Effect of salt grain additions on fibrous peat consolidation

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Peat has been considered a problematic geotechnical material, with extremely high water content, low shear strength and high compressibility. Although initially high, fibrous peat undergoes dramatic reductions in permeability under compression, with secondary compression (creep) accounting for a large proportion of the settlement under loading. The key to accelerating the whole consolidation process for fibrous/hemic peats is to create a means of accelerating water flow from micropores (within the cellular structure) or humus contained in the peat. This paper presents the results of preliminary laboratory trials performed using the hydraulic consolidation (Rowe) cell apparatus to investigate a novel approach involving the addition of salt grains to fibrous peat towards accelerating its rate of primary consolidation and reducing its creep rate. Under similar loading conditions, salt-treated specimens were found to have reduced rate and magnitude of creep settlement, explained by larger volumes of micropore water expelled during primary consolidation.

Notation

C_α	coefficient of secondary compression
C_{sec}	secondary compression ratio
c	salt concentration
c_v	coefficient of primary consolidation
e	void ratio
e_0	initial void ratio
m_p	wet mass of peat
m_s	mass of salt grains
$m_{v \text{ EOP}}$	volume compressibility coefficient based on 'end of primary' consolidation settlement
ρ_w	density of pore water
t	time
u	untreated peat specimen
w	water content

1. Introduction

Peat is considered a problematic geotechnical material, with extremely high water content, low shear strength and high compressibility; secondary compression (creep) accounting for a large proportion of the settlement under loading (Farrell, 2012; Mesri and Ajlouni, 2007; O'Kelly, 2009). Primary consolidation of fibrous peat occurs rapidly on account of its high initial permeability (typically 1000 times that of soft clay/silt deposits), although it undergoes dramatic reductions in permeability under compression (Mesri and Ajlouni, 2007). For instance, in the case

of fibrous peat, the ratio of permeability change index (i.e. change in void ratio to change in logarithm of vertical permeability) to in situ void ratio is typically about 0.25, compared to approximately 0.50 for soft clay/silt deposits (Mesri and Ajlouni, 2007).

Preloading/surcharging in combination with vertical drains is the most widely applied technique used to improve the geomechanical properties of peat and other organic soil deposits (Mesri and Ajlouni, 2007; Mesri *et al.*, 1997; Santagata *et al.*, 2008). However, several investigators (Lake, 1961, 1963; McNulty, 1991; Mesri and Ajlouni, 2007) have suggested that vertical (sand) drains have little effect in accelerating the settlement rate for fibrous peat, considering the peat's high initial permeability and dominant creep effects. Chemical treatments using cement, lime, fly ash or other additives have also been used in practice to improve the geomechanical properties of peat (Deboucha *et al.*, 2008; Hebib and Farrell, 2003; Hughes and Glendinning, 2004; Kalantari *et al.*, 2011; Kazemian *et al.*, 2012; Wong *et al.*, 2008), although the large volumes of additive required often make such techniques prohibitively expensive. As an alternative, researchers (Osorio, 2012; Osorio *et al.*, 2008, 2010) at Trinity College Dublin (TCD) have been investigating the vacuum consolidation technique for accelerating the consolidation of fibrous peat. However, physical/chemical blockage of the vacuum lines, along with difficulties in transporting and setting up the vacuum

equipment at soft peat deposits, has tended to handicap its field application. Another novel approach proposed by the TCD research group involves increasing the degree of humification (decomposition) of fibrous peat in order to reduce creep settlements (Pichan and O'Kelly, 2012, 2013), although destroying the peat material's essentially fibrous structure also has the effect of reducing its coefficient of permeability (Hobbs, 1986; O'Kelly, 2005a, 2006).

One of the most striking properties of peat is its extremely high water content, often in the range of 1000–2000% by dry mass (Hobbs, 1986). Pore water in the open interstices of the peat material is ready to drain under load application. However, a large quantity of water continues to be gradually released over a long period of time on account of peat's large water-holding capacity, provided by both micropores and humified organic content (ASTM, 2004; Hobbs, 1986). For fibrous peats, researchers (Adams, 1965; Berry and Poskitt, 1972; Dhowian and Edil, 1980; O'Kelly, 2013; Wong *et al.*, 2009) have postulated a two-level structure of micro- and macropores. In this context, micropores are provided by the cellular structure within fibrous peat particles. Macropores are formed by the interstitial space between interwoven solid particles. Between one- and two-thirds of the water content of fibrous peat is contained within micropores (Landva and Pheeney, 1980; Ohira, 1977). Primary consolidation mainly involves drainage of macropore water that is ready to drain. The creep portion of fibrous peat settlement is explained by the slow process of drainage from micropores to macropores, which manifests as dramatic reductions in permeability of the material under loading. It is commonly advocated that for fibrous peat, creep occurs simultaneously with the process of primary consolidation (den Haan, 1996; den Haan and Edil, 1994; Edil *et al.*, 1991). In this context, primary consolidation is explained mainly as the hydrodynamic process whereby macropore water drains, along with micropore water flowing into macropores at a slow rate, with creep merely consisting of the later process. In peats having a higher degree of humification, porous structures have been degraded somewhat, although a similar analogue can be invoked, namely gradual release of water occurs from decayed plant humus, a material that also has high water-holding capacity. Landva and Pheeney (1980) investigated the microscopic properties of fibrous peat and observed that there was little visual difference in fabric between that of natural material and the same material compressed under an applied stress of 7 MPa. It is widely accepted that a major consideration regarding the decrease in coefficient of permeability of peat is its large water-holding capacity (Hemond and Goldman, 1985). Hence, the key to accelerating the whole consolidation process for fibrous/hemic peats is to create a means of accelerating water flow from micropores or humus contained within the peat structure.

This paper sets out to investigate the effects of the addition of salt (sodium chloride, NaCl) grains on the compression/consolidation response of fibrous peat under loading towards developing a novel method of ground improvement. Preliminary laboratory

trials have been performed in order to investigate changes in the rates of primary consolidation and creep achieved for salt-treated fibrous peat specimens.

2. Methodology

Based upon the two-level structure and consolidation mechanism described earlier in the paper, the creep portion of the settlement response for slightly decomposed fibrous peat material is largely caused by the secular process of micropore water movement to macropores (de Josselin de Jong, 1968). For humic peat, creep is the manifestation of the gradual release of water molecules from humus. Chen *et al.* (1976) indicated that the sponge-like structure of humus has water and other liquids chemically (or otherwise firmly) bound within microstructures. The process of ionisation of salt grains induces the movement of nearby pore water towards them. Dissolving salt grains also release a high-ion-concentration water layer around them, producing electrostatic potential and concentration potential fields that can attract counter-ions in the micropore water, thereby inducing further movement of fluid with ions. Based on this concept, a new approach is proposed towards accelerating the rate of consolidation and reducing the creep rate for fibrous peat. This involves adding salt grains to the peat during its creep stage (i.e. proportion of macropore water remaining within the peat material is small). Sodium and chloride ions are released around the surface of the salt grains by the ionisation process (Figure 1). As micropore water can transfer to macropores quicker, pore water ready to drain under loading gathers around salt grains during the ionisation process, accelerating drainage from micropores to macropores, thereby accelerating the whole consolidation process for the peat material. For the purpose of this investigation, sodium chloride salt was selected to accelerate consolidation since sodium chloride solution has neutral pH. Increases in pH value of the pore water in peat are likely to cause an increase in the rate of decomposition of constituent organic matter (Pichan and O'Kelly, 2012, 2013).

As the peat material tested in the present study was moderately decomposed, fine, fibrous peat, macropore interstices are very

Figure 1. Sodium chloride grain dissolving in peat macropores

small and contain colloidal matter that can be undecomposed organic constituents of the original plant material, such as lignin, or organic colloids (humus) produced by complete/partial decay of plant material through bacterial processes (Pichan and O'Kelly, 2013). Two hypotheses (Stevenson, 1994) are usually considered in describing the colloidal portion in soils and these are presented below.

In the first hypothesis, which is more applicable for inorganic soils, colloidal substances are assumed to consist of rigid spherical particles, in aqueous solution, include an electric double layer and a mantle of hydration water. For the double layer, the inner layer is immediately adjacent and fixed to the surface of the colloidal particle. The outer layer, of opposite sign, is movable and extends into the supporting medium. For instance, Figure 2 shows the expansion of the diffuse hydration layer for nano-scale silica induced by the presence of sodium ions in pure water (Song *et al.*, 2005) since the hydrated sodium ions are larger in size compared with the water molecules. In the present investigation, the peat test materials considered have low pH values. Hence monovalent H^+ is attracted to the hydration double layer located around the negatively charged colloids. In the presence of sodium cations, the exchange of hydrated Na^+ ions with H^+ occurs, with the extent and rate of this reaction dependent on the cation-exchange capacity of the organic colloid molecules. It should be noted that the cation-exchange capacity of soil organic matter decreases markedly with decreasing pH value (Helling *et al.*, 1964) on account of the decreased ionisation of the acidic groups (mostly $COOH$) at lower pH. For ions of equal valency, the least hydrated have the highest adsorption energy (Stevenson, 1994). Hence in acidic solutions, H^+ is more stably adsorbed to the colloid particle than hydrated sodium ions. The diffuse hydration layer forms on account of electrostatic attraction, since humic particles have negative charge. According to Coulomb's law, the adsorption force is inversely proportional to the square of the distance between the ions and colloid particle. The adsorption force between ions and the colloid particle decrease with the exchange of hydrated sodium ions with water molecules (H_3O^+). Hence water molecules adsorbed in the diffuse hydration layer are easier to drain under loading.

In the second hypothesis, humic colloids (long-chain molecules with two/three-dimensional cross-linked macromolecules) can adopt the configuration of a flexible coil in solution. Since these colloid molecules/polymers have natural negative charge, cations such as H^+ in solution are attracted around colloids. Ong and Bisque (1968) postulated that in the presence of electrolyte, the humus macromolecule changes from a hydrophilic to hydrophobic type colloid. It was believed that in aqueous solution, the polymers assumed a stretched configuration on account of mutual repulsion of negatively charged functional groups. When electrolyte was added, cations are attracted to negative groups, thereby causing a reduction in intermolecular Coulombic repulsion in the polymer chain. This in turn favours coiling of the chain, causing a reduction in the amount of hydration water held by the colloid.

Figure 2. Illustration showing expansion of diffuse hydration layer of nano-scale silica induced by sodium ions in pure water (Song *et al.*, 2005)

Taking a negatively charged organic molecule as $R(COO)H$, the presence of sodium ions also causes a shift in cation attraction to occur in the diffuse hydration layer (Equation 1) and hence more 'free' water can be released.

In summary, the two hypotheses presented above lead to the same conclusion that the presence of sodium ions assists in the release of more free water molecules from the peat structure. The active period of the salt treatment is the period over which salt grains remain undissolved; that is, the effect on the consolidation rate is

marginal once the salt has been fully dissolved. Hence fine salt is expected to have a shorter active duration period compared with coarse salt, leading to the conclusion that an appropriate grading of salt should be chosen when considering an acceleration of the consolidation rate for fibrous peat.

3. Test materials

In the present study, experimental laboratory trials were performed on two saturated peat materials to investigate the repeatability of the proposed treatment method, also considering scale (test specimen and salt grain size) effects. Saturated peat material was obtained from a depth of 2.5 m below the ground surface at Clara raised bog, County Offaly, Ireland. Some of this material was subsequently allowed to decompose further, from H4 to H6 on the scale of von Post (Landva and Pheeney, 1980), in the laboratory environment. These test materials will be referred to as P1 and P2 respectively, with selected properties listed in Table 1. Both peat materials were categorised as hemic or moderately decomposed peat (fibre content, $FC < 67\%$; ASTM, 2007) and classified as SCN-B3-F3(S)-R1(N)-W1(N) on the extended von Post scale (Landva and Pheeney, 1980). Further details on the geomechanical behaviour and properties of the Clara peat under study have been reported by O'Kelly and Zhang (2013) and Zhang and O'Kelly (2013).

The chemistry of the groundwater at Clara raised bog has been reported by Kelly (1993) as follows: calcium (Ca), 140 mg/l; magnesium (Mg), 8.3 mg/l; potassium (K), 1.1 mg/l; sodium (Na), 9.7 mg/l; chloride (Cl), 20.0 mg/l. The solubility of sodium chloride in pure water is 350 g/l at a temperature of 25°C. In the present study, a low concentration of 30 g dry salt/l pore water (from Equation 2, taking the density of pore-water ρ_w as 1 g/ml) was adopted for the trials since, at higher concentrations, electrochemical reactions occurring between the salt solution and experimental apparatus may cause noticeable pitting of steel material in the latter. Two gradings of salt were also considered (Figure 3) in order to investigate possible effects of salt grain size on the peat consolidation rate.

$$2. \quad c = \frac{m_s}{\{m_p[w/(100 + w)]\} / \rho_w}$$

Material type	P1	P2
Water content: %	1014	1081
Specific gravity of solids	1.42	1.50
Degree of humification	H4	H6
Loss in dry mass on ignition: %	98.6	94.9
Fibre content: %	63.5	50.9
pH value	3.8	4.5

Table 1. Selected properties of peat test materials

Figure 3. Grading of salts considered

where c (in g/l pore water) is the salt concentration; m_s is the mass of salt grains; m_p and w are the initial wet mass and water content (as %), respectively, for the peat material.

4. Materials and specimen preparation

Reconstituted specimens of peat test materials P1 and P2 were first consolidated using a 254 mm diameter hydraulic consolidation (Rowe) cell (BSI, 1990), set up for one-way specimen drainage by way of the specimen top surface to atmosphere (O'Kelly, 2005b). These consolidation tests were performed in order to reduce, somewhat, the macropore water that was ready to drain from the test materials. Compared with initial water contents of 1014% and 1081%, the consolidated specimens P1 and P2 had water contents of 602% and 640% respectively.

5. Test programme

After test specimens of P1 and P2 peat materials had been consolidated for cumulative periods of 105 and 17 days, respectively (see Table 2 for further details), additional testing was performed on material from the compressed peat cakes using both 254 and 76 mm diameter hydraulic consolidation cells. In preparation, the peat cake of P1 material was removed from the consolidation cell, crumbled and thoroughly hand-mixed with addition of the fine salt at a concentration of 30 g/l pore water before being compacted back to the same specimen height in the 254 mm diameter consolidation cell. By compacting the test specimens back to the same height achieved at the end of compression loading of the peat cakes, air voids could be excluded as much as possible, thereby maintaining near full saturation, confirmed by measured pore pressure coefficient B values of greater than 0.95 at the start of these tests.

In the case of peat material P2, two 76 mm diameter test specimens were prepared in a similar manner from the peat cake; one specimen had been treated with coarse salt, again at 30 g/l concentration, the other had no treatment. Shorter duration consolidation periods were adopted for salt-treated specimens (see Table 2) in order to reduce exposure of the consolidation cell and instrumentation to possible chemical damage. The settlement and pore water pressure responses and final efflux volume of the test

Peat material	P1			P2	
Cell diameter: mm	254	254	254	76	76
Stage applied stress: kPa	20	40	20	20	40
Material preparation stage:					
Initial height: mm	99.1	83.7	92.0	—	—
Stage duration: days	14	91	7	—	—
Main test: Initial height: mm/stage duration: days					
• untreated	—	—	—	24.65/1	22.35/17
• treated with fine salt	—	58.8/1	—	—	—
• treated with coarse salt	—	—	—	19.05/1	16.53/8

Table 2. Summary of consolidation test programme

specimens were measured. Although the concentration of Na^+ ions was not directly measured, salt concentrations were determined using two approaches. Salt was extracted from solution by oven-drying the pore water expelled from the salt-treated specimens. Salt was also extracted from the test specimens after termination of the consolidation tests. In this case, the test specimens were oven-dried, ground using a pestle and mortar to pass

the 425 μm sieve, soaked in distilled water for a 48 h period after which the suspension was filtered using Whatman number 4 filter paper. The salt was then extracted by oven-drying the filtrate.

6. Test results and analyses

Figure 4 shows axial strain and excess pore water pressure ratio U (i.e. ratio of measured excess pore pressure to stress increment)

Figure 4. Axial strain and pore pressure responses against elapsed time: (a) axial strain for 76 mm diameter specimens; (b) axial strain for 254 mm diameter specimens; (c) pore pressure ratio, U , for 76 mm diameter specimens; (d) pore pressure ratio, U , for 254 mm diameter specimens

responses determine from the settlement and excess pore water pressure data. Note that the specimens have been labelled as follows: test material (cs, coarse salt; fs, fine salt; u, untreated)/cell diameter (mm)/loading stage (kPa)/test duration (days); for example, P1(fs)/254/40/1 indicates peat material P1 treated with fine salt, consolidated in the 254 mm diameter cell under an applied stress of 40 kPa over a period of 1 day.

The data curves for the 76 mm diameter cell in Figures 4(a) and 4(c) show that under the same applied stress and loading period, salt-treated specimen P2(cs)/76/20/1 experienced greater strain compared with untreated peat specimen P2(u)/76/20/1. Dissipation of excess pore water pressure also occurred quicker for the salt-treated specimen for both the 20 and 40 kPa load stages (Figure 4(c)). The same trend was evident in the data curves for the 254 mm cell (Figures 4(b) and 4(d)).

The difference in shape of the strain curves for peat materials P1(u)/254/20/14 and P2(u)/254/20/7 in Figure 4(b) can be attributed to fibre effects, with the P2 material of von Post H6 experiencing greater strain than the P1 material of von Post H4 (FC = 50.9% and 63.5% respectively). Among the 254 mm diameter consolidation tests on P1 material, the P1(fs)/254/40/1 curve defined the lowest strain boundary, which was to be expected since the test material had already been consolidated (and also allowed to age somewhat) over the 91 day loading period under $\sigma_v = 40$ kPa during the material preparation stage. After a relatively short period, the P1(fs)/254/40/1 curve was quickly into secondary compression. This is consistent with the reduced initial value and quicker rate of dissipation of excess pore water pressure (Figure 4(d)) for which the salt effect was also a determinative factor.

Quantitatively, the respective coefficient of primary consolidation, c_v , values calculated by Taylor's method (Taylor, 1942) for salt-treated specimens P2(cs)/76/20/1 and P2(cs)/76/40/8 of 11.5 and 2.2 m²/year are greater than the values of 9.9 and 1.5 m²/year determined for untreated peat specimens P2(u)/76/20/1 and P2(u)/76/40/17, respectively, which confirms a higher consolidation rate for salt treatment. The value of the coefficient of volume compressibility associated with the primary consolidation stage, $m_{v\text{EOP}}$, of 5.3 m²/MN (determined using classical curve-fitting techniques) was also larger for salt-treated specimen P2(cs)/76/20/1 compared with untreated peat specimen P2(u)/76/20/1 (4.1 m²/MN). Similarly, calculated values of the coefficient of permeability, k_v , were marginally greater for salt-treated material; for example, 1.9×10^{-8} and 1.3×10^{-8} m/s for specimens P2(cs)/76/20/1 and P2(u)/76/20/1, respectively. However, under the second load stage at 40 kPa, peat specimen P2(u)/76/40/8 experienced a similar rate of consolidation but greater creep rate than salt-treated specimen P2(cs)/76/40/1 (see Figure 4(a)), with corresponding $m_{v\text{EOP}}$ values of 4.3 and 3.0 m²/MN. Two reasons are proposed to explain this apparent anomaly. First, the salt treatment had produced larger strain under the load stage at 20 kPa, producing lower initial water content (void ratio) values

for the 40 kPa load stage. Second, the salt grains in this specimen would have already been totally dissolved before the start of the 40 kPa load stage, and considering its lower initial water content, the amount of strain produced under 40 kPa load stage was lower compared with peat specimen P2(u)/76/40/8.

The addition of salt grains was also found to have an effect on the creep response. For instance, values of the coefficient of secondary compression ($C_\alpha = \Delta e / \Delta \log t$) and secondary compression ratio ($C_{\text{sec}} = C_\alpha / (1 + e_0)$) for salt-treated specimen P2(cs)/76/20/1 of 0.13 and 0.013, respectively, were marginally greater than corresponding values for peat specimen P2(u)/76/20/1; where e_0 is the initial void ratio and Δe the change in void ratio for a particular load stage and time period t . An apparent tertiary compression evident in the end portion of the strain curve for peat specimen P2(u)/76/40/17 was largely absent for salt-treated specimen P2(fs)/76/40/8 (Figure 4(a)). Tertiary compression is generally associated with strain ensuing from some decomposition of the peat solids occurring over the course of experimental laboratory testing (Mesri *et al.*, 1997). It is postulated that the salt treatment may have changed the salinity of the peat specimen, possibly creating a less favourable environment for microbial decomposition to occur and therefore a more stable creep rate under loading.

From the oven-dried efflux, the water expelled from salt-treated P2 material under loading in the 76 mm diameter consolidation cell had a measured salt concentration of 92 g/l pore water. The measured concentration of salt remaining at the end of consolidation within specimen P2(cs)/76/40/17 was 21 g/l pore water. The initial salt concentration in salt-treated P2 material was 30 g/l pore water. These values, confirmed by a mass balance calculation, indicate that more than one-third of the original salt additive had been removed from the treated peat by way of expelled pore water.

7. Summary and conclusions

Under similar conditions of one-dimensional loading, treatment of fibrous peat specimens by inclusion of a relatively small amount of salt grains (30 g dry salt/l pore water in the present study) was found to produce a faster rate and greater magnitude of primary consolidation settlement, and hence higher coefficient of permeability values compared with untreated peat (control) specimens. More than one-third of the salt additive was removed from the treated peat by way of expelled pore water. In addition, the rate and magnitude of creep settlement were reduced because greater settlement had occurred during the preceding primary consolidation stage, which was explained by the larger volume of micropore water expelled when compared with the control specimens. The active period of the salt treatment was the period over which the salt grains contained in the peat remained undissolved; that is, the effect on the above properties is marginal once the salt grains have fully dissolved. Considering the risk of groundwater pollution brought about by the dissolved salt, further research is required to find alternative, more environmentally friendly additives before trialling the proposed approach in situ.

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