetland in Chahar Mahal and Bakhtiari Province, Iran. In total, 162 test specimens were prepared and subjected to laboratory strength testing (unconfined compression test and direct shear test). Additionally, the pH of each admixture was recorded immediately after mixing, elemental compositions were determined by X-Ray Fluorescence (XRF), and structures were examined using Scanning Electron Microscopy (SEM). It was observed that: (1) the total percentage of pozzolanic compounds in the peat soil was well below the minimum of 70 % set by the standard ASTM C 618 (ASTM 2000), so an additive such as cement, lime or gypsum would certainly be required; (2) specimens stabilised with gypsum or lime showed improvements in unconfined compressive strength (UCS), but those stabilised with ordinary Portland cement exhibited the greatest improvement in UCS (up to 12,200 %) as well as improvements in the direct shear parameters c and φ; (3) according to the XRF tests, additives such as cement, lime and gypsum introduced considerable amounts of Si, Al, Ca and O, which are important for pozzolanic reactions in peat soils; and (4) on the basis of the results of UCS and direct shear tests, the optimum percentage of the additives tested would be 5 %.

KEY WORDS: direct shear test, pozzolan, Unconfined Compressive Strength test, X-Ray Fluorescence

INTRODUCTION

Peat consists of more than 75 % organic substances and is formed when organic matter (usually vegetation) is preserved below a high water table in swamps or wetlands (Jarret 1997, Warburton *et al*. 2004, Youventharan *et al*. 2007, Xintu 2008, Kalantari 2013). In the context of construction engineering, peat is commonly regarded as a problematic deposit with poor geotechnical properties, which invariably requires stabilisation if it is to support any structure and/or infrastructure (Wong *et al*. 2008, Hashim & Islam 2008, Tang *et al*. 2011, Long & Boylan 2012). The main purposes of soil stabilisation are to improve stability, increase bearing capacity, and reduce settlement and lateral deformation (Wong *et al*. 2013). Although various methods are available (Chen & Wang 2006, Zainorabidin & Wijeyesekera 2007), not all of these can be expected to prove both effective and affordable in any particular project. Thus, there is an ongoing need for new methods (Puppala & Musenda 2002). Recent innovations in soil stabilisation include the development of methods that utilise waste materials such as scrap tyres, which are inexpensive, accessible and not harmful to the soil.

Solid waste management is a major environmental concern worldwide, and the generation and accumulation of scrap tyres is a recognised problem (Hambirao & Rakaraddi 2014). Civil engineering projects are increasingly popular destinations for recycled waste materials (Hong & Shahin 2010), and the properties and usually low cost of powdered rubber and chips manufactured from scrap tyres commends them for use as an engineering fill (Humphrey 1999). Several authors have mixed waste rubber tyre powders and/or shredded tyre chips with samples of soft, weak clayey soils and reported that this increases the unconfined compressive strength (UCS), ductility and toughness of the soil (Cetin *et al*. 2006, Akbulut *et al*. 2007, Zolfeghari Far *et al*. 2013, Hambirao & Rakaraddi 2014). Rahgozar & Saberian (2016) investigated the feasibility of extending this approach to the stabilisation of peat soils. They conducted a comprehensive study of the effects of adding sand (filler) at constant dosage (400 kg m^{-3}) and different dosages (5–20 % by weight) of tyre chips on key geotechnical properties of a well-characterised (Rahgozar & Saberian 2015) peat soil from the Chaghakhor Wetland in Iran. The effects included:

1) an increase of unconfined compressive strength (UCS);
2) significant improvement in the ductility of treated samples;
3) increased shear strength parameters (cohesion (c) and angle of internal friction (φ)) of the stabilised peat; and
4) desirable filling of soil pore spaces by the sand (Wong & Hashim 2008), as observed from scanning electron micrographs (SEM) of test specimens.

To set these observations in context, Table 1 summarises the results of some previous research on stabilising peat with different additives and the improvement in UCS achieved in each case. Of the additives listed (other than tyre chips and sand), gypsum and lime are reasonably inexpensive and accessible, and cement appears to be rather effective. Kolay & Pui (2010) found that adding 6 % by weight of gypsum to peat soil increased UCS from 6.5 kPa to 44.94 kPa, whereas Said & Taib (2009) achieved an improvement in UCS from 38.3 kPa to 115.5 kPa by adding 12 % by weight of lime. Wong *et al*. (2008) observed a substantial jump in UCS from 4.5 kPa to 178.6 kPa when they added 225 kg m^{-3} of cement and 75 kg m^{-3} of sand to peat soil, while Nikookar & Karimi Pashaki (2012) observed an increase in UCS from 45 kPa for untreated peat to 264.1 kPa when they added 10 % by weight of both cement and sand.

According to ASTM D4609 (standard guide for evaluating effectiveness of admixture for soil stabilisation), soil stabilisation is effective if the resulting UCS is at least 345 kPa (50 psi) (Sariosseiri & Muhunthan 2009). This was not achieved with any of the peat treatments mentioned so far. However, Skels *et al*. (2013) exceeded the 345 kPa threshold by

Table 1. Summary of some previous research on the use of different additives for stabilisation of peat soil, arranged in order of increasing UCS after treatment. The thick dashed line indicates the position in the list of the UCS threshold (345 kPa) set by the ASTM D4609 standard.

Additive(s)	Dosage of additive(s)		UCS of peat (kPa)		Reference
	weight (%)	kg m^{-3}	untreated	treated	
gypsum	6	-	6.5	44.9	Kolay & Pui (2010)
fly ash	25	-	6.5	109.67	
lime	12	-	38.3	115.3	Said & Taib (2009)
Class F pond ash	20	-	54.0	153.9	Kolay *et al*. (2011)
cement sand	- -	225/300 (75%) 75/300 (25%)	4.5	178.6	Wong *et al*. (2008)
cement sand	10 10	-	45.0	264.1	Nikookar & Karimi Pashaki (2012)
cement	-	300	-	403.3	Skels *et al*. (2013)
sand shredded tyre chips	- 10	400 -	6.3	405.4	Rahgozar & Saberian (2016)
cement calcium chloride sodium bentonite	- - -	270/300 (90%) 12/300 (4%) 30/300 (10%)	-	415.0	Wong *et al*. (2013)

almost 60 kPa (UCS = 403.3 kPa) by adding 300 kg m^{-3} of ordinary Portland cement, and the maximum UCS attained using sand and tyre chips (10 % by weight) by Rahgozar & Saberian (2016) was 405 kPa. This UCS value was slightly exceeded (415 kPa) in only one of the studies identified from literature, in which 300 kg m^{-3} of an additive comprising cement, calcium chloride and sodium bentonite was mixed with peat (Wong *et al*. 2013).

Unlike sand and tyre chips (which are chemically inert in this application), additives such as gypsum, lime and cement (known as binders) react chemically with the peat soil matrix, changing its physical properties such as moisture content, and thus influencing its chemical and engineering properties such as pH, shear strength and compressibility. A pozzolan is a siliceous or siliceous and aluminous material which will, in finely divided form and in the presence of water, react with calcium hydroxide at ordinary (ambient) temperatures to form compounds possessing cementitious properties. In pozzolanic reactions, Ca^{2+} ions from additives (binders) react with alumina and silica in the soil to create calcium silicate hydrate (CSH: $3CaO{\cdot}2SiO_2{\cdot}3H_2O$) and calcium aluminate hydrate (CAH: $3CaO.Al_2O_3$). These compounds then crystallise, increasing soil strength, given adequate curing times (Hebib & Farrell 2003, Tang *et al*. 2011).

The weak structure of peat results from an imbalance between Na^+ and Ca^{2+}. Increasing the concentration of soluble Ca^{2+} can improve aggregation, water infiltration, soil drainage and root penetration. Gypsum ($CaSO_4.2H_2O$) is one of the sub-families of calcium sulphates. This means that each gypsum molecule contains one Ca^{2+} cation, one SO_4^{2-} anion and two molecules of water (H_2O). Thus, gypsum can compensate for the shortage of Ca^{2+} in peat soil for stabilisation purposes.

In lime stabilisation, quicklime (CaO) reacts with water in the soil to form hydrated (slaked) lime ($Ca(OH)_2$). In addition to chemically binding water, this reaction releases heat, which promotes faster reactions and a reduction of water content. Stabilisation of the soil occurs during the reaction because of ion exchange reactions. Untreated peat soils contain relatively small concentrations of the pozzolans that initiate the secondary cementation reactions. Consequently, the interaction between small amounts of hydrated lime $Ca(OH)_2$ and the soil will not have any substantial effect on the secondary stabilisation reactions in untreated soil.

Portland cement is manufactured to achieve a closely controlled combination of calcium, silicon, aluminium, iron and other ingredients. There are two major chemical reactions in cement stabilisation, namely a hydration reaction between cement and water and a pozzolanic reaction between cement and soil minerals. The hydration reaction directs inaugural increases in strength because of the formation of cementation products by drying-up of the water. The pozzolanic reactions, which are long term stabilisation reactions, may continue for years (Walworth 2006). In order to significantly increase soil strength, Skels *et al*. (2013) suggest the addition of cement in large doses.

Rahgozar & Saberian (2016) found that the ASTM threshold was just exceeded (352 kPa) for Chaghakhor peat with 400 kg m^{-3} of sand and a tyre chip dosage of 15 %, and attained more comfortably (405 kPa) when the tyre chip dosage was 10 %. The standard was not met with other tyre chip dosages (117 kPa with 5 % tyre chips, 264 kPa with 20 % tyre chips). Thus, it may be possible to achieve satisfactory outcomes for many types of civil engineering projects on the peatland at Chaghakhor by using these chemically inert additives alone. However, the loads applied to a road may fluctuate significantly and at times exceed the minimum limit of 345 kPa or even 405 kPa. Therefore, in the case of road construction, a stabilisation method involving the addition of sand and tyre chips alone may not be sufficiently reliable for practical application, and the road pavement designer would be obliged to seek higher soil strengths. It might be expected that considerably higher UCS values could be attained by supplementing these additives with an optimised percentage of a binder such as gypsum, lime or cement. The goal of the research described here was to study the effects of adding gypsum, lime or cement, in addition to shredded tyre chips and sand, on the UCS and other properties of Chaghakhor peat, and to determine the curing periods required.

METHODS

Peat

The peat soil tested in this study was an evenly mixed combined sample obtained from five depths (0.6, 1.2, 1.8, 2.4 and 3.0 m) in four 3 m deep pits excavated in fen peatland on the southern shore of the lake at Chaghakhor Wetland (31° 55′ N, 50° 54′ E; Ramsar ID 1939) in Chahar Mahal and Bakhtiari Province, Iran (Figure 1). The peat ranged in thickness from 0.5 m to 4 m, and was 3.4–4.0 m deep at the sampling locations. It was brown to dark brown in colour, insignificantly to slightly decomposed (H2–H4 on the von Post scale, von Post & Granlund 1926), fibric (81 % fibre) with medium ash content (13 %) and highly acidic (pH 4.0). The site, sampling procedure

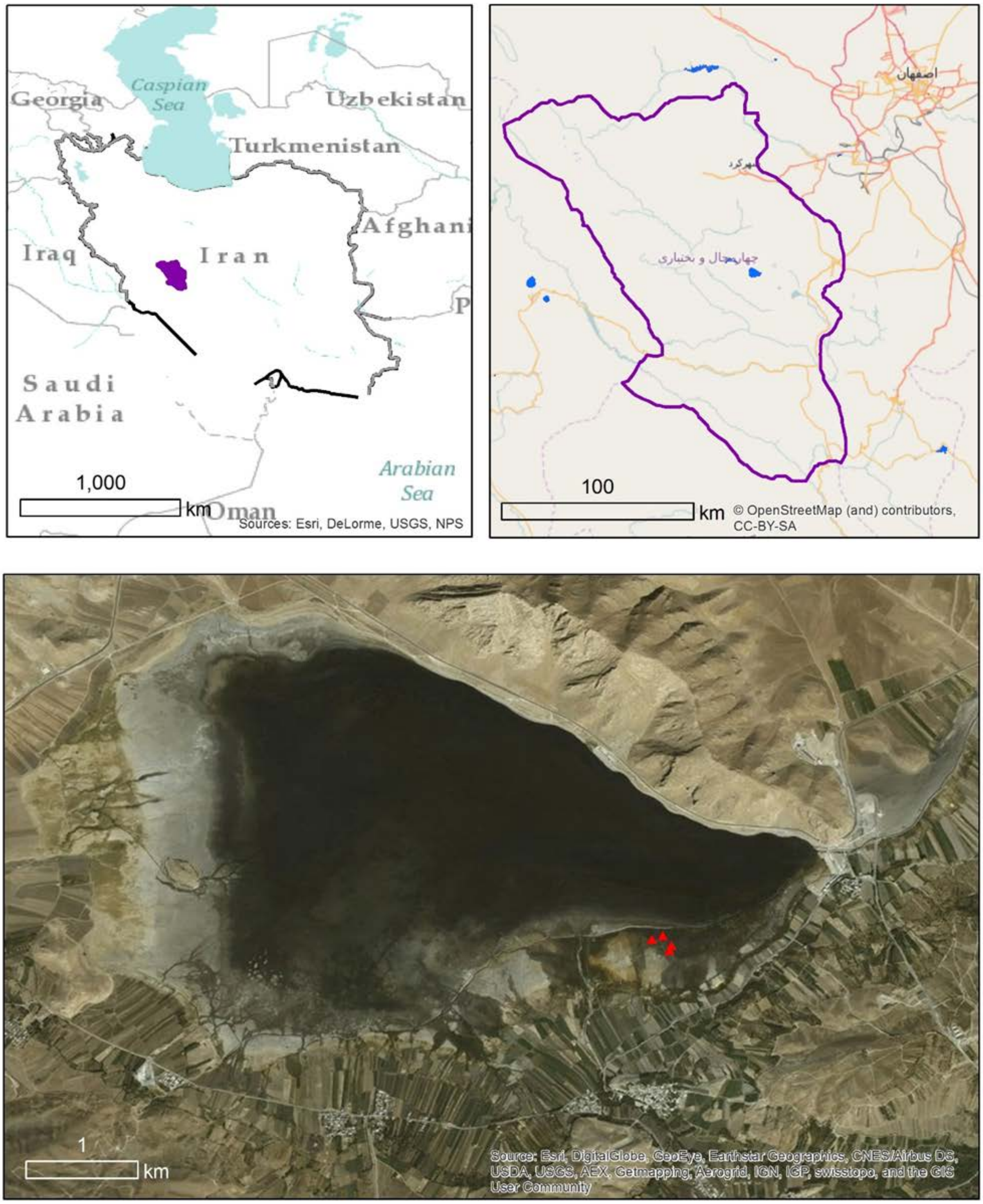

Figure 1. Location of the site where peat was collected. Top left: location of Chahar Mahal and Bakhtiari Province (purple filled shape) within Iran. Top right: location of Chaghakhor Wetland within Chahar Mahal and Bakhtiari Province (purple outline); the area of water (blue) at right-centre of the province represents Chaghakhor Wetland and the population centre at top right of the map is Isfahan. Bottom: remotely sensed imagery of Chaghakhor Wetland and its surroundings, showing the locations of the four sampling pits (red triangles).

and peat characteristics are described in detail by Rahgozar & Saberian (2015). Whilst still at its natural moisture content (446–593 %) but before mixing with additives, the peat soil was homogenised by pushing it through a 2 mm sieve.

Additives and mixing

The sand and tyre chips were as described by Rahgozar & Saberian (2016). Sand was taken from soil mechanics laboratory stock, it was well-graded, and its particle size distribution was in accordance with ASTM F2396-11 (ASTM 2000). Shredded rubber tyre chips (dimensions 20 × 15 × 0.5 mm) were sourced from a local recycling facility in Isfahan. The gypsum, lime and cement were also produced in local factories, to international construction materials standards. To produce each of the admixtures required for testing, the homogenised peat was intimately mixed with the appropriate additives by agitating with a gloved hand for ten minutes (Wong *et al*. 2013). Immediately after mixing, the pH of each admixture was determined using a pH meter according to BS1377: 1990, Test 11 (A).

Strength testing

The strength tests conducted in this study were the unconfined compressive strength (UCS) test (ASTM D2166-06) and the direct shear test (ASTM D3080-04) (ASTM 2000). The objective was to investigate the effect on strength of adding three different binders, each at three different dosages, to peat stabilised with 400 kg m^{-3} of sand filler and 10 % by weight of shredded tyre chips. The effect of curing time was also studied.

The binders tested were gypsum, lime and cement; and the dosages were 5 %, 10 % and 15 %. To study the effect of curing time, the UCS and direct shear tests were performed on different specimens 7, 14 and 28 days after binders were added. Each test was replicated three times on three different specimens. Therefore, 162 samples in total were tested in this study (3 replicates *per* treatment × 3 binders × 3 binder dosages × 3 curing times × 2 tests).

The 81 specimens for unconfined compression testing were cylindrical, 50 mm in diameter, 150 mm tall, and were prepared by packing and tamping the peat admixture into 250 mm lengths of 50 mm internal diameter plastic tubing in four equal layers. The specimens for direct shear testing were packed and tamped into square-section moulds with internal dimensions 60 × 60 × 25 mm, which were filled to a depth of 20 mm. For curing, the prepared specimens were submerged in water and subjected to an initial pressure of 50 kPa, in order to realistically simulate the natural environment of the peat (Wong *et al*. 2013).

After the required period of curing, the specimens were subjected to geotechnical testing. The unconfined compression tests and direct shear tests (undrained, at normal stresses of 55.5, 111 and 222 kPa) were conducted as described by Rahgozar & Saberian (2015, 2016).

Chemical and structural characterisation

According to ASTM C618, in order for a soil sample to be pozzolanic, its total percentage content of pozzolan oxide compounds such as SiO_2, Al_2O_3 and Fe_2O_3 must exceed 70 %. According to Isaia *et al*. (2003) a pozzolanic reaction depends on chemical and physical properties of the additives as well as the filler materials. To chemically characterise the peat soil, the additives, and their admixtures, X-ray fluorescence (XRF) tests were performed using a Bruker S4-Explorer X-Ray Fluorescence (1 kW) instrument. Samples were prepared for XRF testing using the pressed pellet method. The materials tested were the sand, gypsum, lime and ordinary Portland cement additives, as well as air-dried samples of untreated peat and three test specimens which had been treated, respectively, with 15 % of each of the three binders (gypsum, lime and ordinary Portland cement) and cured in water for 28 days. The test results were interpreted semi-quantitatively using SPECTRAPLUS V1.64 software to yield information on chemical composition, expressed as percentage contents of elements and compounds. The tyre chips additive was excluded from XRF testing because the peat soil and/or other additives do not chemically affect them.

Scanning electron micrographs showing the microstructure of example test specimens were obtained using VEGA3 TESCAN apparatus (TESCAN USA Inc., Warrendale, PA 15086, USA).

RESULTS

Table A1 (Appendix) shows the UCS values obtained for specimens stabilised with different percentages of gypsum, lime and cement after different curing periods. The percentage improvements in UCS compared to the untreated peat are also provided. It is clear that, although all specimens with additives showed increased UCS, the greatest improvement was achieved with 15 % ordinary Portland cement after 28 days of curing. This treatment delivered a UCS value that was 122.7 times that of the untreated peat, or an improvement of 12,200 %. The specimens with lime or gypsum showed similar but smaller improvements of up to 9,900 % or 7,400 %, respectively.

Figure 2 shows the relationships between unconfined compressive stress and normal strain for untreated peat, peat with 400 kg m^{-3} of sand, peat with 400 kg m^{-3} of sand and 10 % by weight of shredded tyre chips, and the latter mixture plus 15 % of each of the three additives gypsum, lime and ordinary Portland cement after 28 days of curing. The UCS (label) values increase in the order in which the various mixtures are listed above. Figure 3 shows how UCS varied with curing time for each of the nine treatments with pozzolanic additives, and how UCS after 28 days of curing varied with dosage of each of the binders.

Figure 4 shows the results of direct shear tests conducted with three normal stresses of 55.5, 111 and 222 kPa, according to ASTM D3080-04, with fitted Mohr-Coulomb lines which yield the c (y-intercept) and φ (slope) parameters for each treatment. In addition to the data for specimens with gypsum, lime and Portland cement, the results obtained for untreated peat, and peat mixed with sand and 10 % tyre chips obtained by Rahgozar & Saberian (2016) are shown for comparison. Tables A2 and A3 list the c and φ parameters for stabilised peat with different quantities of stabilising additives, as well as those of the untreated peat soils. These Tables also indicate the percentage improvements in c and φ achieved with the various additives.

For an organic soil stabilisation to be effective, the pH of the stabilised soil admixture must exceed 9 (Tremblay *et al*. 2002, ASTM D4609). pH values for the stabilised peat admixtures immediately after mixing are shown in Table 5. When gypsum (all tested dosages) was added to the peat the pH rose to 7.1, with 5 % lime it rose to 8.0, and with 5 % Portland cement it rose to 8.5. The pH ≥ 9 requirement was met with 15 % lime, and with both 10 % and 15 % Portland cement.

Table 6 provides the XRF test results for oxide compounds in the three pozzolanic binders utilised for the stabilisation of peat in this study. Also, four air dried samples of test specimens with 15 %

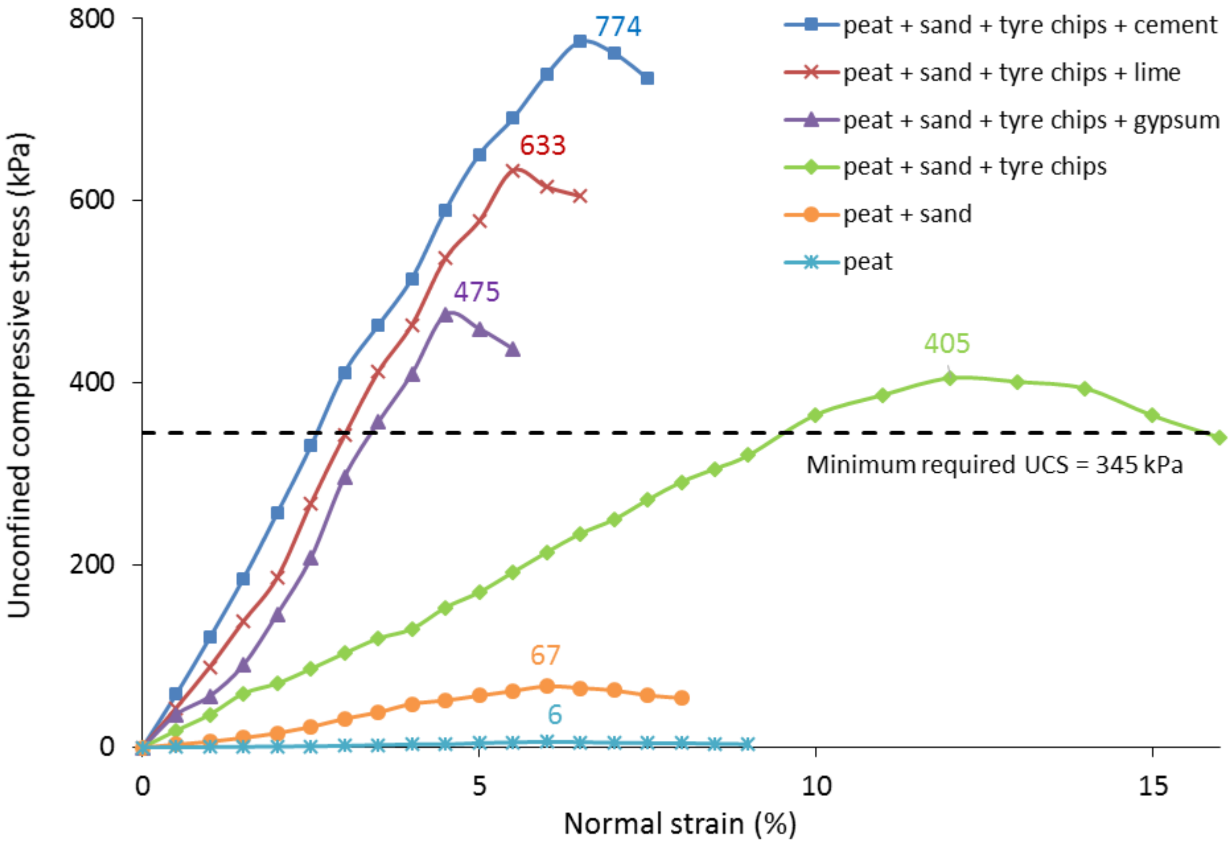

Figure 2. Variation of unconfined compressive strength (UCS) with normal strain in unconfined compression testing for untreated Chaghakhor peat, peat with 400 kg m^{-3} of sand and peat with sand and 10 % by weight of shredded tyre chips, from Rahgozar & Saberian (2015, 2016); and for peat with sand (400 kg m^{-3}), tyre chips (10 %) and 15 % by weight of one of the three pozzolanic additives (gypsum, lime or ordinary Portland cement) after 28 days of curing. In each case, UCS is equal to stress (the label value) at the peak of the stress-strain curve. The minimum UCS requirement set by ASTM D4609 is also shown.

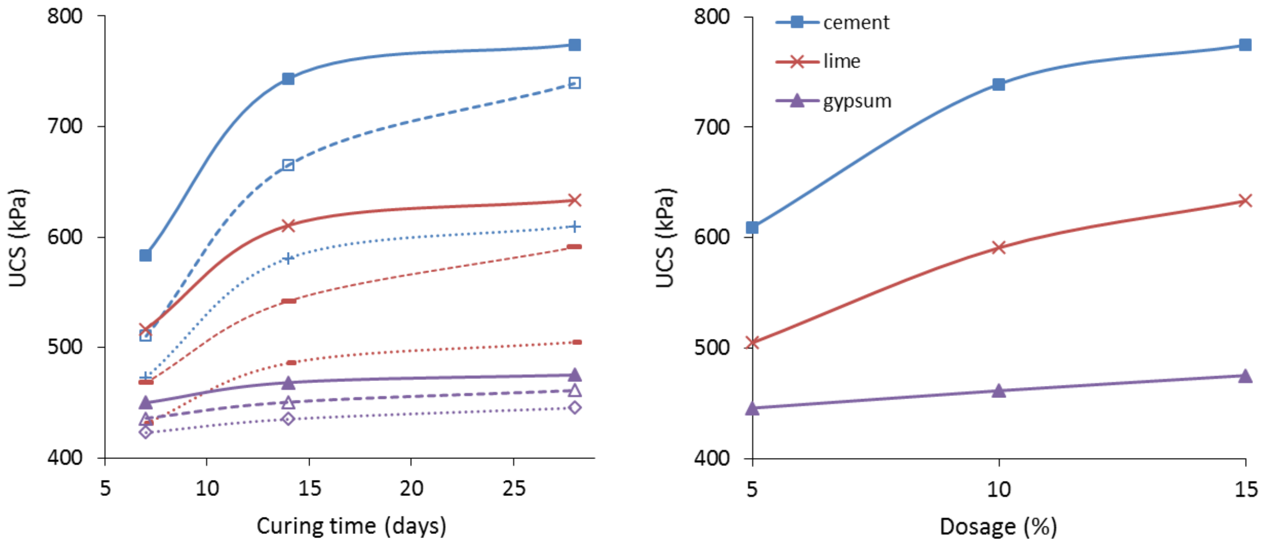

Figure 3. Left: variation of unconfined compressive strength (UCS) with curing time for specimens of Chaghakhor peat stabilised with 400 kg m^{-3} of sand and 10 % by weight of tyre chips, with different percentages of the three pozzolanic additives. For key to symbols, see Figure 4 (below). Right: variation of UCS with dosage (%) of each of the three pozzolanic additives (gypsum, lime, ordinary Portland cement) for the same specimens after a curing time of 28 days.

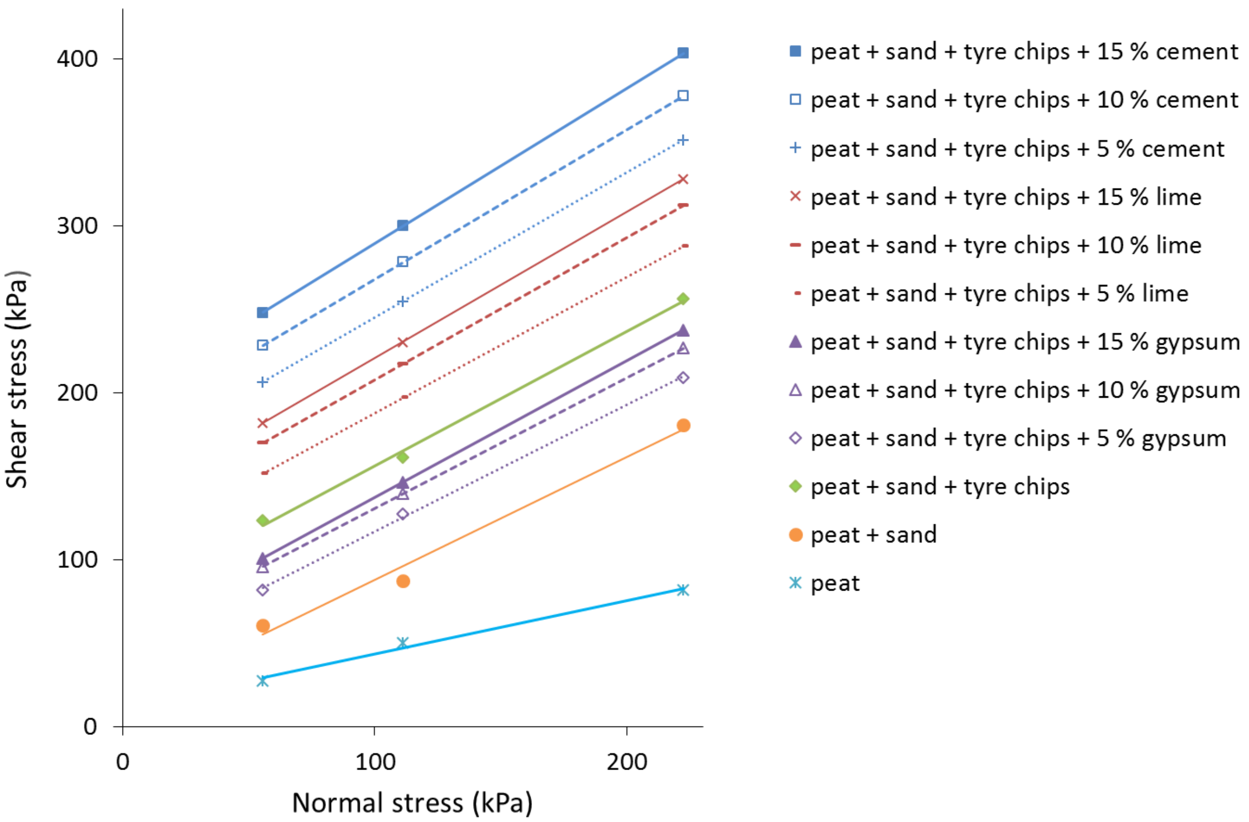

Figure 4. Results of direct shear tests for different soil specimens, with Mohr-Coulomb lines fitted. All sand dosages were 400 kg m^{-3} and all tyre chip dosages were 10 % by weight. The curing time for all specimens containing gypsum, lime or (ordinary Portland) cement was 28 days. Data for untreated peat, peat with sand, and peat with sand plus tyre chips are taken from Rahgozar & Saberian (2015, 2016). In each case, cohesion (c) is given by the y-intercept and angle of internal friction (φ) by the slope of the line.

Table 5. Effect of different percentage dosages of chemical additives (gypsum, lime or ordinary Portland cement) on pH value of the stabilised peat.

additive	dosage		
	5 %	10 %	15 %
gypsum	7.1	7.1	7.1
lime	8.0	8.4	9.1
cement	8.5	9.1	10.1

ordinary Portland cement, 15 % gypsum, 15 % lime (cured for 28 days in water), as well as untreated peat, were examined in X-ray fluorescence (XRF) and the results are presented in Table 7.

Figure 5 shows scanning electron micrographs (SEM) of the air dried samples of untreated peat (Figure 5a) and the stabilised peat (after 28 days' curing) containing 15 % gypsum (Figure 5b), 15 % lime (Figure 5c) and 15 % ordinary Portland cement (Figure 5d). It is clear that the untreated peat was composed of loosely packed fibres and coarse organic particles in random order. Each organic particle contains internal pores which enable the soil to retain a considerable amount of water when fully saturated. Thus, peat soil is characterised by inner pores within the coarse organic particles (organic bodies) and outer pores between the soil particles and fibres, as described by Kogure *et al*. (1993), Gofar (2006) and Wong *et al*. (2009).

DISCUSSION

In its natural condition, the peat soil from Chaghakhor Wetland in Iran had a water content of 446–593 %, a unit weight of 0.88–0.94 ton m^{-3}, an organic content of 85– 89 %, a liquid limit of 334–380 and a UCS of 6.3 kPa. All of these values indicate its weakness. This peat soil is considered to have been effectively stabilised (UCS > 345 kPa) in the present study by treatment with each of the additives gypsum, lime and ordinary Portland cement at percentages by weight of 5 %, 10 % and 15 %, always

Table 6. Content (% by weight) of oxide compounds in dry peat, sand and the three pozzolanic additives tested in this study, determined by X-ray fluorescence (XRF). *Loss on ignition (LOI) (2 hours at 1000 °C) is also shown.

oxide compound	material				
	dry peat	sand	gypsum	lime	cement
CaO	26.76	10.64	33.64	52.41	65.59
SiO_2	13.70	62.87	0.52	3.08	21.74
Al_2O_3	3.69	7.62	0.61	1.12	4.48
Fe_2O_3	2.94	4.59	0.21	0.78	2.83
MgO	1.58	2.71	0.17	0.8	1.28
SO_3	1.22	7.15	42.45	0.71	0.28
K_2O	0.576	0.942	0.325	0.13	0.351
TiO_2	0.244	0.11	0.08	0.03	0.29
SrO	0.162	0.001	0.008	0.001	0.045
P_2O_5	0.130	0.10	0.022	0.11	0.113
Na_2O	0.090	0.425	0.011	0.08	0.212
MnO	0.072	0.017	0.032	0.001	0.144
CuO	0.022	-	-	-	-
ZnO	0.008	0.003	-	-	-
LOI*	48.62	1.74	21.78	40.47	1.81
Total (%)	99.81	98.92	98.86	99.72	99.17

Table 7. Element composition (% by weight) of peat specimens in untreated condition and after stabilisation with sand in combination with one of the tested pozzolanic additives (dosage 15 %) after curing for 28 days, determined by X-ray fluorescence (XRF). The data for untreated peat are taken from Rahgozar & Saberian (2015).

element	material			
	untreated peat	stabilised peat with 15 % ordinary Portland cement	stabilised peat with 15 % lime	stabilised peat with 15 % gypsum
C	48.62	8.44	9.39	9.30
O	29.96	14.01	13.27	13.01
Ca	3.82	38.67	34.41	35.88
Si	8.96	22.30	27.16	24.74
Fe	2.08	5.87	2.69	2.82
Al	2.66	4.53	3.07	2.73
Mg	1.29	1.34	5.50	0.493
K	0.751	2.15	2.62	2.50
S	0.723	0.847	0.656	7.19
Ti	0.290	0.378	0.140	0.170
Cr	-	0.168	0.076	0.110
Sr	0.278	0.160	0.235	0.275
Mn	0.15	0.149	0.080	0.075
Na	0.100	0.531	0.340	0.290
P	0.083	0.075	0.067	0.054
Cl	0.047	0.087	0.110	0.085
Cu	0.042	0.060	0.077	0.075
Zn	0.016	0.025	0.035	0.041
Total (%)	99.87	99.79	99.92	99.83

in combination with 10 % by weight of shredded tyre chips and 400 kg m^{-3} of sand. Other researchers have similarly reported an increasing trend in the UCS of test specimens of peat soil stabilised with gypsum (Kolay & Pui 2010), lime (Said & Taib 2009) and ordinary Portland cement (Deboucha *et al*. 2008, Hashim & Islam 2008, Wong *et al*. 2008, Skels *et al*. 2013). The novelty of the current research is the additional inclusion of shredded tyre chips, along with sand, in the stabilised peat specimens.

According to Figure 2, after 28 days of curing the admixture with 15 % ordinary Portland cement had a modulus of elasticity of 13.72 MPa and a UCS of 774.35 kPa at a normal strain of 6.5 %. These were the highest UCS and stiffness values achieved, but all three admixtures with pozzolanic binders exhibited rather brittle behaviour in which the maximum strength was reached at relatively small elastic strains (Whitlow 2001). This can be attributed to the hydration and pozzolanic effects of the gypsum, lime and/or cement. Similar observations are reported by Sariosseiri & Muhunthan (2009) and Wong *et al*. (2013).

The UCS value observed was always well above the minimum strength specified by ASTM D4609 (Figure 3), the specimens with cement having the highest and those with gypsum the lowest UCS values. Increasing the percentage of gypsum, lime or cement in the mixture always increased the UCS value obtained; although the increase was rather linear in the case of gypsum whereas it was nonlinear for cement and lime.

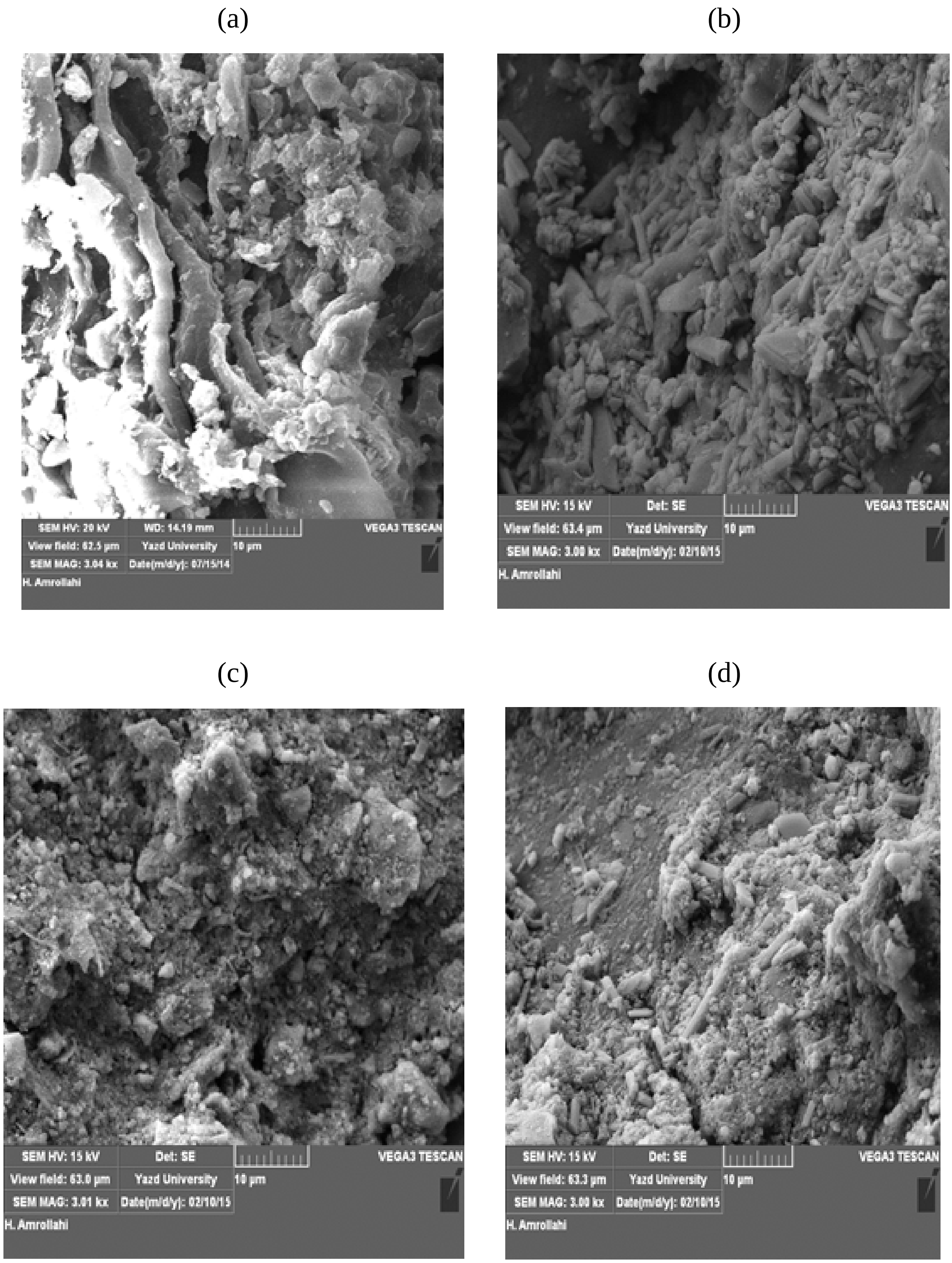

Figure 5. Scanning electron micrographs of: (a) untreated peat; (b) peat stabilised with 15 % gypsum; (c) peat stabilised with 15 % lime; (d) peat stabilised with 15 % ordinary Portland cement. In Cases (b), (c) and (d), sand was also added and the curing period was 28 days.

Figure 3 shows that UCS increased nonlinearly with curing time for all of the test specimens. The very rapid rate of UCS development during the first seven days of curing can be attributed to a combination of the filler effect of the sand, the hydration reaction and the pozzolanic activity of the cement, lime or gypsum. The rate of increase of UCS began to slow down at 7–14 days. Similar trends in the evolution of UCS in cemented materials are reported from the studies of Velosa & Cachim (2009), Kolay & Pui (2010) and Liu *et al*. (2011).

The results of direct shear testing (Tables A2, A3) show that the untreated peat had very low cohesion (c = 11.23 kPa) and angle of internal friction (φ = 17.8°). The highest percentage improvement in c and φ was achieved with ordinary Portland cement (up to 1,650 % and 142 % respectively). Similar but smaller improvements in c and φ were exhibited by the specimens with lime (up to 1,080 % and 130 % respectively) and gypsum (up to 390 % and 120 % respectively). This finding is in agreement with the outcome of research by Cetin *et al*. (2006) and Akbulut *et al*. (2007) investigating the effect of shredded tyre chips on the engineering properties of clayey soil, and by Wong *et al*. (2013) on the stabilisation of peat soil with a combination of Portland cement and sodium bentonite.

It is important to note that the shear strength parameters were not significantly improved by increasing the percentage of cement, lime or gypsum in the admixture from 5 % to 15 %. Therefore, in major civil engineering projects requiring large-volume earthworks, it would be most economical yet still effective in terms of strength improvement to apply only 5 % of such additives.

From the electron micrographs shown in Figures 6b, 6c and 6d, it can be concluded that the stabilised peat soil was characterised by a well-structured soil matrix with very small pores, due to the sand filling a large fraction of the voids and as a result of the pozzolanic activity of additives. This caused the stabilised soil to retain less pore water, and increased its compressive bearing strength. Moreover, the cementation compounds contributed to strong inter-particle bonding, which can offer great resistance to swelling and shrinkage of the soil (Cai *et al*. 2006). Similar cementation crystals functioning as the binding agents of stabilised soils can be observed in SEMs arising from other studies, of clayey soil stabilised with polypropylene fibre and lime (Cai *et al*. 2006), and of peat soil stabilised with sodium bentonite and cement (Wong *et al*. 2013).

It is known that hydration and secondary pozzolanic reactions occur under highly alkaline conditions, due to an increase in the concentrations of Ca^{2+} and OH^- ions. Test specimens with organic acids producing pH lower than 9 in the pore solution strongly inhibit the development of cementing products and cause almost no gain in strength (Tremblay *et al*. 2002). Sariosseiri & Muhunthan (2009) also report an increase in the UCS of stabilised peat soil when the pH value is increased. Therefore, in the current study it was necessary to perform a series of pH tests to investigate the degree of alkalinity of the stabilised peat admixtures immediately after mixing. From Table 5 it is clear that only the specimens containing 10 % and 15 % of ordinary Portland cement and the specimen with 15 % lime met the relevant criterion of pH > 9 (Tremblay *et al*. 2002, ASTM D4609). Our results corroborate the results of Walworth (2006), in that pH was independent of the percentage of gypsum in the admixtures.

It is seen from Table 6 that the percentages of SiO_2, Al_2O_3 and Fe_2O_3 compounds in the peat soil studied here were 13.70 %, 3.69 %, and 2.94 %, respectively, making a total of 20.33 %, which is well below the stipulated minimum of 70 % from ASTM C 618. Therefore, additives such as cement, lime and/or gypsum are certainly required to increase the UCS and shear strength of Chaghakhor peat.

Table 7 shows that the untreated peat was characterised primarily by carbon (C) and oxygen (O) and that other elements comprised only 21.42 % of the soil. Moreover, the concentrations of elements such as Si, S, Al, Ca and Fe, which contribute most to pozzolanic reactions, were low. This is also reported by Lucas (1982) and Andriesse (1988). On the other hand, the stabilised peat contained higher percentages of Ca, Si, Al and O (Table 7), as was shown also by Filippov *et al*. (2009). It is important to stress that these four elements are essential for the formation of CSH and CAH crystals, which are the main cementation products in the stabilised soil.

The only analyte that is common to the stabilised peat (Table 7) and the 'D list' of the EPA toxicity characteristic leaching procedure (TCLP) (http://www.ehso.com/cssepa/TCLP.htm) is Cr at very low concentrations (0.076–0.168 %), indicating minimal environmental hazards associated with the proposed chemically active additives. However, the change in peat pH and the introduction of plant nutrients such as Ca and K are noted as factors to which wetland and peatland biota are potentially sensitive. Investigation of the mobility of introduced chemicals in the Chaghakhor environment, and the ecological sensitivities of this particular Ramsar wetland, is beyond the scope of the present study.

REFERENCES

Akbulut, S., Arasan, S. & Kalkan, E. (2007) Modification of clayey soils using scrap tyre rubber and synthetic fibers. *Applied Clay Science*, 38, 23–32.

ASTM (2000) Annual Book of ASTM Standards, Section Four: Construction, Volume 04.08. American Society of Testing Materials, USA.

Andriesse, J.P. (1988) *Nature and Management of Tropical Peat Soils*. First edition, Food & Agriculture Organisation (FAO), Rome, 29–38.

Cai, Y., Shi, B., Ng, C.W.W. & Tang, C. (2006) Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil. *Engineering Geology*, 87, 230–240.

Cetin, H., Fener, M. & Gunaydin, O. (2006) Geotechnical properties of tyre-cohesive clayey soil mixtures as a fill material. *Engineering Geology*, 88, 110–120.

Chen, H. & Wang, Q. (2006) The behaviour of organic matter in the process of soft soil stabilization using cement. *Bulletin of Engineering Geology and the Environment*, 65, 445–448.

Deboucha, S., Hashim, R. & Alwi, A. (2008) Engineering properties of stabilized tropical peat soils. *The Electronic Journal of Geotechnical Engineering (EJGE)*, 13(E5), 1–9.

Filippov, L., Thomas, F., Filippova, I., Yvon, J. & Morillon-Jeanmaire, A. (2009) Stabilization of NaCl-containing cuttings wastes in cement concrete by in situ formed mineral phases. *Journal of Hazardous Materials*, 171, 731–738.

Gofar, N. (2006) *Determination of Coefficient of Rate of Horizontal Consolidation of Peat Soil*. Laporan Projek Penyelidikan Fundamental, Vot 75210, Faculty of Civil Engineering, Universiti Teknologi, Malaysia, xv+122 pp.

Hambirao, G.S. & Rakaraddi, P.G. (2014) Soil stabilization using waste shredded rubber tyre chips. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, Volume 11(1/5), 20–27.

Hashim, R. & Islam, S. (2008) Engineering properties of peat soils in peninsular Malaysia. *Journal of Applied Sciences*, 8(22), 4215–4219.

Hebib, S. & Farrell, E.R. (2003) Some experiences on the stabilization of Irish peats. *Canadian Geotechnical Journal*, 40, 107–120.

Hong, L. & Shahin, M. (2010) Utilization of shredded rubber tires for cement-stabilized soft clays. In: Puppala, A., Huang, J., Han, J. & Hoyos, L. (eds.) *Ground Improvement and Geosynthetics - Proceedings of the GeoShanghai International Conference, Shanghai, China*, American Society of Civil Engineers, 181–186.

Humphrey, D.N. (1999) Civil engineering application of tire shreds. Presented at *The Tire Industry Conference,* Clemson University, Hilton Head, South Carolina, 16 pp. Online at: https://www.researchgate.net/publication/242230810_CIVIL_ENGINEERING_APPLICATION_OF_TIRE_SHREDS, last accessed 19 Feb 2016.

Isaia, G.C., Gastaldini, A.L.G. & Moraes, R. (2003) Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete. *Cement and Concrete Composites*, 25, 69–76.

Jarret, P.M. (1997) Recent development in design and construction on peat and organic soils. In: Huat, B.B.K. & Bahia, H.M. (eds.) *Proceedings of Recent Advances in Soft Soil Engineering*, Kuching, Sarawak, Malaysia, 1–30.

Kalantari, B. (2013) Civil engineering significant of peat. *The Global Journal of Researches in Engineering: Civil and Structural Engineering*, 13(2-E) Version 1.0, 25–28.

Kogure, K., Yamaguchi, H. & Shogaki, T. (1993) Physical and pore properties of fibrous peat deposit. *Proceedings of the 11th Southeast Asian Geotechnical Conference,* Singapore, 135–139.

Kolay, P.K. & Pui, M.P. (2010) Peat stabilization using gypsum and fly ash. *UNIMAS E-Journal of Civil Engineering*, 1(2), Sarawak, Malaysia, ISBN 1985-3874.

Kolay, P.K., Sii, H.Y. & Taib, S.N.L. (2011) Tropical peat soil stabilization using Class F pond ash from coal fired power plant. *International Journal of Civil and Environmental Engineering*, 3(2), 79–83.

Liu, J., Shi, B., Jiang, H., Wang, G. & Kamai, T. (2011) Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. *Engineering Geology*, 117, 114–120.

Long, M. & Boylan, N. (2012) In-situ testing of peat - a review and update on recent developments. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 43(4), 41–45.

Lucas, R.E. (1982) *Organic Soils (Histosols). Formation, Distribution, Physical and Chemical Properties and Management for Crop Production*. Research Report No. 435 (Farm Science), Michigan State University Agricultural Experiment Station, Michigan, USA.

Nikookar, M. & Karimi Pashaki, M. (2012) The geotechnical improvement of Talesh peat soil with cement. *3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering, Near East University,* *Nicosia, North Cyprus*, 7 pp. Online at: https://www.researchgate.net/publication/236163771_The_geotechnical_improvement_of_Talesh_peat_soil_with_cement, last accessed 20 Feb 2016.

Puppala, A.J. & Musenda, C. (2002) Effects of fiber reinforcement on strength and volume change in expansive soils. *Transportation Research Record: Journal of the Transportation Research Board*, 1736, 134–140 (Paper No. 00–0716).

Rahgozar, M. & Saberian, M. (2015) Physical and chemical properties of two Iranian peat types. *Mires and Peat*, 16(07), 1–17.

Rahgozar, M. & Saberian, M. (2016) Geotechnical properties of peat soil stabilised with shredded waste tyre chips. *Mires and Peat*, 18(03), 1–12.

Said, J.M. & Taib, S.N.L. (2009) Peat stabilization with carbide lime. *UNIMAS E-Journal of Civil Engineering*, 1(1), Sarawak, Malaysia, ISBN 1985-3874.

Sariosseiri, F. & Muhunthan, B. (2009) Effect of cement treatment on geotechnical properties of some Washington State soils. *Engineering Geology*, 104, 119–125.

Skels, P., Bondars, K. & Korjakins, A. (2013) Unconfined compressive strength properties of cement stabilized peat. In: *CIVIL ENGINEERING '13*, 4th International Scientific Conference Proceedings, Volume 4, Part 1, 202–206.

Tang, B.L., Bakar, I. & Chan, C.M. (2011) Reutilization of organic and peat soils by deep cement mixing. *World Academy of Science, Engineering and Technology*, Issue 53, 680.

Tremblay, H., Duchesne, J., Locat, J. & Leroueil, S. (2002) Influence of the nature of organic compounds on fine soil stabilization with cement. *Canadian Geotechnical Journal*, 39, 535–546.

Velosa, A.L. & Cachim, P.B. (2009) Hydraulic-lime based concrete: strength development using a pozzolanic addition and different curing conditions. *Construction and Building Materials*, 23, 2107–2111.

von Post, L. & Granlund, E. (1926) *Södra Sveriges Torvtillgångar I* (*Peat Resources in Southern Sweden I*). Sveriges Geologiska Undersökning, Series C, 335 (= Årsbok 19:2), Stockholm, 127 pp. (in Swedish).

Walworth, J. (2006) Using gypsum and other calcium amendments in southwestern soils. *The University of Arizona College of Agriculture and Life Sciences Cooperative Extension*, AZ1413, Tucson, Arizona, 5 pp. Online at: http://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1413.pdf, last accessed 20 Feb 2016.

Warburton, J., Holden, J. & Mills, A.J. (2004) Hydrological controls of surficial mass movements in peat. *Earth-Science Reviews*, 67, 139–156.

Whitlow, R. (2001) *Basic Soil Mechanics*. Fourth edition, Pearson Education / Prentice Hall, London, UK, 592 pp.

Wong, L.S., Hashim, R. & Ali, F.H. (2008) Strength and permeability of stabilized peat soil. *Journal of Applied Science*, 8(17), 1–5.

Wong, L.S., Hashim, R. & Ali, F.H. (2009) A review on hydraulic conductivity and compressibility of peat. *Journal of Applied Sciences*, 9, 3207–3214.

Wong, L.S., Hashim, R. & Ali, F.H. (2013) Utilization of sodium bentonite to maximize the filler and pozzolanic effects of stabilized peat. *Engineering Geology*, 152, 56–66.

Xintu, L. (2008) Conditions of peat formation. *Encyclopedia of Life Support Systems (EOLSS)*, Vol. II, 11 pp.

Youventharan, D., Bujang, B.K.H. & Azlan, A.A. (2007b) Engineering properties and compressibility behavior of tropical peat soil. *American Journal of Applied Sciences*, 4(10), 768–773.

Zainorabidin, A. & Wijeyesekera, D.C. (2007) Geotechnical challenges with Malaysian peat. *Advances in Computing and Technology 2007*, Proceedings of the AC&T 2nd Annual Conference, School of Architecture, Computing and Engineering, University of East London, 252–261.

Zolfeghari Far, S.Y., Kassim, K.A., Eisazadehb, A. & Khari, M. (2013) An evaluation of the tropical soils subjected physicochemical stabilization for remote rural roads. *The 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering*, *Procedia Engineering*, 54, 817–826.

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Appendix

Table A1. Unconfined compressive strength (UCS) of Chaghakhor peat with different combinations of additives and curing times. For each combination, the test results for the three replicate specimens (raw data) are shown on the left, and the mean UCS value on the right. Beneath each mean value, the figure in italics (*%inc*) is the percentage increase in UCS compared with untreated peat (top row). The data for specimens without supplements (top three rows) are taken from Rahgozar & Saberian (2016). The results of all 81 of the UCS tests carried out during this study are shown in the bottom nine rows of the Table. Shading indicates the improvement in UCS achieved: no shading indicates an improvement of ≤ 6000 %; lightest shading > 6000–8000 %; medium shading > 8000–10000 %; darkest shading > 10000 %.

additives			curing time (days)							
sand (kg m^{-3})	tyre chips (%)	binder	0		7		14		28	
			raw data	mean *%inc*	raw data	mean *%inc*	raw data	mean *%inc*	raw data	mean *%inc*
-	-	-	5.9 6.5 6.5	6.3 *0*	-	-	-	-	-	-
400	-	-	65.3 67.5 68.7	67.2 *966*	-	-	-	-	-	-
400	10	-	402.4 405.7 408.1	405.4 *6334*	-	-	-	-	-	-
400	10	5 % gypsum	-	-	428.9 419.1 420.7	422.9 *6600*	441.5 427.6 436.5	435.2 *6800*	457.4 437.8 441.6	445.6 *6900*
		10 % gypsum	-	-	436.4 444.9 426.4	435.9 *6800*	456.2 451.9 444	450.7 *7000*	472.1 453.7 458.1	461.3 *7200*
		15 % gypsum	-	-	454.5 451.3 443.9	449.9 *7000*	476.2 471.8 456.9	468.3 *7300*	487.2 472.7 465.4	475.1 *7400*
400	10	5 % lime	-	-	436.2 429.7 428.3	431.4 *6700*	491.5 487.2 479	485.9 *7600*	516.9 496.4 500.8	504.7 *7900*
		10 % lime	-	-	474.1 467.2 463.9	468.4 *7300*	548.5 542.4 536	542.3 *8500*	607.6 586.1 578.7	590.8 *8300*
		15 % lime	-	-	520.4 512.3 517.7	516.7 *8000*	619.5 610.2 602.4	610.7 *9600*	645.9 633.4 620.6	633.3 *9900*
400	10	5 % cement	-	-	479.5 470.5 468.1	472.7 *7390*	578.5 586.7 577.2	580.8 *9100*	621.7 602.8 604.0	609.5 *9550*
		10 % cement	-	-	516. 8 507.6 506.8	510.4 *8000*	671.1 658.2 666.9	665.4 *10400*	747.4 727.9 741.7	739.0 *12000*
		15 % cement	-	-	591.2 584.6 575.3	583.7 *9150*	748.7 734.8 747.6	743.7 *11600*	789.5 772.6 761.1	774.4 *12200*

Table A2. Cohesion (c, kPa) of Chaghakhor peat with different combinations of additives and curing times (from direct shear test). For each combination, the test results for the three replicate specimens (raw data) are shown on the left, and the mean cohesion value on the right. Beneath each mean value, the figure in italics (*%inc*) is the percentage increase in the parameter compared with untreated peat (top row). The data for specimens without supplements (top three rows) are taken from Rahgozar & Saberian (2016). The results of all 81 of the direct shear tests carried out during this study are shown in the bottom nine rows of the Table. Shading indicates the improvement in cohesion achieved: no shading indicates an improvement of ≤ 500 %; lightest shading > 500–800 %; medium shading > 800–1100 %; darkest shading > 1100 %.

additives			curing time (days)							
			0		7		14		28	
sand (kg m^{-3})	tyre chips (%)	binder	raw data	mean *%inc*	raw data	mean *%inc*	raw data	mean *%inc*	raw data	mean *%inc*
0	0	-	10.4 11.1 11.2	11.2 *0*	-	-	-	-	-	-
400	0	-	13.1 16.0 12.9	14.0 *25*	-	-	-	-	-	-
400	10	-	74.3 75.9 77.1	75.8 *574*	-	-	-	-	-	-
400	10	5 % gypsum	-	-	35.3 29.5 26.4	30.4 *170*	47.5 38.4 39.2	41.7 *270*	42.7 53.4 41.6	45.9 *300*
		10 % gypsum	-	-	38.2 32.4 36.5	35.7 *210*	45.2 52.7 41.9	46.6 *310*	59.5 48.6 48.2	52.1 *360*
		15 % gypsum	-	-	47.7 40.3 36.2	41.4 *260*	57.6 53.4 41.4	50.8 *350*	63.1 58.4 44.4	55.3 *390*
400	10	5 % lime	-	-	79.7 76.6 70.5	75.6 570	101.2 90.8 91.2	94.4 *740*	114.8 104.6 100.1	106.5 *840*
		10 % lime	-	-	98.6 87.2 85.1	90.3 700	107.5 118.5 103.1	109.7 *870*	129.2 124.1 113	122.1 *990*
		15 % lime	-	-	112.7 99.7 98.1	103.5 *820*	129.6 115.3 120.2	121.7 *900*	142.6 127.8 128.3	132.9 *1080*
400	10	5 % cement	-	-	113.1 97.1 95.8	102.0 *800*	137.4 125.2 128.6	130.4 *1050*	164.1 155.9 155.5	158.5 *1420*
		10 % cement	-	-	130.6 119.8 112.6	121.0 *980*	155.1 145.6 146.6	149.1 *1200*	186.3 175.7 173.8	178.6 *1500*
		15 % cement	-	-	144.8 132.6 128.2	135.2 *1100*	173.7 158.4 165.6	165.9 *1380*	209.7 188.5 191.0	196.4 *1650*

Table A3. Angle of internal friction (φ) of Chaghakhor peat with different combinations of additives and curing times (from direct shear test). For each combination, the test results for the three replicate specimens (raw data) are shown on the left, and the mean angle of internal friction value on the right. Beneath each mean value, the figure in italics (*%inc*) is the percentage increase in the parameter compared with untreated peat (top row). The data for specimens without supplements (top three rows) are taken from Rahgozar & Saberian (2016). The results of all 81 of the direct shear tests carried out during this study are shown in the bottom nine rows of the Table. Shading indicates the improvement in φ achieved: no shading indicates an improvement of ≤ 110 %; lightest shading > 110–120 %; medium shading > 120–130 %; darkest shading > 130 %.

additives			curing time (days)							
			0		7		14		28	
sand (kg m^{-3})	tyre chips (%)	binder	raw data	mean *%inc*	raw data	mean *%inc*	raw data	mean *%inc*	raw data	mean *%inc*
0	0	-	17.6 17.8 17.8	17.8 *0*	-	-	-	-	-	-
400	0	-	38.5 35.2 35.5	36.4 *104*	-	-	-	-	-	-
400	10	-	37.6 39.7 39.1	38.8 *118*	-	-	-	-	-	-
400	10	5 % gypsum	-	-	33.8 37.2 34.0	35.0 *97*	36.9 34.8 35.1	35.6 *100*	38.5 34.2 36.2	36.3 *103*
		10 % gypsum	-	-	38.2 34.7 37.2	36.7 *106*	39.5 38.1 35.2	37.6 *110*	40.4 37.7 36.2	38.1 *114*
		15 % gypsum	-	-	39.4 36.6 37.7	37.9 *113*	39.4 37.5 38.6	38.5 *116*	41.6 39.0 37.3	39.3 *120*
400	10	5 % lime	-	-	38.9 36.1 34.2	36.4 *100*	39.5 36.9 37.9	38.1 *113*	41.1 38.2 38.3	39.2 *119*
		10 % lime	-	-	38.5 36.8 37.5	37.6 *110*	41.1 38.7 37.8	39.2 *120*	41.9 38.7 40.9	40.5 *128*
		15 % lime	-	-	40.4 37.7 37.4	38.5 *115*	42.5 39.6 38.2	40.1 *125*	43.4 40.2 40.0	41.2 *130*
400	10	5 % cement	-	-	36.1 38.9 37.8	37.6 *110*	41.3 37.9 40.2	39.8 *123*	42.5 39.8 40.4	40.9 *130*
		10 % cement	-	-	39.8 37.5 37.0	38.1 *113*	42.9 40.1 37.3	40.4 *127*	43.4 40.2 42.1	41.9 *135*
		15 % cement	-	-	33.8 37.2 34.0	39.5 *120*	36.9 34.8 35.1	41.5 *134*	38.5 34.2 36.2	43.0 *142*