Physical and chemical properties of two Iranian peat types

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SUMMARY

Because peat has high organic content and high natural water content, it is potentially problematic for civil engineering projects involving construction on peatland. Therefore, it is important to understand the physical, chemical and geotechnical properties of the peat. The aim of the study reported here was to investigate the properties of two Iranian peat types. Peat and water samples were collected from sites within two extensive wetland areas (Chaghakhor Wetland and Gavkhuni Swamp) where construction works are planned. Both sites had peat layers more than three metres thick, which were sampled at depths of 0.6, 1.2, 1.8, 2.4 and 3.0 metres below ground level with four replicates per site. Degree of humification was determined in the field. Laboratory tests were conducted to determine the pH of water and peat; and the natural (field) moisture content, organic content, ash content, bulk density, dry density, density of solids, liquid limit, initial void ratio, linear shrinkage, unconfined compressive strength, shear strength and falling-head permeability of each peat sample. We also investigated the elemental compositions and microstructure of the peats using X-Ray fluorescence and scanning electron microscopy. The laboratory tests of physical and geotechnical properties indicated that, for construction purposes, Chaghakhor peat is weaker than Gavkhuni peat.

KEY WORDS: Chaghakhor Wetland; Gavkhuni Swamp; geotechnical properties of peat; Iran; peat strength

INTRODUCTION

Peat covers approximately 0.5 billion hectares (0.5×10^8 km^2) or 3.5–4.0 % of the land area of the world, and 95 % of this peatland is in the northern hemisphere (Franzén 2006, Deboucha *et al*. 2008). Peat soils are found in most countries and regions except for desert and polar zones. The two countries with the most extensive peat cover are Canada (170 million hectares) and Russia (150 million hectares) (Lappalainen 1996, Joosten & Clarke 2002).

Peat deposits are formed when organic matter accumulates more rapidly than it decays over thousands of years. Usually, this occurs when the microbial degradation of plant residues is retarded as a result of poor aeration and acidic conditions below a high water table in mires or wetlands. The resulting peat deposit often consists of more than 75 % organic substances (Andriesse 1988, Boylan *et al.* 2011), and the high water absorbing capacity of the peat promotes its continued accumulation (Jarret 1997, Warburton *et al*. 2004, Xintu 2008, Kalantari 2013).

There are various classification systems for mires, peatland and peat based on: (1) the surface vegetation of the site; (2) the chemical and physical properties, genetic processes and botanical origin of the peat; (3) topography; and (4) the geomorphology of the terrain. Some frequently-used peat classification systems are known as von Post (von Post 1924), Hobbs (Hobbs 1986), Radforth (Radforth 1969), Russian (Hartlén & Wolski 1996) and ASTM (Gofar 2006). Of these, the best-known and most practical are von Post and ASTM.

In general, due to the high content of organic matter and water, peat is extremely soft and compressible. In order to understand how peat soil will behave in connection with construction works, it is essential to determine its physical, chemical and geotechnical properties.

From a civil engineering viewpoint, peat is commonly regarded as a deposit with low bearing capacity, low shear strength and high consolidation settlement. It is usually acidic (i.e., it has low pH), with low hydraulic conductivity, relatively low plasticity, and varying particle size distribution. In its natural state, peat soil exhibits low bulk density, high porosity and, thus, considerable compressibility (Andriesse 1988, Huat 2004, Youventharan *et al*. 2007a, Hashim & Islam 2008, Wong *et al*. 2008, Zainorabidin & Wijeyesekeram 2008). Its physical characteristics are determined by its structure at both macroscopic and microscopic scales.

The aim of this article is to describe the principal physical, chemical and geotechnical properties of peat samples collected from two contrasting peatland types in Iran.

METHODS

Study sites

The peat soil samples that were tested in this study were collected from two peatlands in the vicinity of Isfahan (Esfahan), Iran. The Chaghakhor peatland in Chahar Mahal and Bakhtiari Province (Figure 1a) is an area of fen which lies at 3830 m a.s.l., 160 km south-west of Isfahan, within the 2300 ha wetland that includes the 1687 ha Ramsar site known as Chaghakhor (or Choghakhor) Wetland (31° 55′ N, 50° 54′ E; 2270 m a.s.l.; Ramsar ID 1939) (Ebrahimi & Moshari 2006, Ramsar 2010). The Gavkhuni peatland (Figure 1b) is located at 1470 m a.s.l. in Isfahan Province on the central plateau of Iran, 140 km south-east of Isfahan. The Gavkhuni Swamp (32° 15′ N, 52° 45′ E) occupies the terminal basin of the Zayandeh-Rud River, which rises in the Zagros Mountains about 300 km to the west. This wetland extends to around 47,000 ha (470 km^2) with maximum dimensions 25 × 50 km; its area increasing in rainy years and shrinking remarkably, due to evaporation, during dry summers (Soltani *et al*. 2009, Tayebi *et al*. 2012). It is classified as saltmarsh and includes expanses of bare salt- and mud-flats, the vegetation being limited to some *Tamarix* and *Phragmites* at the mouth of the river and, elsewhere, a low cover of halophile species (Carp 1980). The locations chosen for sampling were in areas that are being considered for future civil engineering projects; specifically, tourism-related development at Chaghakhor and the construction of a railway at Gavkhuni. Preliminary auger testing indicated the presence of moderately deep peat deposits (Lim 1989) at our sampling locations (Table 1), with peat thickness 0.5–4 m at Chaghakhor and 0.4–3.5 m at Gavkhuni.

Collection of samples

At each site, four pits were incrementally dug to 3.0 m depth, using an excavator, to expose the succession of strata for easy visual examination (Whitlow 2001). In all cases, the position of the water table was obvious at around 0.4 m below the ground surface and it was necessary to pump out seepage water as the excavations were deepened. Peat samples were collected from the floors of the pits when pit depth reached 0.6, 1.2, 1.8, 2.4 and 3.0 m. At each depth, an undisturbed sample (approximately 100 g) for determination of bulk density and fibre content was obtained using a cylindrical corer 50 mm in diameter and 50 mm high, and a bulk sample of disturbed peat 30 cm in diameter and ~ 20 cm thick was collected for the other tests. Degree of decomposition was determined in the field according to the squeezing method of von Post (Table 2), which classifies peat on the basis of plant residues, stage of decomposition, physical properties and genetic processes (von Post 1924, von Post & Granlund 1926, Landva & Pheeney 1980, Andriesse 1988,

(a) (b)

Figure 1. Photographs of (a) the Chaghakhor peat study site and (b) the Gavkhuni peat study site.

Table 1. Sampling locations and total peat thickness.

Site	Core no.	Latitude	Longitude	Total peat depth (m)
Chaghakhor	1	31° 54' 50.03" N	50° 55' 26.47" E	3.6
	2	31° 54' 51.56" N	50° 55' 27.04" E	3.8
	3	31° 54' 54.44" N	50° 55' 24.60" E	3.4
	4	31° 54' 53.33" N	50° 55' 21.37" E	4.0
Gavkhuni	1	32° 15' 41.19" N	52° 50' 35.05" E	3.0
	2	32° 15' 23.57" N	52° 49' 59.73" E	3.2
	3	32° 15' 12.48" N	52° 49' 52.26" E	2.9
	4	32° 15' 06.68" N	52° 49' 35.54" E	3.1

Table 2. Degree of decomposition according to von Post (after Landva & Pheeney 1980).

Condition of peat before squeezing			Condition of peat on squeezing			
Degree of humification	Soil colour	Degree of decomposition	Plant structure	Squeezed solution	Material extruded between fingers	Nature of residue
H1	white or yellow	none	easily identified	clear, colourless	nothing	not pasty
H2	very pale brown	insignificant		yellowish/pale brown-yellow		
H3	pale brown	very slight	still identifiable	dark brown, muddy		
H4		slight	not easily identified	very dark brown, muddy	some peat	somewhat pasty
H5	brown	moderate	recognisable but indistinct			strongly pasty
H6		moderately strong	indistinct (clearer after squeezing)		about one-third of the peat	very strongly pasty
H7	dark brown	strong	faintly recognisable		about one-half of the peat	
H8		very strong	very indistinct	very dark brown, pasty	about two-thirds of the peat	
H9	very dark brown	nearly complete	almost unrecognisable	very dark brown, muddy	nearly all peat as fairly uniform paste	
H10	black	complete	not discernible	very dark brown, muddy	all the peat; no free water visible	n/a

Malterer *et al*. 1992). A water sample was also collected at each site.

Physical and chemical properties

Bulk density was determined by a drive-cylinder method based on ASTM D2937-00. The sample was extruded from the sampling cylinder, then a representative specimen was cut from it. The length, diameter and mass of the specimen were measured, and bulk density was calculated by dividing the mass of the specimen by its volume.

Natural (field) moisture content, organic content and ash content were determined according to the ASTM standard D2974-87. At least 50 g of bulk-sampled peat was weighed out, then dried in an oven at 105 °C for a minimum of 16 hours and thereafter until there was no change in mass after further drying periods in excess of one hour. The oven-dried sample was then ignited in a muffle furnace at 440 °C, continuing until it was completely ashed and no further change of mass occurred after a further period of heating. Natural moisture content (%) was calculated by subtracting oven-dried mass from the original wet mass and expressing as a percentage of oven-dried mass. Ash content (%) was derived by expressing the mass of the residue that remained after heating in the muffle furnace as a percentage of oven-dried mass. Organic matter content (loss on ignition; %) was then derived by subtracting ash content (%) from 100.

Dry density (γ_d ; Mg m^{-3}) was calculated according to the formula of Den Haan (1997):

$$\gamma_d = 35.075\omega^{-0.856} \quad [1]$$

where ω is natural moisture content (%) as above.

Density of solids (previously termed particle density) is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at the same temperature, and was determined according to ASTM D854. First, 10 g of dried peat was placed in a water pycnometer (specific gravity bottle), distilled water was added until the pycnometer was about half full, and a partial vacuum was applied to remove entrapped air. The pycnometer was then filled up with distilled water, stoppered, wiped and weighed. Density of solids was calculated from the mass of oven-dried soil, the mass of the pycnometer when filled with water and soil as described above, and its mass when filled with water only.

The liquid limit of a soil is the greatest water content at which it still retains its plasticity; adding more water causes it to become a thick liquid. Liquid limit was determined as a percentage of oven-dried mass according to ASTM D4318-00, using water collected from the same trial pit as the sample. This test is performed in a special device containing a cup that is dropped from a controlled height. A pat of sieved soil is mixed thoroughly with water, placed in the cup, its surface is smoothed and then a groove is cut across the surface. The liquid limit is the moisture content at which the cup must be dropped 25 times to close a 10 mm length of the groove.

Void ratio is the ratio of the volume of voids to the volume of solids in the soil. For the determination of initial void ratio, ASTM D2435 (standard test method for one-dimensional consolidation properties of soils using incremental loading) was followed, and the void ratio at the end of primary consolidation for each pressure increment was calculated. In this test, the soil is assumed to be 100 % saturated, and each stress increment is maintained until excess pore water pressures are essentially dissipated.

Linear shrinkage is the decrease in one dimension of a soil mass, expressed as a percentage of the original dimension, when the water content is reduced from a given value to the shrinkage limit. It was determined according to ASTM D427. A mould of known volume was exactly filled with sampled peat whose water content was adjusted to just exceed the liquid limit during filling. After weighing and drying according to a standard procedure, the peat was removed from the mould as a block and its volume was determined by displacement of mercury from an initially brim-full glass cup. Volumetric shrinkage (% of dry soil mass) could then be derived from the volume and mass of the dried peat block and the volume of the mould. Linear shrinkage (%) was calculated as a cube-root function of the volumetric shrinkage. Note that, because mercury is a hazardous substance and an acceptable alternative (Test Method D4943) is available, ASTM withdrew D427 in March 2008.

Fibre content was determined according to ASTM D1997-91. A known mass of undisturbed, undried peat was soaked in 5 % sodium hexameta-phosphate for 15 hours, then washed through a 100-mesh (150 μm) sieve by applying a gentle flow of tap water. The fibrous material remaining on the sieve was dried to constant mass at 105 °C, and this mass was expressed as a percentage of the oven-dried mass of the same wet mass of unsieved peat.

The pH of peat and groundwater was measured in the laboratory using a pH meter according to BS 1377:1990 Test 11 (A). This is a common standard for peat soils.

The results for fibre content, ash content and pH were used to further assign the peats amongst the ASTM classes summarised in Table 3 (Head 2006).

Table 3. Peat classes according to ASTM (2000).

Fibre content	fibric:	> 67 % fibres
	hemic:	33–67 % fibres
	sapric:	< 33 % fibres
Ash content	low ash:	< 5 % ash
	medium ash:	5–15 % ash
	high ash:	> 15 % ash
Acidity	highly acidic:	pH < 4.5
	moderately acidic:	pH 4.5–5.5
	slightly acidic:	pH > 5.5 and < 7
	basic:	pH ≥ 7

Geotechnical properties

Unconfined compressive strength (ASTM D2166-06), direct shear strength (ASTM D3080-04) and falling-head permeability (ASTM D5084-03) tests were performed on the peat samples in order to quantify their mechanical properties.

Each specimen for the unconfined compression test was prepared by loading and tamping four equal layers of bulk-sampled peat into a 250 mm long, 50 mm internal diameter plastic tube, to a height of 150 mm. The specimen was then placed on the test apparatus, load was applied to produce axial strain at a rate of 1 % per minute, and the dial readings for load and deformation were manually recorded at 30-division increments of deformation until it was clear that the maximum of the load-deformation curve had been exceeded (i.e., the specimen had failed). The unconfined compressive strength of the specimen was the maximum load recorded during this test.

For direct shear strength tests, the specimens were prepared in square cross-section moulds with internal dimensions 60 × 60 × 25 mm. Following ASTM D3080-04, a series of three direct shear tests with normal stresses of 55.5, 111 and 222 kPa was conducted on each specimen. The relationship between maximum shear stress (at failure) in each test was plotted against normal stress to derive cohesion (the y-intercept) and angle of internal friction (the slope of the graph in degrees).

For falling-head tests, each specimen was packed into the chamber of a permeameter (dimensions 100 mm internal diameter × 250 mm height) to approximately 20 mm below the rim, then compacted using a tamping device. The upper porous ceramic plate was placed directly on top of the packed peat before the upper section of the chamber was replaced and secured. The thickness of the specimen was then measured and recorded. The falling head burette was clamped to the support rod at the maximum practical height, then the metre stick was placed behind the burette so that the height difference between the water surface in the burette and the chamber outflow port could be read. The water level in the burette was recorded, then water from the burette was allowed to flow through the specimen for a measured time period, at the end of which the water level in the burette was again recorded. The coefficient of permeability (m s^{-1}) was calculated from the two burette readings, dimensions of the specimen and permeameter apparatus, and the time interval, using a standard formula.

Chemical and structural characterisation

In order to chemically characterise the peats, X-ray fluorescence (XRF) tests were conducted on air-dried peat using a Bruker S4 Explorer X-Ray Fluorescence Spectrometer (1 kW). Specimens (40 mm diameter) were prepared using the pressed pellet method. The outputs of the tests were analysed semi-quantitatively using SPECTRAPLUS V1.64 software, which delivered percentage elemental composition values.

To reveal the microstructure of the peat samples, scanning electron micrographs were obtained using VEGA3 TESCAN apparatus (TESCAN USA Inc.).

RESULTS

Physical and chemical properties

Table 4 lists mean values for the basic properties of Chaghakhor and Gavkhuni peats, based on all (20) samples analysed from each site. The Chaghakhor peat samples varied in colour from brown to dark brown, and they were insignificantly to slightly decomposed (H2–H4 on the von Post scale; Table 2). In terms of the ASTM standard (Table 3) they were fibric (81 % fibre), medium ash (13 %) and highly acidic (pH 4.0). In contrast, Gavkhuni peat was uniformly brown, strongly to almost completely decomposed (H7–H9), hemic (39 % fibre), high ash (24 %) and moderately acidic (pH 5.5). The pH of peat was 4.0 at Chaghakhor and 5.5 at Gavkhuni, and the pH of groundwater was 4.5 at Chaghakhor and 6.0 at Gavkhuni. Otherwise, in comparison with Gavkhuni peat, Chaghakhor peat had higher organic content, initial void ratio, moisture content, liquid limit and linear shrinkage; and lower bulk density, dry density and density of solids.

Table 4. Physical and chemical properties of Chaghakhor and Gavkhuni peats. SD: standard deviation (n=20).

Soil property	Site				Quotient Chaghakhor/ Gavkhuni
	Chaghakhor		Gavkhuni		
	mean	SD	mean	SD	
Fibre content (%)	81	0.62	39	0.7	2.07
Initial void ratio	7.32	0.084	4.61	0.051	1.59
Natural moisture content (%)	501	44.78	353	29.32	1.42
Linear shrinkage (%)	55	1.18	43	1.18	1.28
Organic content (%)	87	1.84	76	1.71	1.15
Liquid limit (%)	350	15	307	6.85	1.14
Bulk density (Mg m^{-3})	0.92	0.018	0.99	0.017	0.93
Density of solids	1.52	0.041	1.65	0.024	0.92
Dry density (Mg m^{-3})	0.19	0.0068	0.29	0.0095	0.66

The samples from deeper peat layers at both sites showed higher degree of humification (von Post scale) than those from shallow layers (Table 5). The basic properties of all samples of Gavkhuni and Chaghakhor peat are plotted against sampling depth in Figures 2–4. Bulk density, dry density, density of solids and ash content increased with depth; whereas all of the other measured properties declined to a greater or lesser degree as depth below the soil surface increased.

Table 5. Humification values (von Post scale, see Table 2) for all sampling depths at Chaghakhor and Gavkhuni.

Depth (m)	Chaghakhor	Gavkhuni
0.6	H2	H7
1.2	H2	H7
1.8	H2	H8
2.4	H3	H8
3.0	H4	H9

Geotechnical properties

Figures 5 and 6 show typical results of unconfined compressive and shear strength tests for the two peat types. The results of all of the geotechnical tests are summarised in Table 6. Although both peats exhibited very low unconfined compressive strength, Gavkhuni peat was almost 1.5 times stronger than Chaghakhor peat. At a standard temperature of 20 °C, the permeability coefficients of the Chaghakhor and Gavkhuni peats were in the order of 10^{-5} and 10^{-7} m s^{-1}, respectively (Table 6); i.e., comparable to those of very fine silty sand. Thus, although both peats were porous and moderately permeable, the coefficient of permeability for the less-decomposed Chaghakhor peat exceeded that of Gavkhuni peat by two orders of magnitude.

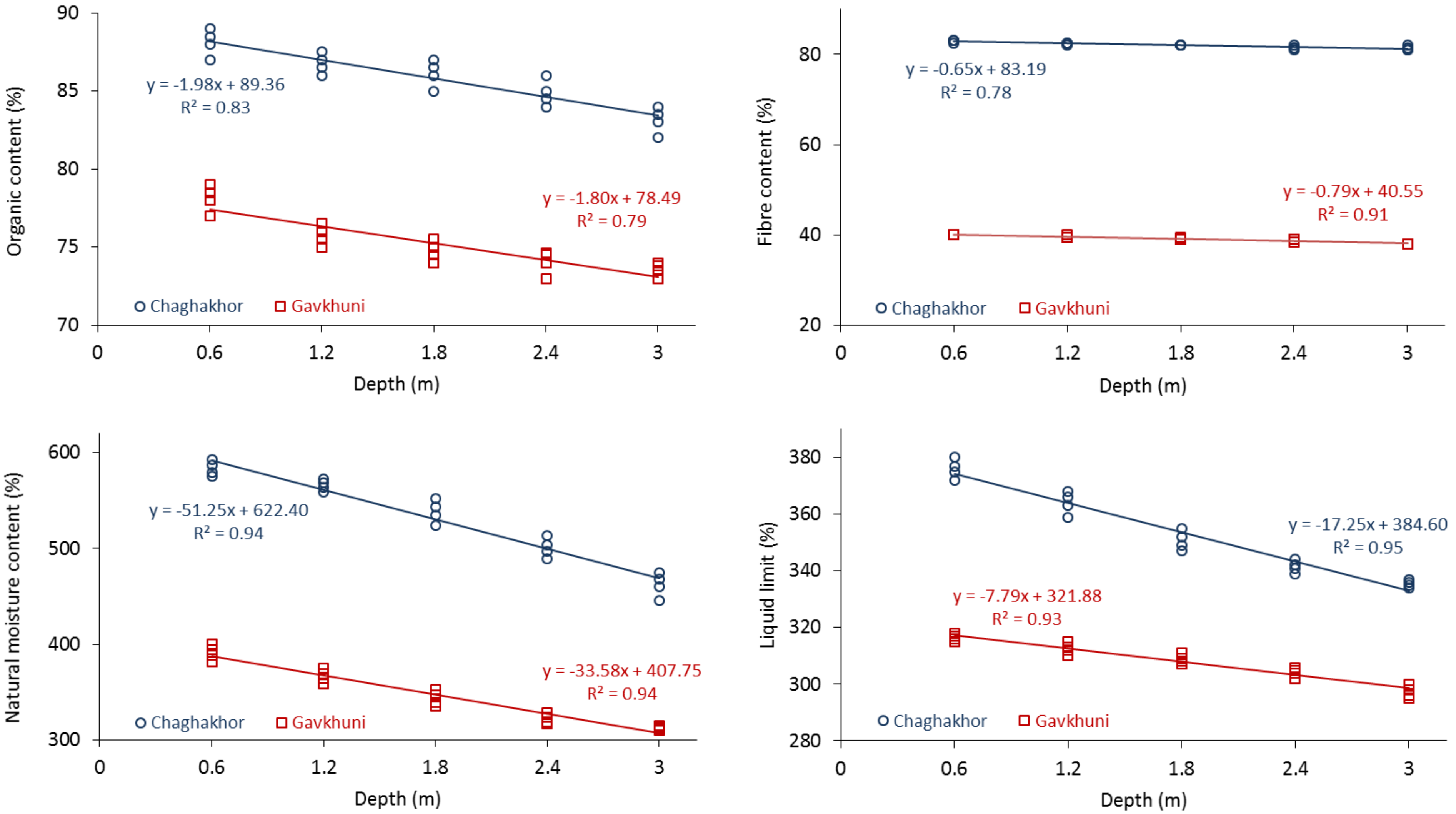

Figure 2. Variation with depth below the soil surface in organic content, fibre content, natural moisture content and liquid limit of peat samples collected from Chaghakhor (blue circles) and Gavkhuni (red squares).

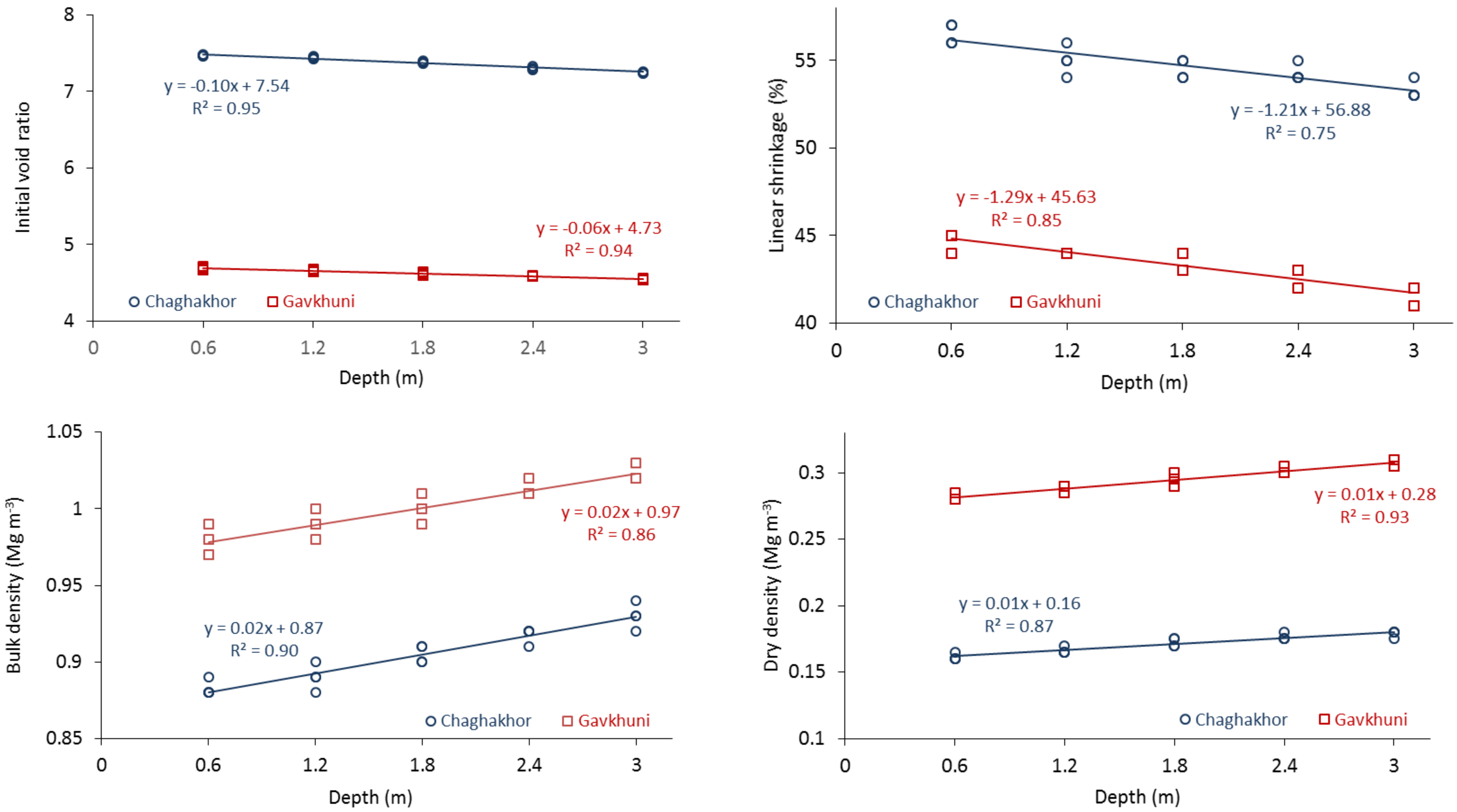

Figure 3. Variation with depth below the soil surface in initial void ratio, linear shrinkage, bulk density and dry density of peat samples collected from Chaghakhor (blue circles) and Gavkhuni (red squares).

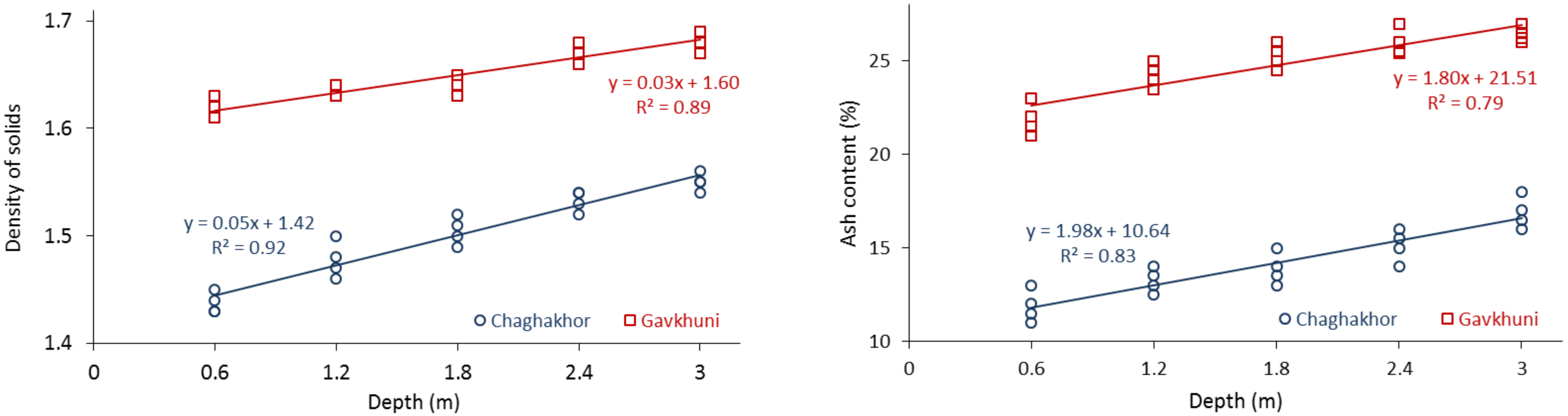

Figure 4. Variation with depth below the soil surface in density of solids and ash content of peat samples collected from Chaghakhor (blue circles) and Gavkhuni (red squares).

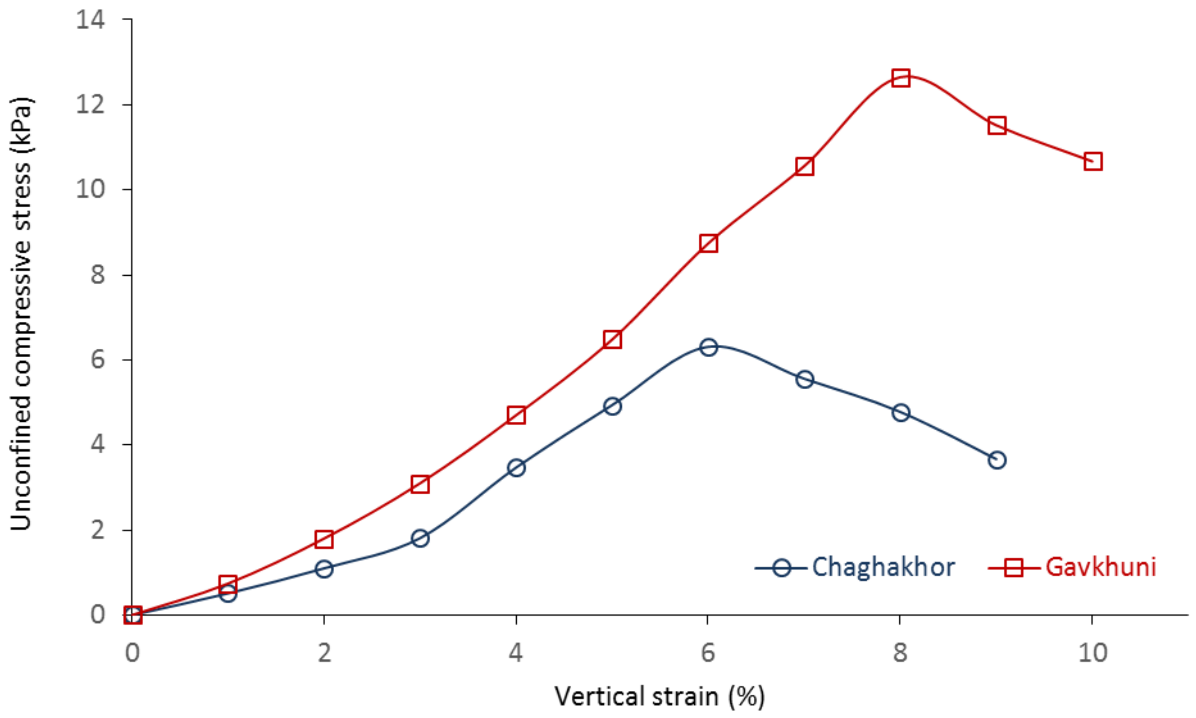

Figure 5. Typical stress-strain curves produced during unconfined compression testing of Chaghakor and Gavkhuni peats. Unconfined compressive strength is equal to stress at the peak of each curve, which indicates the maximum load applied before failure of the specimen occurred.

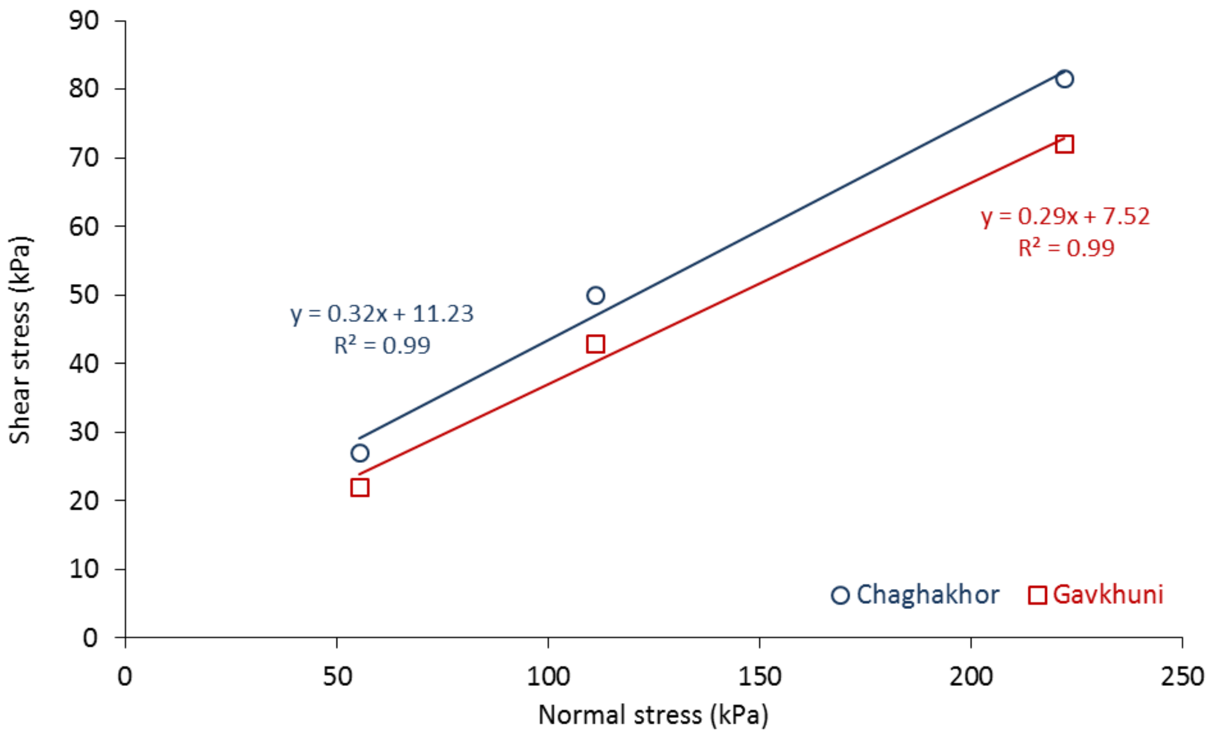

Figure 6. Typical results from shear strength testing of Chaghakhor and Gavkhuni peats. For the Chaghakhor sample tested here, cohesion is 11.23 kPa (the y-intercept) and the angle of internal friction is 17.74 degrees ($\tan^{-1}$ 0.32). For the Gavkhuni sample, cohesion is 7.52 kPa and the angle of internal friction is 16.17 degrees.

Chemical and structural character

The results of the XRF tests showed that the carbon (C) and oxygen (O) contents of the peats were high, accounting for 78.6 % of total mass in Chaghakhor peat and 89.2 % of total mass in Gavkhuni peat (Table 7).

The scanning electron micrographs of air-dried samples of both peats (Figure 7) show that they are composed of loosely-packed fibres and coarse organic particles arranged in random order. Each coarse organic particle has inner pores, which enable the soil to retain a considerable amount of water when fully saturated. Hence, these peat soils are characterised by inner pores within the coarse organic particles and outer pores between the outer surfaces of soil particles and fibres.

Table 6. Geotechnical properties of Chaghakhor and Gavkhuni peats.

	Chaghakhor	Gavkhuni
Unconfined compressive strength (kPa)	4.2–6.5	11.6–13.8
Cohesion (kPa)	10.4–12.1	7.2–9.3
Angle of internal friction (degrees)	17.6–17.8	16.3–16.7
Coefficient of permeability at 20 ℃ (m s^{-1})	$6.76–7.23\times10^{-5}$	$5.47–5.82\times10^{-7}$

Table 7. Elements in the Gavkhuni and Chaghakhor peats, derived by X-Ray Fluorescence (XRF) and expressed as percentages of dry mass.

Element	Chaghakhor peat	Gavkhuni peat
C	48.62	58.95
O	29.96	30.21
Si	8.96	3.40
Ca	3.82	1.57
Al	2.66	1.13
Fe	2.08	1.38
Mg	1.29	0.935
K	0.751	0.507
S	0.723	0.991
Ti	0.290	0.301
Sr	0.278	0.277
Mn	0.15	0.085
Na	0.100	-
P	0.083	0.120
Cl	0.047	-
Cu	0.042	0.027
Zn	0.016	0.009
Total	99.87	99.89

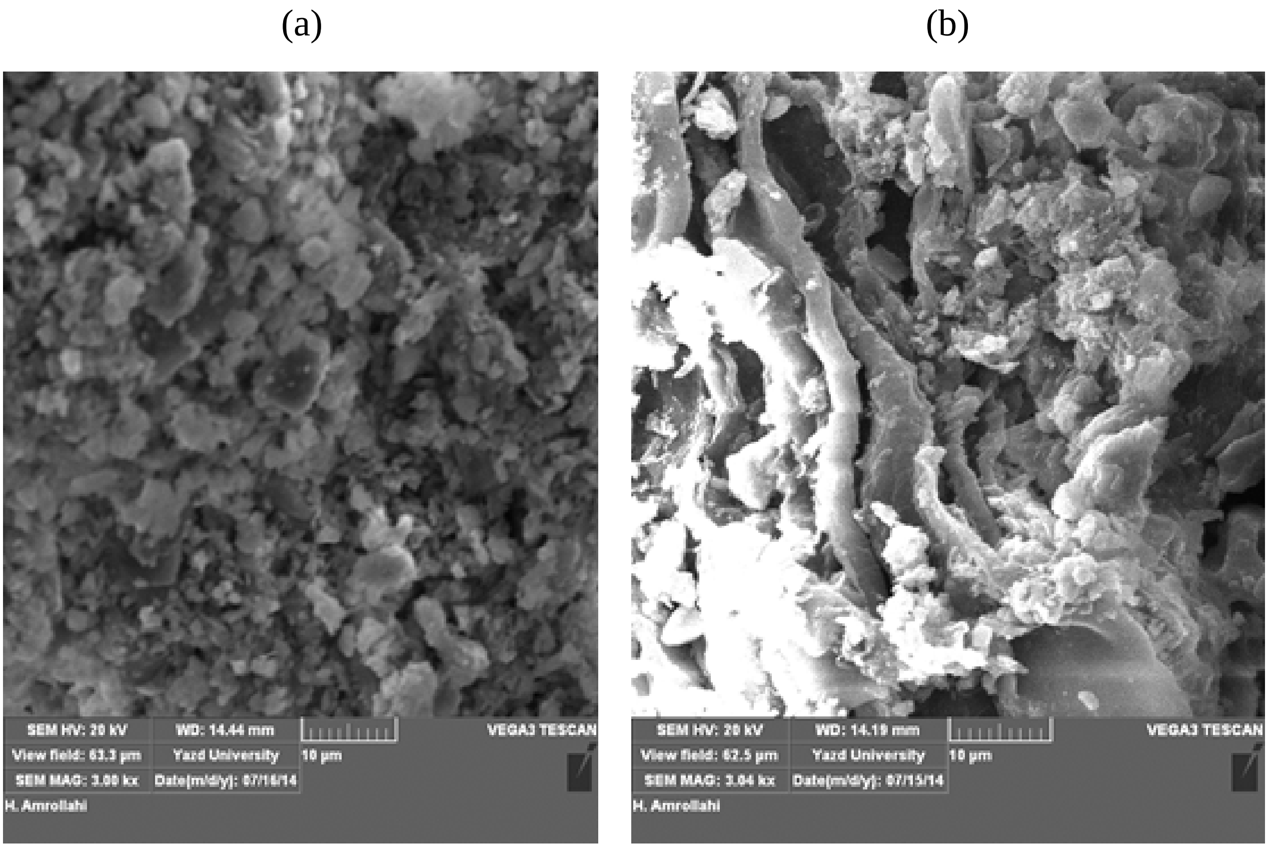

Figure 7. Scanning electron micrographs of (a) Gavkhuni peat and (b) Chaghakhor peat.

DISCUSSION

Physical and chemical properties

Generally, peat soils are very acidic with low pH values, often in the range 1–7 (Macfarlane & Rutka 1962, Lea & Browner 1963, Radforth & Brawner 1997). The pH values we obtained for Chaghakhor and Gavkhuni peats were near the middle of this range, at 4.0 and 5.5, respectively (Table 4). Natural peat soils also have high water content. This results not only from their fibrous structure, which causes large void spaces; but also from the high cation exchange capacity of organic matter, which increases the attraction of water molecules (Macfarlane 1969, Huang *et al*. 2009). These attributes presumably account for the high water contents of Chaghakhor (446–593 %) and Gavkhuni (310–400 %) peats. Water content decreased with increasing depth below the soil surface and, thus, with increasing degree of decomposition (Figure 2), by 31% over the humification range H7–H9 in the case of Gavkhuni peat by and 37% over the range H2–H4 for Chaghakhor peat.

Bulk density depends on botanical composition, degree of decomposition, amount of compaction, moisture content, void ratio, mineral and organic content and density of solids (Andriesse 1988). Typically, soils with high organic content have low bulk density, especially when fibre content is also high (i.e., low degree of decomposition and/or high organic content). The organic particles in peat soil create open structures with large void spaces. Therefore, the reduction of bulk density with increase of organic content is substantial (Zainorabidin & Wijeyesekera 2008, Huang *et al*. 2009). However, the mineral content of peat soils can also increase the density of solids (Macfarlane 1969, Ajlouni 2000, Huang *et al*. 2009). The density of solids for Gavkhuni peat (1.61–1.69) was higher than that for Chaghakhor peat (1.43–1.56) by 9 %, on average, and this may account for much of the difference in bulk density (0.97–1.03 Mg m^{-3} *versus* 0.88–0.94 Mg m^{-3}) (Figure 3, Table 4).

The liquid limit of peat soil depends on both the high water absorption capacity of organic matter, which raises the liquid limit; and the aggregation of soil mineral fractions by organic substances, which has an opposite effect (Husein Malkawi *et al*. 1999, Huang *et al*. 2009). In general, the liquid limit of Chaghakhor peat (334–380 %), which had higher organic content, exceeded that of Gavkhuni peat (295–318 %) by 12 % (Figure 3, Table 4).

The initial void ratio of soils is an indicator for their compressibility. According to Hanrahan (1954) the initial void ratio of peat is usually high, in the range 5–15. Therefore, the compressibility of peats is generally higher than that of inorganic soils. During decomposition, large pore spaces collapse and void ratio decreases (Boelter 1974). The initial void ratio of Chaghakhor peat (7.23–7.48) was 37 % higher than that of Gavkhuni peat (4.54–4.71) (Figure 3, Table 4), but was practically independent of degree of decomposition within each of these peat types.

The linear shrinkage of Chaghakhor peat (53–57 %) was, on average, 22 % higher than that of Gavkhuni peat (41–45 %). This result conforms with the findings of Gofar (2006) and Huang *et al*. (2009) that linear shrinkage decreases as organic content increases. An inverse relationship between linear shrinkage and degree of decomposition has been observed by von Post & Granlund (1926), Landva & Pheeney (1980), Karlsson & Hansbo (1981) and Huat (2004).

All of these results indicate that Gavkhuni peat is more integrated and should, therefore, be stronger than Chagakhor peat.

Geotechnical properties

The relationship between stress and strain for a specified material is known as its stress-strain curve. This curve is unique to the material and is determined by recording the amount of deformation (strain) at distinct intervals of tensile or compressive loading (stress). Figure 5 shows unconfined compressive stress-strain curves (with normal strain) for typical samples of the studied peats peaking at stress values of 12.65 kPa (Gavkhuni) and 6.31 kPa (Chaghakhor). Overall, the unconfined compressive strength of Chaghakhor peat was 4.2–6.5 kPa, and less than half that of Gavkhuni peat (11.6–13.8 kPa) (Table 6). Macfarlane (1969) and Youventharan *et al*. (2007b) showed that peat soils have low unconfined compressive strengths of less than 15 kPa. Huang *et al*. (2009) observed that the strength of peat declines rapidly with increasing organic content. This is an expected result because the strength of soil is highly dependent on water content, and the natural water content of a soil generally increases with organic content. Furthermore, the decomposition of organic soil usually leads to an increase of unconfined compressive strength, due to elimination of voids and the resulting increase of peat density (Husein Malkawi *et al*. 1999).

Shear strength is a term used in soil mechanics to describe the magnitude of the shear stress that a soil can withstand. Although peat near the base of a typical wet bog may be unable to withstand normal effective stress in excess of around 5 kPa (as demonstrated in our unconfined compressive strength tests), the normal stresses (55.5–222 kPa) applied in our shear strength tests would be realistic for peat soil that had been stabilised for construction purposes.

The shear resistance of soil is a result of friction and interlocking of particles, and possibly also cementation or bonding at particle contacts. Due to interlocking, particulate material may expand or contract when it is subject to shear strain. The stress-strain relationship levels off when the material stops expanding or contracting, and when inter-particle bonds are broken. Peat is considered to be a mostly frictional or non-cohesive material due to its fibre content and the spatial orientation of the fibres (Adams 1965), and it is clear that both of the peat types we tested have frictional behaviour and high angles of internal friction. However, high friction angle will not necessarily reflect high shear strength because the fibres are not always solid and may be filled with water and gas. On the other hand, the presence of fibres will modify the strength behaviour of peat since they provide reinforcement, create effective stress where there is none, and introduce anisotropy.

Cohesion is the component of shear strength that is independent of interparticle friction. Angle of internal friction is the angle on the graph (Mohr's Circle) of shear stress and normal effective stresses at which shear failure occurs. On average, cohesion and angle of internal friction were lower for Gavkhuni peat (7.2–9.3 kPa; 16.3–16.7 degrees) than for Chaghakhor peat (10.4–12.1 kPa; 17.6–17.8 degrees) by 27 % and 6 %, respectively. Similar values of cohesion (7–12 kPa) and internal friction angle (16–18 degrees), rising with increasing water content and/or decreasing bulk density (a secondary effect) have been reported from both un-drained shear strength and effective shear strength testing of peats from different parts of the world (Landva & La Rochelle 1983, Den Haan 1997, Huat 2004, Zainorabidin & Wijeyesekera 2008).

Studies of the physical and hydraulic properties of peats have indicated that they are moderately porous, with medium hydraulic conductivity. Hobbs (1986) showed that coefficient of permeability is one of the most significant geotechnical characteristics of peat; the lower the coefficient of permeability, the lower the rate of consolidation will be. The data shown in Table 6 agree with the results of Colley (1950) and Hanrahan (1954), who obtained coefficients of permeability for peats between 10^{-5} and 10^{-8} m s^{-1}.

MacFarlane (1969) and Stevenson (1994) pointed out that peats with higher degree of decomposition tend to impede water movement by seepage. Due to the deformed structure and collapsed pore spaces of the more highly decomposed Gavkhuni peat, its coefficient of permeability is two orders of magnitude lower than that of Chaghakhor peat.

Chemical and structural character

The elemental compositions of the peats that we studied are dominated by carbon (C) and oxygen (O) (Table 7). Similar results are reported by Lucas (1982) and Andriesse (1988). The sum of C and O content for Chaghakhor peat is 78.6 %, whereas for the more highly decomposed Gavkhuni peat the total dosage of C and O is higher, at 89.2 %. This result is in agreement with the report of EKONO (1981).

The microstructure of the peat as revealed by the scanning electron micrographs is in conformity 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 water-filled inner voids, while the organic spaces are water-filled outer voids between the soil particles (Gofar 2006, Wong *et al*. 2009). From the microscopic structure of the peats shown in Figure 7, it is evident that Chaghakhor peat contains more void spaces than the more highly decomposed Gavkhuni peat. In other words, degree of decomposition appears to have an effect on void spaces, in that less void space is observed in the structure of the more highly decomposed peats.

Iranian peats in wider context

Generally, different peats may have very different combinations of properties depending on the original vegetation composition and prevailing climatic regime. In Table 8, some properties of the Chaghakhor and Gavkhuni peats are compared with literature values for Malaysian (wood) and Irish (*Sphagnum*-sedge bog) peats. Several properties of Chaghakhor peat (von Post classification, natural moisture content, organic content, initial void ratio, density of solids and cohesion) are similar to those of the Malaysian peat. Gavkhuni peat, on the other hand, shows greater similarity to the Irish peat in terms of von Post classification, natural moisture content and bulk density.

Table 8. Comparison of ranges of values obtained (across all samples analysed) for some properties of Chaghakhor and Gavkhuni peats with data for other peat types reported in the scientific literature. Data for Malaysia are from Wong *et al*. (2013) and those for Ireland are from Yang & Dykes (2006) and Dykes (2008).

Soil property	Chaghakhor	Malaysia	Ireland	Gavkhuni
Humification (von Post)	H2–H4	H3–H7	H8–H10	H7–H9
Organic content (%)	82–89	88–97	> 97	73–79
Natural moisture content (%)	446–593	596–693	270–360	310–400
Bulk density (Mg m^{-3})	0.88–0.94	-	1.00–1.06	0.97–1.03
Density of solids	1.43–1.56	1.33–1.49	-	1.61–1.69
Liquid limit (%)	334–380	-	633–980	295–318
Initial void ratio	7.23–7.48	7.91–8.12	-	4.54–4.71
Cohesion (kPa)	10.4–12.1	10	-	7.2–9.3

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Submitted 30 May 2015, final revision 25 Sep 2015
Editor: Olivia Bragg

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