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Strength and compressibility characteristics of peat stabilized with sand columns

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Abstract. Organic soils exhibit problematic properties such as high compressibility and low shear strength; these properties may cause differential settlement or failure in structures built on such soils. Organic soil removal or stabilization are the most important methods to overcome geotechnical problems related to peat soils' engineering characteristics. This paper presents soil mechanical intervention for stabilization of peat with sand columns and focuses on a comparison between the mechanical characteristics of undisturbed peat and peat stabilized with 20%, 30% and 40% of sand on the laboratory scale. Cylindrical columns were extruded in different diameters through a nearly undisturbed peat sample in the laboratory and filled with sand. By adding sand columns to peat, higher permeability, higher shear strength and a faster consolidation was achieved. The sample with 70% peat and 30% sand displayed the most reliable compressibility properties. This can be attributed to proper drainage provided by sand columns for peat in this specific percentage. It was observed that the granular texture of sand also increased the friction angle of peat. The addition of 30% sand led to the highest shear strength among all mixtures considered. The peat samples with 40% sand were sampled with two and three sand columns and tested in direct shear and consolidation tests to evaluate the influence of the number and geometry of sand columns. Samples with three sand columns showed higher compressibility and shear strength. Following the results of this laboratory study it appears that the introduction of sand columns could be suitable for geotechnical peat stabilization in the field scale.

Keywords: peat; sand; geotechnical stabilization; mechanical characteristics

1. Introduction

The total global peatland area is estimated to be about 4×10^6 km^2, and peat in Europe accounts for 24.02% of the global peatland area (Liu and Liu 2009). Peat is one of the prevailing groups of soils found in Germany with a cumulative area of 15276 km^2 (Montanarella *et al*. 2006). Peat deposits form from the accumulation and fossilization of partly decomposed and fragmented remains of plants (Soper and Osbon 1922). Peat is normally characterized as a fibrous organic soft soil and categorized as a geotechnically problematic soil. Fibrous network elements and a hollow cellular structure are illustrated in Fig. 1. Ohira (1977) and Landva and Pheeney (1980) mentioned

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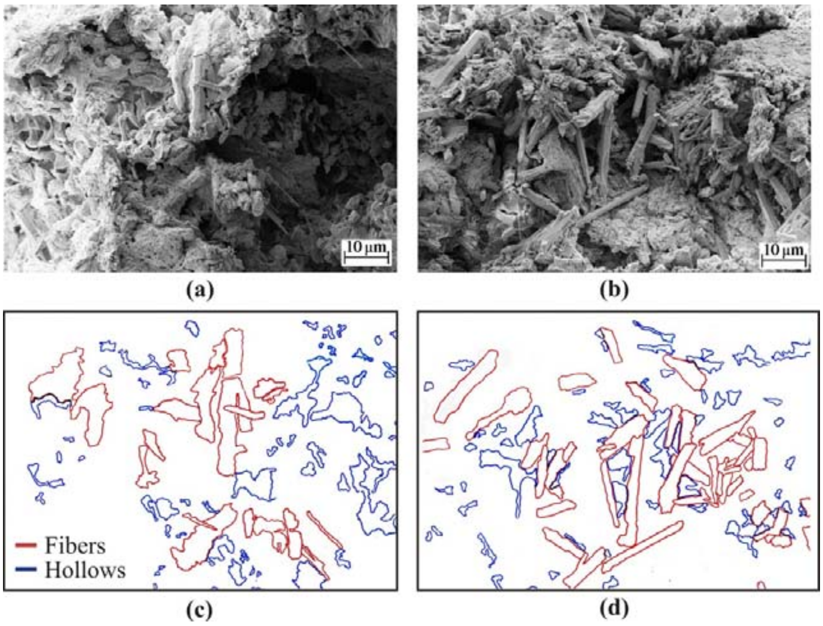

Fig. 1 (a) Vertical section; (b) horizontal section of Blockland peat showing fibrous network elements and cellular structure of perforated hollows. Fibers and hollows sketches of Blockland peat (c) vertical section; and (d) horizontal section

that this hollow cellular structure of fibrous peat particles provides voids full of water hosting one-third to two-thirds of the peat water content, the remaining being water within the fibers themselves (Mesri and Ajlouni 2007). Surficial peat deposits which have not been stressed by overlying inorganic soils have high values of initial water content of about 500 to 2000% (Mesri and Ajlouni 2007).

Andriesse (1988) and Islam and Hashim (2008) revealed that the bearing capacity of peat is very low and is influenced by incompletely decomposed woody materials and high *in-situ* water levels (Roslan and Islam 2008). An excessive construction settlement even in the early stages of loading means peat is unstable for supporting construction foundations.

Exposed to overburden pressure peat is able to undergo extremely large settlement because of peat's distinctive property of extremely high *in-situ* void ratio and simultaneous water expulsion from within and among the peat particles during both primary and secondary compression (Mesri and Ajlouni 2007). Because of the viscous behavior of polymeric organic substances the creep portion of settlement in peat is a significant part of the total settlement. Primary consolidation takes place very fast while secondary consolidation dominates the major part of total settlement (Mesri and Ajlouni 2007).

Fibrous peats are frictional materials with high values of friction angle but shear deformations required to mobilize the maximum frictional resistance in fibrous peats are often 5 to 10 times those required for soft clay deposits (Mesri and Ajlouni 2007). Organic soils are generally weak in their natural states owing to the capacity to retain high water contents, but significant strength gain is achievable with consolidation (Edil and Wong 2000). MacFarlane (1969) reported that significant increases in the shear strength of peat occurs after the pore water pressures are largely dissipated following experience in placing fills on peat (Mesri and Ajlouni 2007).

Peat stabilization as compared with peat removal is a fast and cost effective method to deal with the geotechnical problems of peat soils. Stabilizers aim to improve the engineering characteristics of natural soils and make the soil appropriate for the foundation constructions. Perhaps the most traditional way of organic soil stabilization is the so called "deep mixing" method where a stabilizer is mixed with peat. Ahnberg *et al*. (1995) mentioned cement as the best choice for stabilization of peat soils when compared with lime which was used as the traditional stabilizer. Yang *et al*. (1998) suggested new methods in peat stabilization with cement which were called Dry Mixing Method (DMM) and Dry Jet Mixing (DJM) and were more effective than wet mixing. Deformation and stiffness parameters of stabilized Irish peat were investigated in the laboratory by Hebib and Farrell (2000). Cement, pulverized fuel ash (pfa), lime, pelletized blast furnace slag (bfs) and gypsum were used as binders. Eight different compositions of binders were used: cement alone; 80% cement with 20% pfa and lime; 60% cement with 40% pfa and lime; 40% cement with 60% pfa and lime; 20% cement with 80% pfa and lime; bfs alone; 60% bfs with 40% cement; and 85% bfs with 15% gypsum. These combinations were tested at binder amounts of 150, 200 and 250 kg/m^3 dry weight of binder per soil volume. The binders that performed best in unconfined compression tests were cement alone and 85% bfs with 15% gypsum. Stabilization with pfa and lime was found to be not effective in organic soils. The compressibility characteristics of the cement-stabilized peat were investigated for different curing times of 28, 90 and 240 days. Improvements in the coefficients of consolidation and secondary compression were observed for both curing times and binder composition. The effect of different percentages of cement, bentonite and sand as additives on mechanical properties of peat soils was investigated by Deboucha *et al*. (2008). They observed that increasing the additive content and curing period increased California Bearing Ratio (CBR) values, cement and sand reduced the plasticity compared with natural peat, and cement increased the unconfined compressive strength of peat. In addition, they observed that the materials changed from acidic to alkaline after being treated with these additives. In the same year, Roslan and Shahidul modeled the construction of soil-cement columns for the stabilization of peat. They used cement, bentonite, sand and calcium chloride as materials to mix with peat to make columns. The study showed that the unconfined compressive strength of peat increased significantly after stabilization. Wong *et al*. (2008) analyzed the unconfined compressive strength and initial permeability of peat soils stabilized by mixtures of Portland cement, ground granulated blast furnace slag, and siliceous sand. They outlined significant increases in the unconfined compressive strength of stabilized peat compared with undisturbed peat. Interestingly, they observed that if black humic acid in peat is not neutralized by an adequate binder, the acid tends to react with calcium hydroxide liberated from cement hydrolysis which in turn retards the development of undrained shear strength of stabilized peat. Kalantari *et al*. (2010) stabilized peat using ordinary Portland cement (OPC) as a binding agent, and polypropylene and steel fibers as chemically inert additives. Unconfined compressive strength of peat increased by 748.8% using 5% OPC, 0.15% polypropylene fibers and 2% steel fibers. Volume shrinkage index (VSI) was measured for un-stabilized and stabilized samples. The highest VSI recorded was 36.19% for un-stabilized peat and the minimum was 0% for sample containing 30% OPC, 0.15% polypropylene fibers and 2% steel fibers. One of the most recent studies made by Huat *et al*. (2011) in peat soil stabilization with columns formed by deep mixing method concerns the effect of cement as the traditional binder combined with sodium silicate as a chemical binder and kaolinite as a filler on undrained shear strength of peat. They concluded that compressibility decreased with an increase in the cement content, and outlined the importance of the column area ratio on compressibility parameters. All of the above-mentioned methods involved mixing techniques which require a considerable amount of money and time on large projects.

As peat soils are formed in or very near to the ground water table, introducing binders such as lime, cement or ash may cause unwanted interactions with the ground water. In addition, for peat sites stabilized with pozzolanic binders like cement, it is likely that the shear strength values

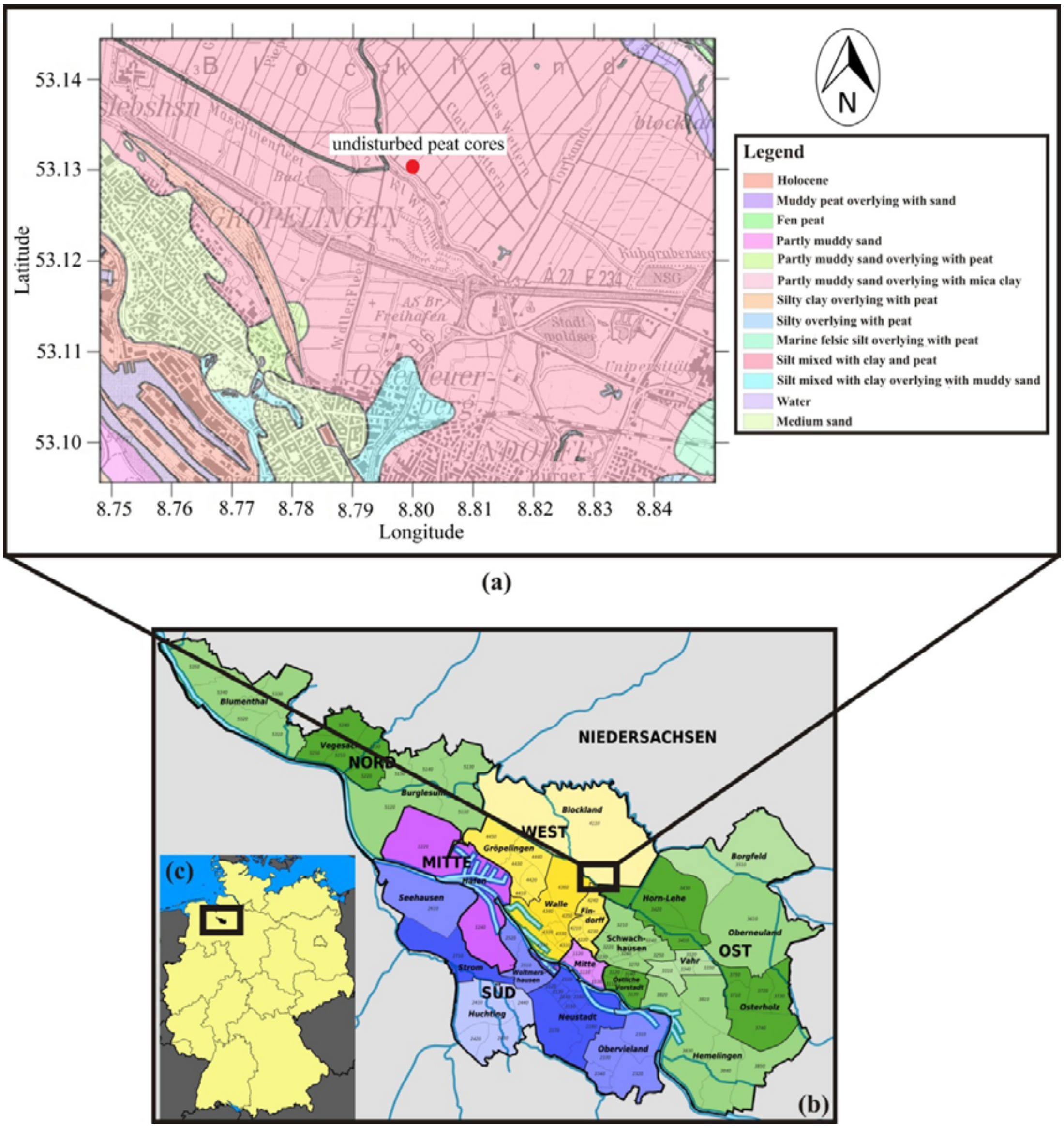

Fig. 2 (a) Geological map of area and location of undisturbed Blockland peat cores (Geological Survey of Bremen, in prep.); (b) graphic map of Bremen City (Wikimedia Commons/Creative Commons); and (c) graphic map of Germany (Wikimedia Commons/Creative Commons) degrade with time. The physicochemical properties of the soil, geological and hydro-geological conditions of the area, the properties and the quality of the binder or the additive used, the mixing method and consequently the mechanical equipment and the curing conditions all influence the strength of a soil-cement mixture (Porbaha 2000). Humic acids as a part of peat's organic matter form stable complexes with calcium attributed to intermolecular association involving H-bonding and to polymerization through bridging polyvalent cations (Sharma *et al*. 1996). These chemical reactions between peat's organic matter and pozzolanic binders cause a rapid decrease in the amount of unreacted binders in the mixture. Technically this leads to inefficient bonding between binders and soil particles. In addition, chemical reactions between peat particles and pozolanic materials might cause contamination in underground water reservoirs.

A scarcity of lands with good soil conditions means that there is often no other choice but to construct on problematic soils such as peat. However, structures founded on peats may face bearing failure and excessive differential settlements which could result in short and long term damage of the construction. In order to control the problems associated with peat, an industrially available, chemically inactive and financially affordable material is desirable as the stabilizer. In the 18^{th} and 19^{th} century, people started to settle and to cultivate the North German peat bog areas but to deal with the problems of peat, a large scale peat removal was technically not the option. Alternatively, the peat was trenched away locally down to the Plesitocene sands, the narrow trenches were then filled with sands to provide better foundation. Huat (2004) reported a work of Kurihara *et al*. from 1994 on the central Hokkaido expressway in Japan built on peat where they used sand as the additive. In this case, the sand was used as drains to treat peat layers; treated layers experienced smaller post construction settlement than non-treated sections. Accordingly, as sand possesses all the qualifications required in a stabilizer, we selected quartz sand as the stabilizer for this study. The most important benefit of using sand as a stabilizer is its environmentally friendly behavior; it also has the benefit to require no curing time, and the shear strength characteristics will not degrade with time due to chemical interactions with the humic acids. Sivakumar *et al*. (2004) have examined the load-deformation performance of specimens of soft clay reinforced with single sand columns of various lengths. They observed that the presence of the granular columns greatly improved the load-carrying capacity of the soft clay. It was noted that columns longer than approximately five times their diameter did not show further increases in load-carrying capacity.

In summary, peat soils possess poor geotechnical properties and stabilization is the method to fix the problems related to peat, sand is environmentally friendly material which can be used to treat peat soils and sand columns are known to be an effective in improving performance of soft soils. Thus the aim of this study is to investigate the stabilization of peat with sand columns. As an advantage, this method requires no mixing, thus minimizing site disruption and cost. It is expected that sand columns expedite consolidation of peat and increase the stability of the peat layer. Sand columns are added comprising various percentages of the sample volume and different geometries in the laboratory scale. The permeability, consolidation and shear strength parameters of treated samples and a natural peat are determined and compared. This approach has not been previously reported in the literature.

2. Materials and method

2.1 Sample origin and preparation

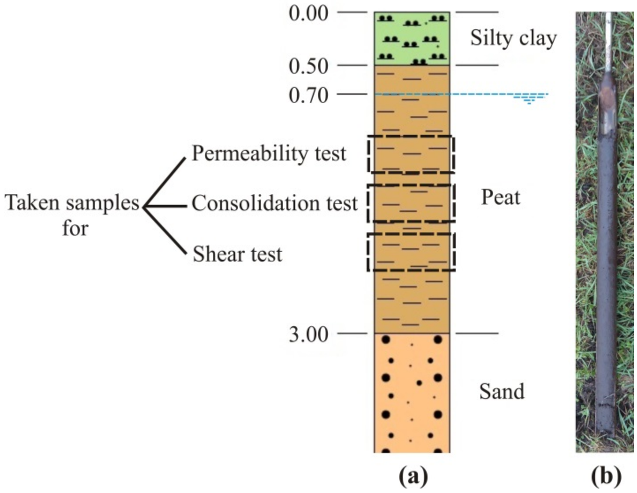

Fig. 3 (a) Lithological column of the Blockland peat core and location of samples taken for permeability, consolidation and shear test; and (b) undisturbed peat sample in Gouge auger. Peat samples for the laboratory program were selected from a similar depth interval from a single sampling spot to avoid a bias in peat pre condition and material properties. Peats near the agricultural top and close to the Pleistocene base where excluded

Table 1 Basic properties of Blockland peat

Basic peat soil property	Values
Color	Dark brown
Initial void ratio (e)	3.70 – 3.84
Specific gravity	1.67 – 1.81
Bulk density (kg/m^3)	983 – 1089
Liquid limit (%)	388 – 412
Plastic limit (%)	202 – 243
Initial water content (%)	507 – 544
Ash content (%)	68.10 – 74.30
Organic content (%)	25.70 – 31.90
Fiber content (%)	32.60 – 37.10
pH	4.43 – 4.96

Peat soil samples for laboratory investigations were sampled in Blockland, Bremen, Germany (Fig. 2). Blockland was selected as a typical German peat and for its close distance to the University of Bremen geotechnics laboratory and availability of land for sampling. The Blockland peats underlie 0.5 m of agricultural silty clay top soil and extended until 3 m where they overlie a massive layer of late Pleistocene sand (Fig. 3). A hand auger was used to excavate first 0.5 m of top soil and Gouge auger probing with a diameter of 100 mm was used for undisturbed sample collection and characterizing soil stratigraphy.

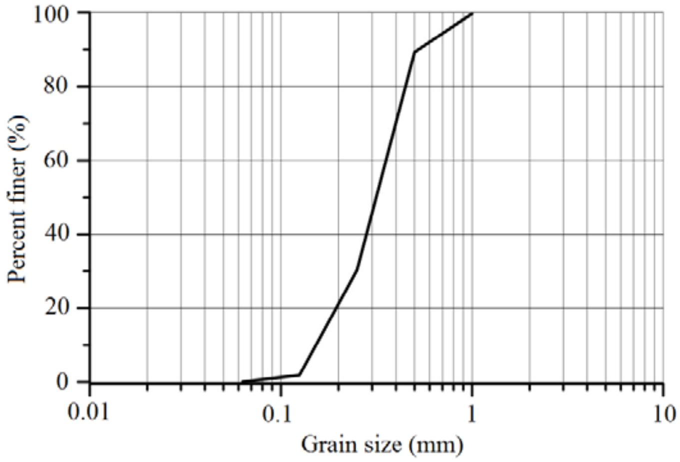

Fig. 4 Grain size distribution of sand

The peat samples retrieved from the auger were cut into decimeter long cylindrical pieces wrapped in plastic foil and then transferred into half liners. Applying this method, undisturbed peat samples of 10 cm length, suitable for laboratory testing, were prepared. These proved adequate for the laboratory testing. Field examination of the trial site, performed in October 2011, indicated that ground water level was 0.7 m from the natural ground surface and the peat samples had high values of water holding capacity. The Blockland peat's basic geotechnical relevant properties are presented in Table 1.

The sand additive used in this study was collected from a fossil, late Pleistocene in land dune located in the eastern part of Bremen, Germany. The almost pure quartz sand is from an onshore source, well-graded with a density of 2650 kg/m^3. Sands of this origin and composition are industrially available in large quantities from sand pits. The grain size distribution of the sand additive is presented in Fig. 4.

Two or three vertical holes were formed through peat samples by using cylindrical steel extruders of different diameters to make place for the sand (Table 2). The hole diameters were filled with sand for the permeability, consolidation and direct shear tests (Fig. 5). Dry sand was poured into these cylindrical holes in three equal stages comprising one-third of the volume for each stage. After each addition, the sand was compressed by regular taps on the outside perimeter of the consolidation or direct shear ring until no further change in volume of sand columns was detected by visual observation. As the height of samples within consolidation or direct shear rings is constant, in order to create test samples with different proportions of sand to peat, volumes of sand in columns were manipulated by changing the diameter of the holes. Prepared samples were then installed carefully in consolidation or shear test apparatus.

Different volume ratios of sand to peat were achieved by using different diameters of sand columns (Table 2).

2.2 Laboratory program

Two series of laboratory tests were carried out to measure permeability, consolidation and

Table 2 Diameter and height of ring and sand columns in consolidation and direct shear tests

Soil	Consolidation test				Direct shear test			
	Ring		Sand columns		Ring		Sand columns	
	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)
Natural peat (UP)	5.06	1.48	-	-	5.64	2.5	-	-
80% peat + 20% sand (80P20Sc) - 2 columns	5.06	1.48	2 × 1.15	1.48	5.64	2.5	2 × 1.25	2.5
70% peat + 30% sand (70P30Sc) - 2 columns	5.06	1.48	2 × 1.40	1.48	5.64	2.5	2 × 1.55	2.5
60% peat + 40% sand (60P40Sc) - 2 columns	5.06	1.48	2 × 1.60	1.48	5.64	2.5	2 × 1.80	2.5
60% peat + 40% sand (60P40Sc) - 3 columns	5.06	1.48	3 × 1.05	1.48	5.64	2.5	3 × 1.20	2.5

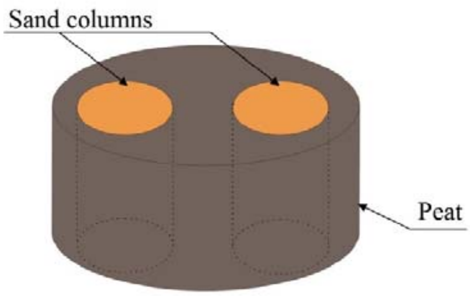

Fig. 5 Method used to set up sand columns in specimen

shear strength of the peat stabilized with sand columns and to compare with unaltered peat. Loading ranges are set to simulate *in-situ* conditions and conditions common to geotechnical projects such as residential buildings. Initially the peat fabric from the undisturbed samples was analyzed by scanning electron microscopy (SEM). The geotechnical laboratory work included permeability, shear strength and compressibility tests. All tests were performed on extruded, undisturbed peat samples and three different volume properties of sand and peat:

1. Natural peat (denoted as NP)
2. 80% of Peat (P) with 20% of Sand column (Sc) (denoted as 80P20Sc)
3. 70% of Peat (P) with 30% of Sand column (Sc) (denoted as 70P30Sc)
4. 60% of Peat (P) with 40% of Sand column (Sc) (denoted as 60P40Sc)

In a second series of experiments the influence of the number of sand columns using the 60P40Sc volumetric percentage was evaluated.

4. 60% of Peat (P) with 40% of Sand column (Sc) (denoted as 60P40Sc) – 2 sand columns
5. 60% of Peat (P) with 40% of Sand column (Sc) (denoted as 60P40Sc) – 3 sand columns

A maximum of 40% of sand replacing peat was selected as an economic and practical threshold

- above this a total removal of close surface peats is likely more feasible. The samples with different volumetric proportions of peat and sand in columns were subjected to permeability (BS 1377: part 5), 1-D consolidation (BS 1377: part 6) and direct shear (BS 1377: part 7) tests.

The compressibility characteristics of the stabilized peat and untreated peat samples were evaluated by standard one dimensional consolidation testing. One step of unloading was performed during the consolidation testing to evaluate the swelling characteristics of the samples. To investigate the creep behavior of the samples, the coefficient of secondary compression, C_{α}, was determined from the e-log(t) curves 4–24 hours after applying each load increment, assuming that secondary consolidation started the last 4 hours after loading (Hebib and Farrell 2000). The vertical permeability of the samples was determined by falling head tests at the end of each load step in the course of the one dimensional consolidation testing following the example of Mesri and Ajlouni (2007). Readings were taken 2 hours after primary consolidation had stopped.

3. Test results and discussion

3.1 Permeability

The results of the permeability testing are illustrated in Fig. 6.

The natural peat sample shows a high initial hydraulic conductivity, which decreases fast with increasing overburden pressure (Fig. 6). The void ratio, size of flow channel perpendicular to the direction of flow, and shape of flow channels parallel to the direction of flow are the parameters that determine the permeability of all kinds of soils (Mesri and Ajlouni 2007). The nonuniform cellular structure of the undisturbed fibrous Blockland peat is illustrated in Fig. 7 is the main reason for the high initial permeability. The marked decrease in hydraulic conductivity with increasing overburden pressure results from the closing of the macropores and fissures (Mesri and Ajlouni 2007).

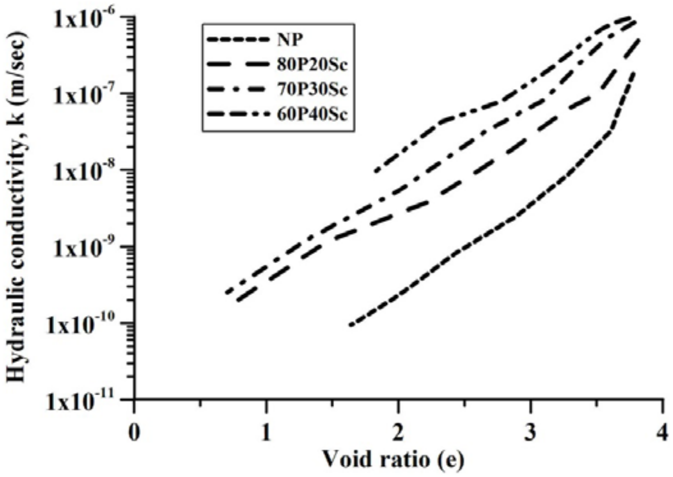

Fig. 6 Hydraulic conductivity vs. void ratio

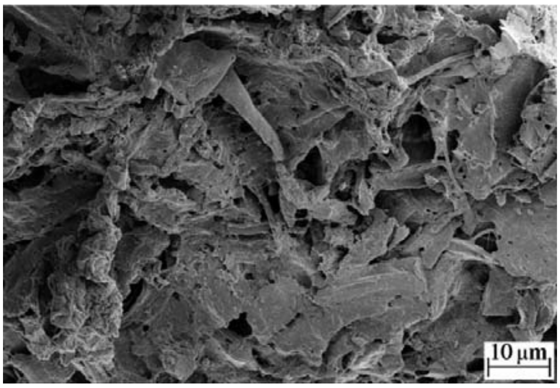

Fig. 7 Scanning electron microphotograph of a horizontal section of Blockland peat showing fabric

As the percentage of sand increases in the samples, the values of the hydraulic conductivity also increases compared with NP, with the most permeable samples being 60P40Sc (Fig. 6). At e = 3.70 hydraulic conductivity of NP is close to the treated samples, but as the void ratio decreases, this gap becomes greater and reaches its maximum at e = 1.80. This shows the impact of sand columns on hydraulic conductivity of treated samples at different stages of loadings. Peat in its natural condition possesses very high initial hydraulic conductivity, and at the earliest stage of loading peat plays an important role in the hydraulic conductivity of the treated samples. However, as the overburden pressure increases, peat fibers become more compact which reduces the hydraulic conductivity. Meanwhile, for the treated samples, sand facilitates drainage and increases hydraulic conductivity. The introduced sand columns provide a preferred pathway for vertical drainage of the peat samples and this effect is clear at all stages of loading. At a given void ratio of a fibrous peat, Dhowian and Edil (1980) stated a coefficient of horizontal permeability (k_h) 300 times greater than a coefficient of vertical permeability (k_v). Hence the vertical drainage through the sand columns is very effective in expediting the drainage of peats and increasing the relative vertical hydraulic conductivity of peat.

3.2 Compressibility

Fig. 8 presents the void ratio decline with increasing consolidation pressure for the first series of experiments with none or two added sand columns. Presentation of compressibility results relies on calculation of a void ratio; in the case of peat with discrete sand columns there is no single void ratio value to describe the tested sample as the peat and sand will have different void ratios. To overcome this, the void ratio of the peat material alone was calculated; to facilitate this calculation, the volume of peat alone was used in the equation. Consequently, the consolidation graphs of stabilized peat samples only demonstrate the compressibility behavior of the peat component, and not peat and sand together. Sand was filled into the columns in different volumes according to different compositions stated in Table 2. The sand columns are considered as elements which influence the compressibility behavior of the peat layer, but it is the compressibility of the peat itself that is of interest in this study.

The initial void ratios of all 4 samples are similar but diverge with increased loading. It is clear that 70P30Sc achieved greater compaction than the other mixtures at all values of consolidation

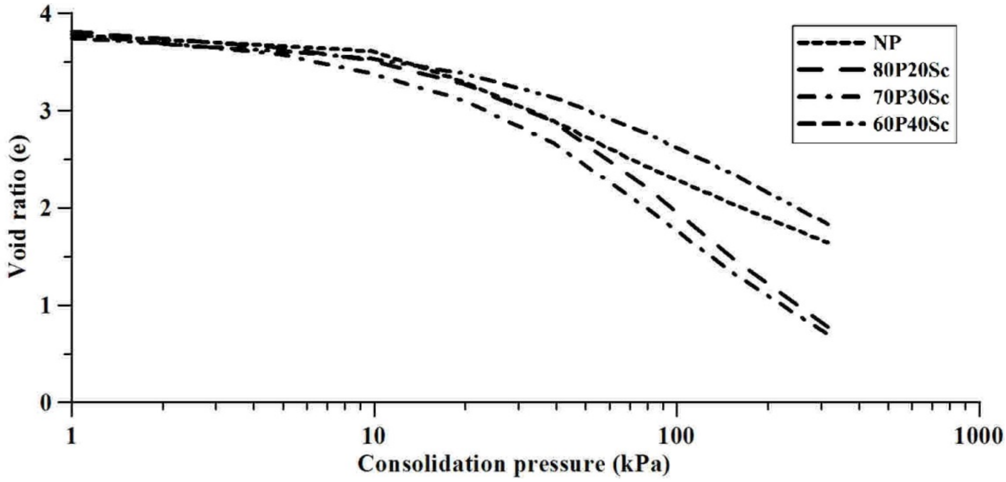

Fig. 8 Void ratio versus consolidation pressure

pressure. In eight stages of loading, the void ratio of 70P30Sc decreased from 3.78 to 0.71 compared with 3.74 to 1.84 for 60P40Sc. The consolidation behavior of 80P20Sc was intermediate between 70P30Sc and NP. As discussed above, sand columns provide an improved pathway for vertical drainage of the peat samples which directly shorten the time of consolidation and lead to faster consolidation of peat layer. By increasing the percentage of sand in samples, better drainage lead to faster consolidation under different loading increments which can be seen in the 80P20Sc and 70P30Sc curves.

On first sight surprisingly in 60P40Sc, the compressibility is lower than that of NP. Compared with NP, compressibility of peat was increased by adding 20% sand and achieved its greatest values on samples with 30% sand, however, the compressibility decreased in samples with 40% sand. Thus, a peak in compressibility was achieved at 30% sand volume. In this case it is believed that the exerted loads were transferred to the sand columns rather than the peat, effectively preventing peat compression. This is due to the geometry of the two-column experiment for which the size of the sand columns in the 60P40Sc samples means that more than 60% of a diameter of the sample section that passes through the center of the sand columns is comprised of sand. Thus, in spite of the good drainage provided by a high percentage of sand in the samples, the decrease of void ratio in peat sample did not follow the trend of the 80P20Sc and 70P30Sc samples. Hebib and Farrell (2000) observed that cement-stabilized peat cured for 240 days displays the lowest void ratio among all samples they considered. At a consolidation pressure of 100 kPa, the void ratio of the 240 days cement-stabilized peat sample is ~4.80. Meanwhile, in samples treated with sand columns, the void ratio of the 70P30Sc sample, which displays the lowest void ratio among all samples considered in this study, reduced to 1.80 at the same consolidation pressure.

Measured swelling percentages of samples are presented in Table 3.

The relative value for swelling decreased as the percentage of sand increased in the samples. These results indicate that swelling of the sand is less than that of the peat and with an increase of the sand percentage in a sample, the relative value for swelling decreases. According to Table 3, NP has the highest and 60P40Sc has the lowest swelling potential. Value of swelling for 70P30Sc is closer to 60P40Sc than that of 80P20Sc which indicates an over proportional decrease in swelling

Table 3 Swelling values during unloading of samples in consolidation test

Soil	Swelling (%)
NP	2.55
80P20Sc	2.42
70P30Sc	1.89
60P40Sc	1.70

with increasing sand percentages of the samples.

The coefficient of consolidation, c_v, is one of the most important parameters obtained from the consolidation test, gaining particular importance in the preloading technique for ground improvement (Sridharan and Nagaraj 2012). Fig. 9 shows the measured variation of c_v with consolidation pressure. Increase in percentage of sand in samples shortens the drainage distance to sand columns and leads to higher values of c_v.

The maximum and minimum values of c_v at the beginning of consolidation were 9.76 cm^2/min for 60P40Sc and 0.72 cm^2/min for NP respectively. With increased consolidation pressure, values of c_v also decreased in all samples. Among all samples NP showed the lowest and 60P40Sc showed the highest values of the coefficient of consolidation for all load ranges. We relate this to the larger diameter sand columns in the 60P40Sc sample which we infer considerably increased the permeability and Young's modulus and thus increased the speed of consolidation. In the study conducted by Hebib and Farrell (2000), values of c_v for cement-stabilized samples increased quickly as the consolidation pressure was approached, reached a maximum and then dropped with increasing load. The authors did not describe the reason for this phenomenon. Among the cured samples, the 240 days cured sample possessed the least c_v among all samples.

The development of C_α at different consolidation stresses is shown in Fig. 10.

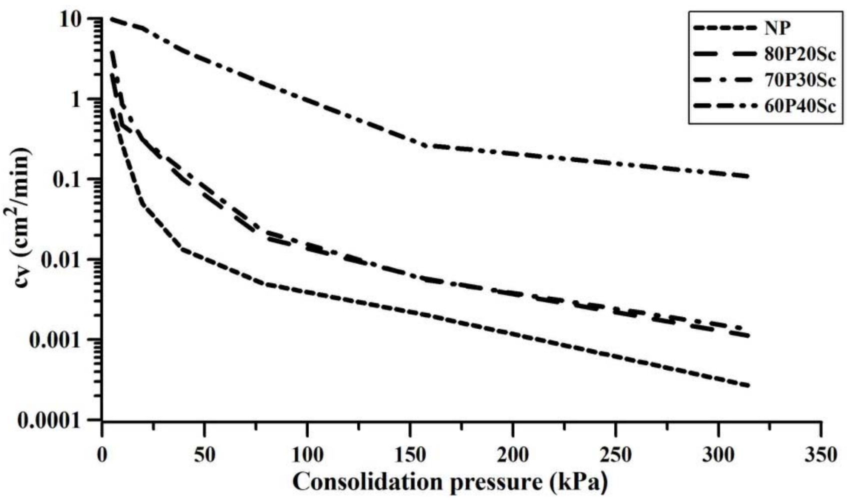

Fig. 9 Variation of cv with consolidation pressure

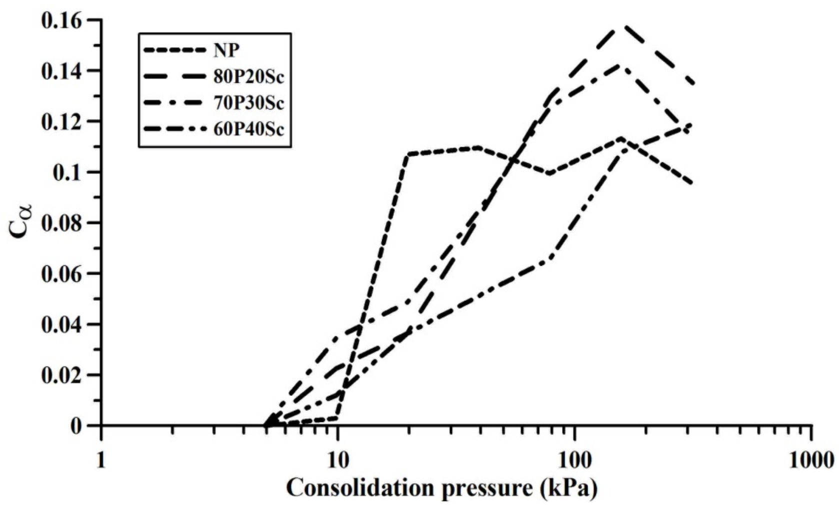

Fig. 10 C_α versus consolidation pressure

As the applied normal pressure rises during consolidation the plastic and viscous deformation of the peat fibers increases, leading to markedly ascending values of C_α in all samples. In NP, C_α increased rapidly at early stages of loading but from applied pressures of 20 kPa onwards, the creep (C_α) stays approximately constant. In the 60P40Sc case, C_α is showing the lowest ascending slope and no threshold pressure where the creep became constant. In the 80P20Sc and 70P20Sc samples, C_α starts to drop off in last stage of loading at 150 kPa. Sand columns in the samples helped the peat to decrease void ratio in a faster trend. As the percentage of sand in the samples increases, the maximum value of the coefficient of secondary compression also increases as seen in the 70P30Sc and 80P20Sc samples. The C_α behavior for the 60P40Sc case is again an exception lower maximum values of C_α and lower slopes are related to the high percentage of sand and its associated higher internal strength against one axial deformation. Larger sand columns in sample 60P40Sc prevented the applied pressure to be effectively conducted to the surrounding peat. The C_α behavior of the 60P40Sc sample closely mimics the c_v and void ratio data. Hebib and Farrell (2000) observed that C_α values of cement-stabilized peat samples were very low, and increased continuously throughout the loading process, indicating that creep is not controlled by the stabilization methods they trialed. They explained that for cement-stabilized peat, creep could be associated with a structural breakdown of the bindings. They also observed that C_α was affected by curing time as it decreased with increasing curing time.

Consolidation properties of peat samples treated with sand columns are more consistent and reliable compared with cement-stabilized peat samples. In particular, the samples in this study displayed a greater reduction of void ratio, and a consistent decrease of c_v under consolidation pressure compared with cement-stabilized peat samples. A yield C_α at relatively low consolidation pressure was also achieved for the peat treated with sand columns which was absent in the cement stabilized samples.

3.3 Shear strength

A series of water saturated and drained direct shear tests was performed on the conditioned and

Table 4 Maximum drained shear stress of samples in different applied normal pressure

Normal stress (kPa)	Maximum shear stress (kPa)			
	NP	80P20Sc	70P30Sc	60P40Sc
20	33.55	35.40	39.20	26.82
40	43.22	51.12	54.42	36.734
60	74.38	91.04	98.36	59.19

Table 5 Internal friction angle of samples

Soil	Peak friction angle φ_p (Degree)
UP	45.59
80P20Sc	54.35
70P30Sc	55.93
60P40Sc	38.98

natural peat samples. Direct shear tests were performed by GISA direct shear apparatus with shear rate of 0.01 mm/min. The results of these tests are presented in Table 4.

All samples show a clear trend of increasing shear strength with increasing normal stress as expected (Table 4). The maximum shear strength increases with the presence of sand columns in the 80P20Sc and 70P30Sc samples. 70P30Sc showed the highest maximum shear stress among all samples. Shear strength of 60P40Sc was expected to be higher than 70P30Sc's based on the trends seen in the samples with smaller added sand volumes, but it decreased dramatically compared with 70P30Sc's results. This phenomenon is also observed in internal friction angle (φ) of the samples. Table 5 summarizes the angles of internal friction for all samples acquired during direct shear tests of the first test series.

Samples 80P20Sc and 70P30Sc exhibited an internal friction angle of 55.93° and 54.35° respectively, whereas the friction angle was 38.98° for sample 60P40Sc. Comparing the internal friction angle value of NP with the 80P20Sc and 70P30S samples, considerable improvement was achieved by adding sand columns to peat (Table 5). Sand columns helped 80P20Sc and 70P30Sc samples to consolidate faster, hence bringing more solid soil material into the shear zone. As the degree of consolidation of peat increased, its shear strength also increased. We infer that greater compressibility of 80P20Sc and 70P30Sc leads to better compaction of peat fibers which generates higher internal friction angle comparing with NP (Table 5), this is consistent with the findings of Edil and Wong (2000). Since 60P40Sc showed a lower overall compressibility than all other samples (Fig. 8), its ultimate shear strength value is consequently the smallest. Lower compressibility at 60P40Sc prevents peat fibers engaging properly against each other and this leads to lower ultimate shear strength and internal friction angles of the bulk sample. Hebib and Farrell (2000) performed unconfined compression tests on stabilized peat samples. They observed an increase in unconfined compressive strength for all stabilizers when compared with the shear strength of the natural peat. The addition of 15% gypsum to the bfs tripled the strength achieved when using bfs alone. In addition, good results were obtained in cement stabilization and strength increased considerably with curing time. Studies performed by Deboucha *et al*. (2008), Roslan and Islam (2008), Wong *et al*. (2008), Kalantari *et al*. (2010) and Huat *et al*. (2011) indicated increases of unconfined compressive strength for cement-stabilized peat samples. Meanwhile, because of cement units in stabilized samples, none of the researchers used direct shear or triaxial tests to measure shear properties of samples. Significant increases in shear strength were achieved on cement-stabilized peat samples but it involves mixing which requires large volumes of cement and considerable cut, mixing and filling activities in commercial projects.

3.4 Influence of sand column number and geometry

To qualitatively evaluate the influence of the number and geometry of the added sand columns a second series of experiments have been conducted. As a part of this experimental series, direct shear and consolidation tests were repeated on samples with 60% Peat and 40% Sand volumes with the sand arranged in two and three columns. Aiming to evaluate the effect of sand columns number and geometry variations on compressibility and shear properties.

3.4.1 Compressibility

Fig. 11 shows the change of void ratio with increase of consolidation pressure for 60P40Sc samples with two and three sand columns. For better interpretation, samples with two and three sand columns will be hereafter denoted as 60P40Sc-2c and 60P40Sc-3c respectively.

At the beginning of applying consolidation pressure, values of void ratio for both samples were the same but samples showed different behaviors with a further increase in consolidation pressure. After $\sigma'_v = 20$ kPa, 60P40Sc-3c was undergone greater compressibility compared with 60P40Sc-2c (Fig. 11). Although the overall volume of sand in both samples was the same, two key differences are recognized:

- the sand in two columns has a smaller surface area in contact with the peat, and hence allows for less water infiltration from the peat to the sand, and
- edge effects between the columns and the fixed outer rim of the sample rings prevents expansion of the sand columns with applied load.

By reducing the drainage capability of the peat sample a lower degree of compressibility is

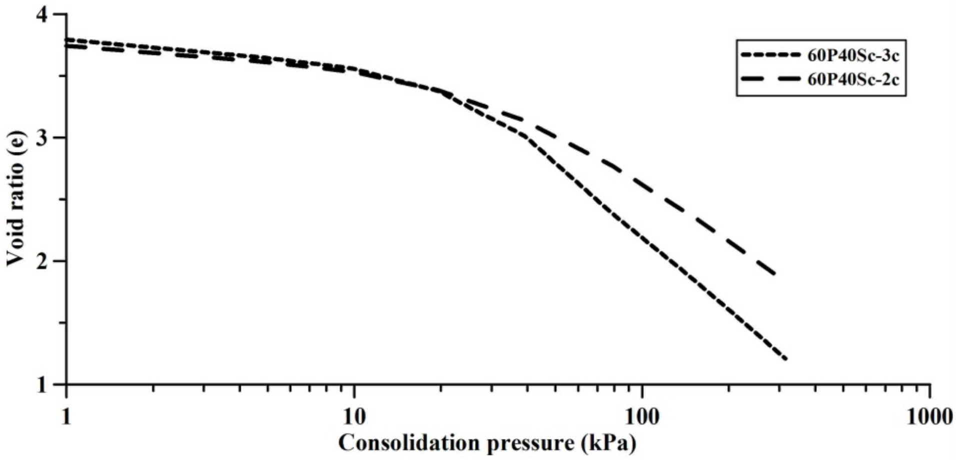

Fig. 11 Void ratio versus consolidation pressure of 60P40Sc specimens

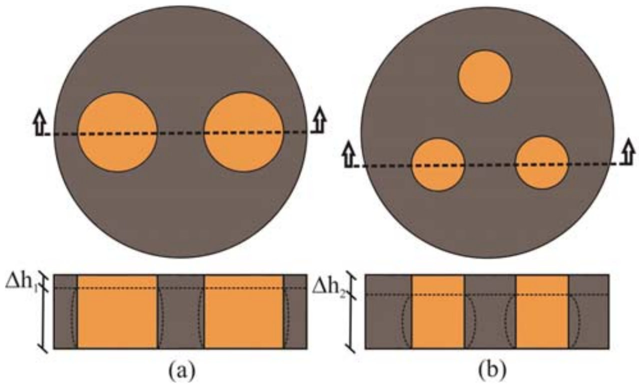

Fig. 12 60P40Sc samples plan and section in direct shear and consolidation ring with (a) two columns; and (b) three columns

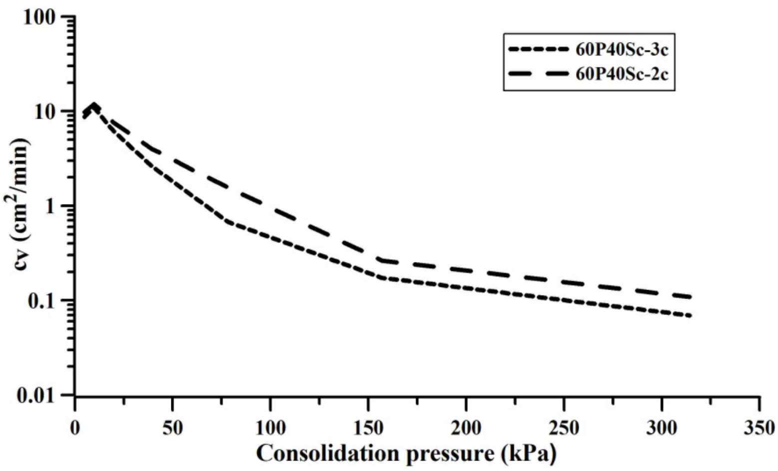

Fig. 13 Variation of c_v with consolidation pressure of 60P40Sc specimens

achieved for the two column samples compared with three columns. At 60P40Sc-2c, 63% of the section is occupied with sand which allows less deformation of peat at this section, but for 60P40Sc-3c sand columns occupy only 45% of the section which allows greater deformation of the peat and hence expansion of the sand columns at this section (Figs. 12(a)-(b)). Lade and Wasif (1988) performed a study evaluating effects of height to diameter ratio in triaxial sandy specimens with height/diameter (H/D) ratios of 1 and 2.5. They observed that the most consistent barrel shape like deformation were from those samples with H/D = 1. Accordingly, in Fig. 12, under the effect of consolidation pressure, deformation of sand columns in 60P40Sc-2c with greater H/D ratio was found to be lower than 60P40Sc-3c ($\Delta h_1 < \Delta h_2$). If deformation of the sand columns is prevented by edge effects, then the sample will be unable to compress.

During unloading the observed swelling value of 60P40Sc-2c with a value of 1.70% was also lower than that of 60P40Sc-3c with a value of 1.81%. The larger swelling was observed in the sample with the greater deformation under consolidation pressure.

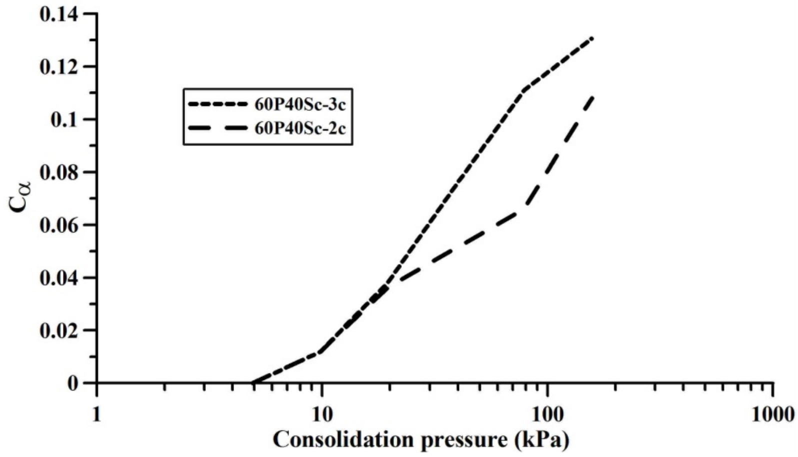

Fig. 14 Cα versus consolidation pressure of 60P40Sc specimens

Table 6 Maximum drained shear stress of 60P40Sc samples in different applied normal pressure

Normal stress (kPa)	Maximum shear stress (kPa)	
	60P40Sc-2c	60P40Sc-3c
20	26.82	29.52
40	36.73	47.35
60	59.19	79.06

The observed coefficients of consolidation, c_v, of both 60P40Sc-2c and 60P40Sc-3c are very similar. A slightly faster consolidation of 60P40Sc-3c can be observed in Fig. 13.

The likely better drainage provided by the three sand columns may be explained by shorter drainage passways and larger circumferences of the drain column hulls. In addition, based on greater compressibility of 60P40Sc-3c, the Young's modulus value of 60P40Sc-3c is higher than that for 60P40Sc-2c at the same consolidation pressure. Greater permeability and Young's modulus of 60P40Sc-3c lead to greater values of c_v.

At early stages of consolidation, the coefficient of secondary compression, C_α, indicating the creep potential, was the same in both samples but as the applied normal pressure increases within the consolidation cell, 60P40Sc-3c achieved greater C_α values (Fig. 14). This fits to the observed greater deformation of 60P40Sc-3c under the applied normal pressure.

3.4.2 Shear strength

Results of the shear test performed on 60P40Sc-2c and 60P40Sc-3c are presented in Table 6.
At each applied normal stress, 60P40Sc-3c showed a greater maximum shear stress (Table 6). As discussed earlier, the 60P40Sc-2c samples showed reduced consolidation compared with samples with less sand and hence reduced strength as fiber interactions were not developed to the same extent. In 60P40Sc-3c samples, the greater consolidation achieved is reflected in higher shear strength. In particular, a better interlocking of the more consolidated peat fibers increases the internal friction angles (Table 7).

Table 7 Shear strength parameters of 60P40Sc samples

Soil	Peak friction angle φ_p (Degree)
60P40Sc-2c	38.98
60P40Sc-3c	51.06

4. Conclusions

A series of laboratory experiments was performed to investigate the permeability, compressibility and strength parameters of Blockland peat and Blockland peat stabilized with sand columns. Permeability of natural peat was improved significantly by adding sand to the samples and achieved maximum values at the sample with 40% sand. The sand columns provided a shorter pathway for water to dissipate and thus improved the drainage of peat. In consolidation tests, the sample with 70% sand showed greater compressibility than all other samples. Vertical drainage provided by sand columns leads to faster consolidation of the peat layer. Meanwhile, the sample with 60% sand showed lower compressibility than that of natural peat. This is attributed to the load being carried by the greater sand column volume instead of being transferred to the peat, and this resulted in lower compression compared with the sample with 70% sand.

In terms of strength, an eye catching improvement of shear strength was exhibited in samples treated with sand columns. Sand columns expedite the consolidation rate, resulting in an increase in overall shear strength. By adding sand to peat, the shear strength of samples increased and reached an optimum value on samples with 70% peat and 30% sand. Shear strength values started to decrease in peat samples with 40% sand which is related to the lower consolidation state of those samples. Likewise, the maximum improvement in values of internal friction angle was observed on the peat samples treated with 30% sand, but was no improvement over natural peat was seen for the samples with 40% sand. Internal friction angles in the 60% peat and 40% sand samples decreased to values lower than undisturbed peat. As one conclusion, samples with 70% peat and 30% sand showed overall better geotechnical properties with regard to compressibility behavior and soil strength.

The influence of sand column number and geometry on compressibility and shear strength was qualitatively examined in samples containing 60% peat and 40% sands. Specimens with three sand columns showed greater compressibility, greater maximum shear strength and internal friction angle since the samples exhibited lower c_v and higher C_α compared to samples with two sand columns. The consolidation and shear results of the 60% peat and 40% sand experiments with two and three sand columns demonstrated the fact that geometry and spacing factors influence compressibility and shear strength of stabilized peats.

It appears that the insertion of sand columns could be a suitable way for peat soil stabilization. The mechanism by which improvement is believed to occur is through improved drainage through the sand columns leading to greater capacity for consolidation of the peat fiber network. Increased consolidation leads to tighter interlocking of the fibers, and hence increased shear strength and angle of internal friction. The poor geotechnical behavior of peat in its natural state is a result of the very high water contents which effectively separate the fibers into a loose network. By artificially enhancing drainage, the high compressibility of peat can be exploited to bring the fibers into much closer contact to dramatically improve the geotechnical performance. However, to achieve fibers interlocking, loading of the treated samples are necessary and for *in-situ* trial preloading of treated peat with sand columns can provide adequate deformation and increase fibers contact.

In all cases the approach has to be adapted to the intended application and its associated load and geometry requirements. *In-situ* tests on stabilized peat with sand columns have to be done to measure *in-situ* mechanical properties of treated soil prior to constructional loading. In order to apply this method at *in-situ* trial, careful local evaluation of the variable physical properties of peat is essential since peat is a highly variable material. However, it is anticipated that this method is applicable for peat soils elsewhere with same basic properties. While cement-stabilizing techniques for peat soils have been introduced in several studies, previous experimental examples suggested the impact of sand trenches on peat soils, and soft soil treatment technique using sand columns has been introduced by other researchers to treat non-organic soils, this paper presents the first laboratory based research on peat soil treated with sand columns, and has shown the possibility of sand being considered as an easily available and environmental neutral stabilizer for peat rich soils.

Further laboratory, field-studies numerical modeling and careful thoughts on the upscaling of laboratory results are required to develop the ideas presented here toward a possible application. A measurement of loads using load cells may provide greater insight into the response to applied load of peat and sand piles in different samples. *In-situ* tests on stabilized peat with sand columns have to be done to measure *in-situ* mechanical properties of treated soil prior to constructional applications.

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