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Atterberg limits are not appropriate for peat soils

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This paper reports on the challenges associated with the determination of the Atterberg limits for peat, fundamental issues regarding the appropriateness of Atterberg limit concepts applied to peat and peaty soils and their use in characterising the engineering behaviour of these materials. As demonstrated in the present study, different sample preparation methods and preloading of the peat material (which gives the organic solids some stress history because of their compressible nature) can result in significantly different Atterberg limit values being measured. The significance of reinforcement and scale effects related to the peat fibres for the thread-rolling method is investigated. It is concluded that the Atterberg limit tests are not appropriate for peat in that the deduced plastic range for the peat test material is notional and the calculated liquidity index values are not reliable indicators of its consistency. In assessing the likely engineering behaviour of peat material, a more useful suite of index tests is its natural water content, organic content, fibre content and degree of humification.

Notation

a	water content for s_{ur} = 1 kPa
b	gradient of log w–log s_{ur} relationship
d	thread diameter at crumbling condition in 'PL' test
F	ratio of reduction in soil thread diameter at crumbling condition to its starting diameter
'PL'	'plastic limit' for crumbling of soil thread at diameters greater than 3 mm during the rolling out procedure
s_{ur}	saturated remoulded undrained strength
$s_{ur(PL)}$	saturated remoulded undrained strength at the plastic limit
U	average degree of consolidation
u	maximum pore water pressure
u_b	specimen back-pressure
w	water content
σ_3	cell pressure
σ'_3	effective confining pressure

Introduction

The Atterberg limit tests are the most common tests specified by practising geotechnical engineers. The liquid limit (LL) and the plastic limit (PL) have physical meanings for remoulded fine-grained mineral soils and they correlate with many fundamental soil parameters used in design and construction practice. The Atterberg limit testing of peat and other highly organic soils (e.g. sewage sludge/biosolids and water-treatment residue materials) is regularly performed in practice and research work despite fundamental issues regarding its appropriateness for such materials (O'Kelly, 2014, 2015), as well as conflicting viewpoints in the literature on the value and significance of testing that adopts the conventional experimental soil mechanics approach when applied to peat soils.

Peat material can range from fresh fibrous material to amorphous material and, as such, has significantly different fabric and microstructure compared with fine-grained mineral soil. The high cation-exchange ability of the peat-forming plants produces strong adsorption complex and greater interparticle adherence, contributing to extremely high values of natural water content (generally in the range of 500–2000%) and also LL (Hobbs, 1986). Unlike pure frictional contacts in remoulded mineral soil, connectivity between the fibres in peat material having low humification is provided by cellular connections and fibre entanglement (Landva *et al*., 1986; O'Kelly and Orr, 2014). These fibres have relatively high tensile stiffness and strength, as well as providing conduits for the preferential flow of water. Further, the open cellular structure of the organic solids in peat means that they are themselves porous, flexible and compressible in nature, leading to the two-level structure of micro- and macro-pores (Adams, 1964; Berry and Poskitt, 1972; Dhowian and Edil, 1980). Hence, for peats that are not completely humified, the idea of an individual (distinct) soil particle may strictly not apply. The physics and chemistry of peat and the nature of its organic matrix exert important influences on deduced Atterberg limit values (Asadi *et al*., 2011; Hobbs, 1986; Yang and Dykes, 2006).

Atterberg limit testing can be problematic for peat material, mainly on account of the peat fibres, which introduce reinforcement and scale effects. The sample preparation method used in preparing mineral soil for Atterberg limit testing is usually also adopted for preparing the peat test material, with any partly decomposed plant solids present mechanically broken down into a very fine detritus before testing. The Atterberg limit testing of

mineral soil is performed on the soil fraction passing the 425 μm sieve, giving a minimum specimen (thread) diameter (i.e. 3 mm following the British Standard (BSI, 1990)) to maximum particle-size ratio for the plastic limit test of 3/0·425 ≈ 7·1. Despite following a careful sample preparation procedure, organic fibres greater than 425 μm in size usually remain in the test material (see experimental data presented later), introducing scale and reinforcement effects, particularly in performing the standard thread-rolling method for PL determinations. The chemistry and pH of any water added to the peat material in producing the homogeneous paste for testing can also significantly influence the deduced value of LL (Asadi *et al*., 2011; Hanrahan *et al*., 1967; Yang and Dykes, 2006).

This paper presents an in-depth literature review of Atterberg limit testing as applied to peat, and by using reported and original test data, the following issues are explored for the deduced LL and PL values

- significance of differences between standard and proposed sample preparation methods used to produce the homogeneous paste material for testing
- effect of preloading of the peat material, specifically regarding the determination of the value of LL
- reinforcement and scale effects related to the peat fibres, particularly regarding the determination of the value of L_P.

These aspects allow consideration of the microstructure, the effect of the fibres and the 'stress history' of the solid particles in the peat test-material on the deduced LL and PL values. The preloading effect has not been investigated previously in relation to Atterberg limit determinations and it relates to the compressible nature of the peat solids, particularly for less humified peat material. For this paper, fall-cone LL and thread-rolling PL testing was performed on specimens prepared from slightly decomposed peat material, investigating different sample preparation methods. The fall-cone LL method is the preferred/standard method of determination of the LL value according to British Standard BS EN 1377–2:1990 (BSI, 1990).

In relation to scale effects for the PL test, if the diameter of 3 mm at which the thread of soil should crumble (BSI, 1990) were not significant and crumbling at larger diameters could be allowed, it might be that the effect of the maximum particle (fibre) size diminishes (Barnes, 2013). On this premise, a novel study was performed in the present investigation to investigate potential benefits of using larger soil thread diameters (>3 mm) for the failure condition in the thread-rolling method. This paper concludes with a discussion on the appropriateness and usefulness of Atterberg limit testing applied to peat and other highly organic soils.

Experimental materials and methods

The test material investigated in the present study was slightly decomposed peat, which (compared with amorphous peat material) would highlight more clearly some of the challenging aspects and inconsistencies of Atterberg limit testing applied to peat. The subject peat material was sampled from a depth of 2 m at the Clara raised bog (County Offaly, Ireland), with a full description of this *Sphagnum* peat deposit and its geotechnical properties presented by O'Kelly and Sivakumar (2014), O'Kelly and Zhang (2013) and Zhang and O'Kelly (2014, 2015). Over most of the bog depth, the peat was slightly decomposed, and as explained in these publications, the sampled material was classified as SCN–H4–B3–F3 (S)–R1(N)–W1(N), according to the modified von Post peat classification system (Landva and Pheeney, 1980). A sufficient quantity of peat material for performing the full test programme was sampled from the same horizon and subsequently thoroughly mixed (crumbled) by hand in the laboratory to achieve homogeneity. The sampled peat material had undergone a slight amount of humification in situ and it had a natural water content of 590%, a particle density of 1·42 Mg/m^3, a loss on ignition (LOI) value of 98·6% and a pH value of 3·8. All water content determinations were performed by oven-drying the test specimens at a temperature of 105–110°C over a 48 h period, which produces acceptable results for peat (O'Kelly and Sivakumar, 2014; Skempton and Petley, 1970).

The LL and PL tests were performed on the materials prepared as follows, after the larger fibres and any pieces of woody matter present had been removed using tweezers, as per the British Standard (BSI, 1990).

(*a*) Material P_r: produced by thoroughly mixing/macerating the material for 10 min using two palette knives to produce a fine pulp. Any remaining woody matter and visible (coarse) fibres were removed from the pulp material using tweezers (method given by British Standard BS EN 1377–2:1990 (BSI, 1990) and also adopted in the study by Skempton and Petley (1970)).
(*b*) Material P_s: the fraction of material P_r passing the 1·18 mm sieve.
(*c*) Material $P_{b\text{-}s}$: produced by comminuting the material using a domestic food liquidiser and then sieving past the 425 μm sieve. The material produced satisfies the standard particle-size fraction requirement for Atterberg limit testing. Visual and tactile observations of the blended material indicated that 10 min of blending action was adequate to achieve a uniform paste.
(*d*) Material $P_{b\text{-}s\text{-}w}$: a 100 mm dia. by 200 mm long specimen of the $P_{b\text{-}s}$ material was isotropically consolidated in the triaxial apparatus to achieve an effective confining pressure (σ'_3) of approximately 30 kPa. After disassembling the apparatus, the consolidated specimen was crumbled and then sufficient water was added to the material, with thorough mixing, to produce a uniform paste for LL testing.

This is the first study to systematically investigate (*i*) the effect of the different sample preparation methods described on deduced PLs and (*ii*) the use of liquidisers in preparing the peat test material (i.e. material $P_{b\text{-}s}$). The above sequence of (*a*) to (*d*) represents an increasing destruction (removal) of the soil structure. In preparing these materials, the sieving process

involved rubbing the wet peat material under light hand pressure through the delineating sieve, with the objective of removing (i.e. not producing further mechanical breakdown of) any coarser fibres/woody matter present. In all cases where the water content had to be increased in preparing the test material, peat water from its natural source was used, since water chemistry (Hanrahan *et al*., 1967; Yang and Dykes, 2006) and pH (Asadi *et al*., 2011) exert important influences on the deduced values of LL.

To investigate the scale effect related to the peat fibres on the deduced PL value, a series of trials was performed using the P_r peat material in which soil threads having different initial diameters were formed and then rolled out following the standard procedure. This approach has been investigated previously, but for fine-grained mineral soils, considering thread diameters of up to about 6 mm for the crumbling diameter requirement, and was shown to produce acceptable PL values (Haigh *et al*., 2014; Prakash *et al*., 2009). The premise of the present research was to investigate much larger thread diameters for the crumbling diameter requirement (i.e. up to about 20 mm), in an attempt to overcome the scale effect related to the peat fibres on the deduced values of PL. Soil threads whose diameters could be reduced following the rolling out procedure would be consistent with the PL test methodology and also representative of the plastic nature of the starting sample of P_r test material. The water content was then reduced in steps, with the rolling-out procedure repeated (for the different initial thread diameters investigated) for each step. Following the observation by Haigh *et al*. (2014) that since the stress is only ever applied to one (vertical) axis of the soil thread at any given time during the rolling-out procedure, the stress state is analogous to triaxial compression. Hence, some unconfined compression tests were performed at 2% axial strain/min on 38 mm dia. by 76 mm-long specimens prepared from samples of the P_r and $P_{b\text{-}s}$ materials (i.e. these specimens were prepared from materials produced in the same manner as for the Atterberg limit tests) for a range of different water content values.

Experimental results and analyses

'Particle' size distribution

Figure 1 shows the particle size distribution curves determined from wet sieve analysis of the test materials. The percentage by dry mass passing the 425 μm sieve and the fibre content (FC) values, determined as the percentage by dry mass retained on the 150 μm sieve (ASTM, 2013), are reported in Table 1. A scanning electron micrograph of the $P_{b\text{-}s}$ material, which reveals the short serrated nature of the remaining peat fibres present within this material's cellular-spongy matrix, is shown in Figure 2.

Liquid limit

Effect of different sample preparation methods on deduced LLs

Figure 3 shows the cone penetration depth against water content relationships determined from fall-cone tests on the different test materials, with the deduced fall-cone LL values (i.e. water content for 20 mm penetration depth of the 80 g, 30° cone (BSI, 1990)) reported in Table 1.

Depending on the sample preparation method adopted, greater mechanical breakdown of the plant material produced lower LL and PL values and also lower plasticity index (PI), with the higher LL deduced for material P_r, reflecting the greater reinforcement effect provided by its remaining peat fabric. This is not surprising given that the nature and structure of the fibres of peat present in the different test materials, even though of the same origin, are quite

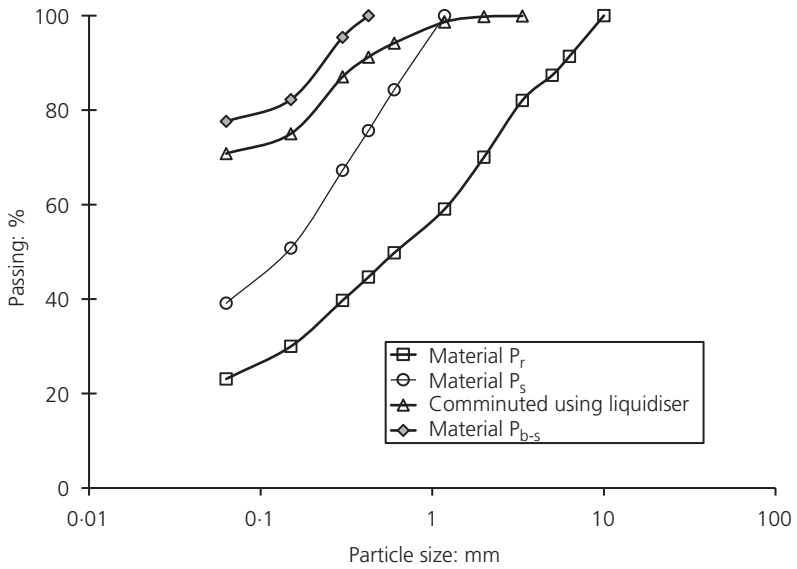

Figure 1. 'Particle' size distribution curves for the peat test materials

Material	Dry mass passing through sieve size: %			LL: %	PL: %	Plasticity index: %	Fibre content: %
	150 μm	425 μm	1·18 mm				
P_r	30	45	59	1064	578	486	70
P_s	51	76	100	907	474	433	49
$P_{b\text{-}s}$	82	100	100	762	446	316	28
$P_{b\text{-}s\text{-}w}$	82	100	100	712	np	—	28

np, test not performed.

Table 1. Grading and index properties of the peat test materials

different. This reinforcement effect depends on the fibre content, the fibre size and the distribution of the fibres in the soil mass. Similar general experimental findings have been reported for amorphous organic clay (LOI = 57%) by O'Kelly (2014) and highly humified blanket bog peats by Yang and Dykes (2006), although they did not consider test material prepared using a liquidiser. In the present study, the reinforcement effect was reduced for test material P_s, and more so for material $P_{b\text{-}s}$, by the removal of fibres larger than 1·18 and 0·425 mm, respectively, resulting in greater cone penetration depths for specimens having the same water content value.

Effect of material preloading on deduced L_L

Figure 4 shows the volumetric strain and average degree of consolidation (U) responses for the isotropically-consolidated saturated specimen of $P_{b\text{-}s}$ material, from which the test material $P_{b\text{-}s\text{-}w}$ was prepared by rewetting with through remoulding. The U data presented in Figure 4 were derived from the pore water pressure measured after temporarily closing the valves on the specimen drainage lines at different stages during the consolidation test. For each of these undrained periods, the build-up in pore water pressure with elapsed time was monitored by a pressure transducer connected via the specimen base pedestal, from which the maximum pore water pressure (u) value was estimated, with the corresponding U value (as percentage) determined by

$$U = \left(\frac{\sigma_3 - u}{\sigma_3 - u_b}\right)100 \quad 1.$$

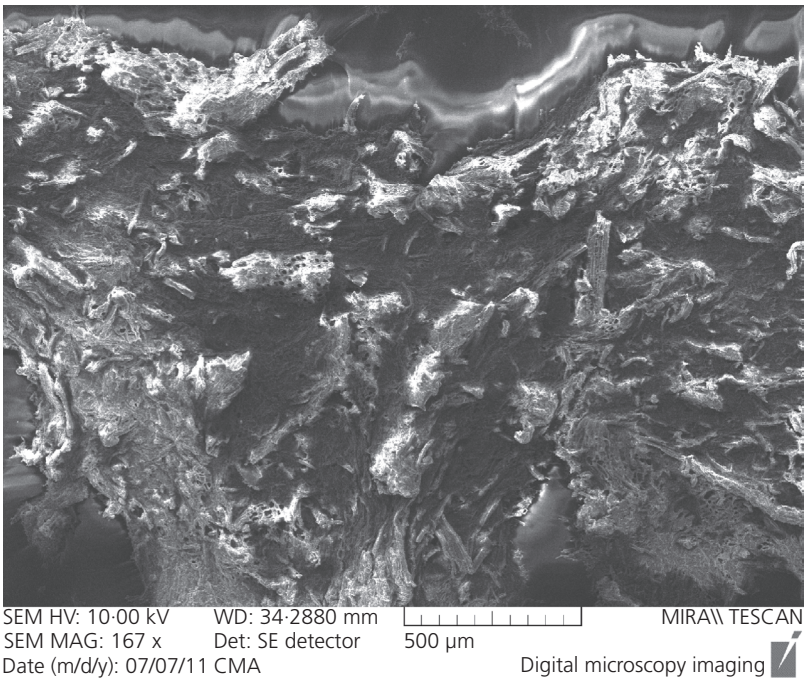

Figure 2. Scanning electron micrograph of blended peat passing the 425 μm sieve (test material $P_{b\text{-}s}$) (Reprinted, with permission, from the *Geotechnical Testing Journal*, 36, (3), copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428)

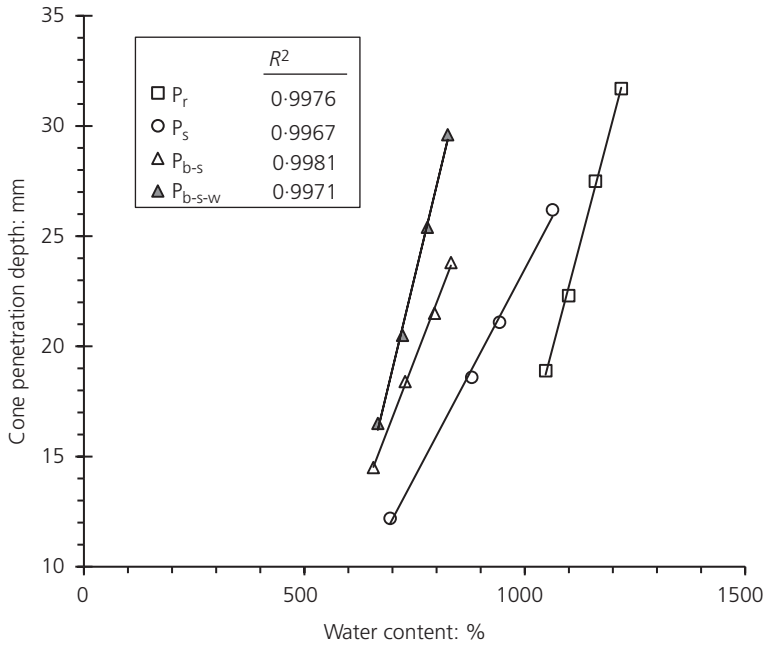

Figure 3. Cone penetration depth against water content relationships. Note: R^2, coefficient of determination from best-fit regression line

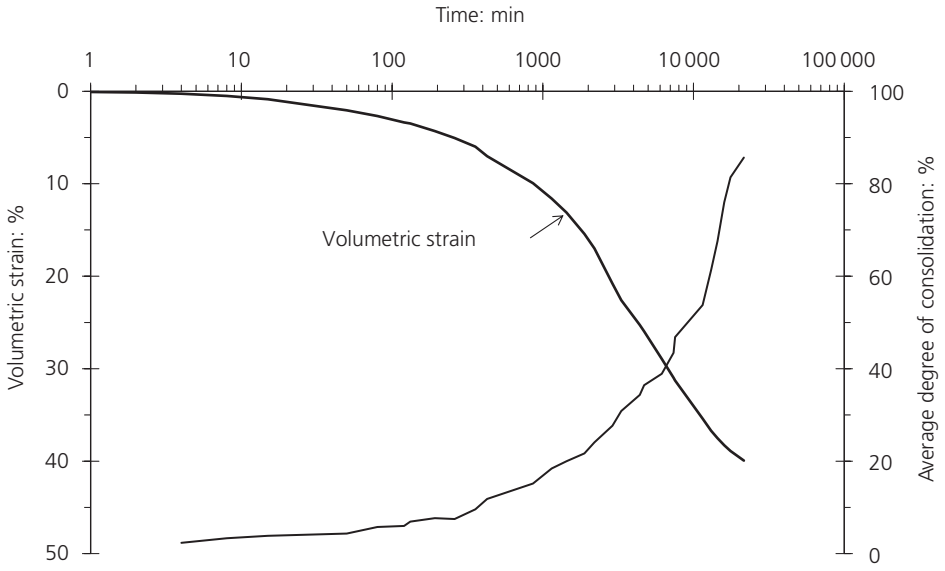

Figure 4. Triaxial consolidation of 100 mm dia. by 200 mm long specimen of P_{b-s} test material to achieve a σ'_3 value of approximately 30 kPa, with all-around specimen drainage provided

where σ_3 is the applied cell pressure and u_b is the specimen back pressure, with values of 230 and 200 kPa, respectively, used in the present investigation. Further details on this experimental approach are given by O'Kelly (2005).

Within the limits of experimental error, identical LL values would be deduced from testing of specimens of a fine-grained mineral soil prepared in these manners. However, the LL of test material P_{b-s-w} was found to be 6·6% (or in absolute terms, 50% water

content) lower than that deduced for material P_{b-s}. This dependency of LL on preloading for the P_{b-s-w} material may be explained as follows.

Isotropic consolidation over a 15 d period to achieve a σ'_3 value of ~30 kPa (Figure 4) reduced the water content of the test specimen of P_{b-s} material from 1065% to 525%, with the interparticle and intracellular water fractions both reducing in accordance with consolidation hypothesis B (den Haan, 1996; den Haan and Edil, 1994). This concept assumes that for peat, creep (explained by the slow drainage of water from the micropores to the macropores) occurs simultaneously with consolidation. Subsequent wetting and mixing of the triaxial-consolidated material to form a paste having a water content of 870% (i.e. above its LL value) produced material comprising relatively higher interparticle, and hence lower intracellular, water fractions. The former is contained within the interstitial space between the peat solids; the latter, within the open cellular structure of these solids. According to O'Kelly (2014), the intracellular water fraction has no significant influence on the quick-undrained strength. From theoretical analysis by Koumoto and Houlsby (2001), the British Standard (BSI, 1990) fall-cone LL value corresponds to a dynamic remoulded undrained shear strength (s_{ur}) of 2·66 kPa. Water content determinations are based on the total mass of water evaporated by oven drying – that is, both the intracellular and interparticle water fractions. Hence, compared with test material P_{b-s}, the relatively higher interparticle water fraction of material P_{b-s-w} gave rise to the slightly lower value of LL measured. In other words, although the consolidated peat material had been wetted and thoroughly mixed, its peat solids (particularly that of the serrated peat fibres) retained some stress history because of their compressible nature; that is, some permanent reduction in the micropore volume had occurred. These findings would suggest that preloading is another determining factor for the value of LL deduced for peat. From a review of the literature, this is the first experimental study to demonstrate such an effect. Hence, LL testing of the same peat material performed both before and after, for example, drained strength or compressibility testing, would produce different experimental LL values. Similarly, partially dried peat material, when wetted to water contents greater than the LL and then allowed to equilibrate, could be expected to have a lower LL value compared with the original peat material. For all of these scenarios, the likely effect would generally be greater for more fibrous peat material.

Plastic limit

Standard L_P testing

Soil threads of test material P_r, which had been prepared following the sample preparation method given in British Standard BS EN 1377–2:1990 (BSI, 1990), and of the refined materials P_s and P_{b-s} could be rolled out to 3 mm in diameter, with the respective PL values reported in Table 1. However, it was observed that the bulk test materials exhibited plastic behaviour (i.e. these materials were easily remoulded by hand) at water contents below these PL values, indicating that the measured PL values were notional and they did not represent the limit of workability (i.e. brittle–ductile transition) for the processed peat materials. It was postulated that the scale effect due to the larger fibre sizes and also the greater proportion of fibres might have explained, somewhat, the excessively high PLs, which is explored in the following section. For instance, the ratios of the minimum specimen/thread diameter (i.e. 3 mm) to the maximum particle size for test materials P_s and P_{b-s} were ~2·5 and 7·1, respectively, with measured PLs of 474% and 446%, respectively. Other factors were also at play since material P_{b-s} satisfied the particle-size fraction requirements for Atterberg limit testing (i.e. <425 μm), but it still produced a 'PL' value greater than the water content at its brittle–ductile transition, as evidenced by the fact that a moist soil mass of this test material could be moulded in the form of a ball for water contents below the measured PL value. This would suggest that the nature of the porous organic solid particles of the peat material, which are flexible, permeable and compressible in nature (Landva and Pheeney, 1980; Zhang and O'Kelly, 2014), is another significant factor.

'PL' determinations based on crumbling of soil threads at greater than 3 mm in diameter

Figure 5 presents the results of PL tests performed on test material P_r (prepared using the sample preparation method given by the British Standard (BSI, 1990)), with the rolling-out procedure in these tests commencing with soil threads having initial diameters ranging from 6 to 20 mm. For test material that was too wet, the very soft threads broke on attempting to roll them out, because 'free' water on the thread surface caused adhesion to the flat glass plate. Being wet of the 'plastic limit', soil threads having initial diameters ranging from 6 to 20 mm could be rolled out, yielding and elongating in the process, with failure of the threads occurring by both longitudinal and transverse shear (Figure 6).

Referring to Figure 5, the factor F is the reduction in diameter achieved at the crumbling condition for the soil thread, expressed as a fraction of its initial diameter. As per clause 5.3.3.4 of BS EN 1377–2:1990 (BSI, 1990), an F value of 0·5 is adopted in the standard method for the determination of the PL; that is, the initial (starting) thread diameter of 6 mm specified is reduced by the rolling-out procedure to produce a soil thread of about 3 mm in diameter. From Figure 5, the value of 'PL' for test material P_r appears to increase approximately linearly with increasing thread diameter, from PL = 578% to 'PL' = 616% (a 6·6% relative increase in water content) for thread diameters of 3 and 18 mm, respectively, at the crumbling condition. Compared with PL (crumbling for the standard 3 mm diameter thread requirement), the percentage errors for 'PL', considering thread diameters of up to 6 mm for the failure (crumbling) condition, were negligibly small (1·2% relative increase) and are considered within an acceptable range, in line with the findings by Prakash *et al*. (2009) for a variety of mineral soils. They reported that the difference in water contents at crumbling for soil thread diameters of 2, 4, 5 and 6 mm, when compared with the 3·2 mm thread condition adopted in ASTM (2010), was negligibly small. Further, Haigh *et al*. (2014) reported that for mineral soil, there is no statistically significant trend of varying water content with the soil thread diameter at failure for the rolling-out procedure.

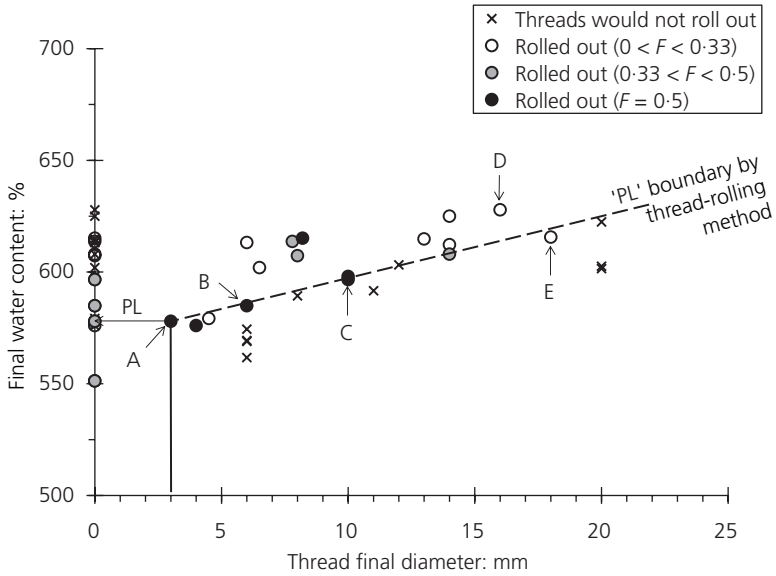

Figure 5. Thread rolling of test material P_r for different initial soil thread diameters and water contents. Data labels A to E refer to images in Figure 6

For water contents below the 'PL' boundary, soil threads having diameters ranging from 6 to 20 mm (or greater) could be readily formed, but they failed (shearing longitudinally and transversely) on attempting to roll them out, consistent with the definition of the plastic limit. However, this behaviour was not consistent with the behaviour of the bulk test material, which was readily remoulded by hand at lower water contents. In other words, the determination of 'PL' based on crumbling of the soil threads at larger diameters (≫3 mm) did not produce more meaningful PL values; rather, the contrary occurred. One plausible explanation is that for larger soil thread diameters, the rolling-out procedure cannot produce an even reduction in water content over the thread radius, with the thread core remaining wetter than its surface. Further, these findings also appear to suggest that the scale effect related to the peat fibres postulated for the 3 mm-dia. soil thread is minor, and as described earlier in the paper, the nature of the porous organic solids of the peat material is a more significant factor. However, fibre reinforcement may tend to prevent elongation of the soil thread during the rolling-out procedure. For instance, O'Kelly and Zhang (2013) reported that the same P_r material deformed almost one dimensionally when tested in drained triaxial compression, with measured Poisson's ratio values ranging between 0·04 and 0·05 for specimen axial strains of up to 20%.

Comparison between observations from L_P tests and results of unconfined compression tests

Figure 7 presents the deviatoric stress against strain response for materials P_r (w = 456–641%, PL = 578%) and $P_{b\text{-}s}$ (w = 265–615%, PL = 446%) tested in unconfined compression. All of the specimens tested underwent general (ductile) bulging, indicating that their water content values were within the plastic range. For the P_r test specimens, no shear plane had developed for applied axial strains in excess of 20%, whereas localised shear failure was observed to occur for large axial strains (>12%) in the case of the $P_{b\text{-}s}$ test specimens at the lower water contents investigated. Compared with the $P_{b\text{-}s}$ (FC = 18%) specimens, the axial strain corresponding to the peak deviatoric stress was significantly greater for the P_r (FC = 70%) specimens. These behaviours are indicative of the internal (lateral) reinforcement provided by greater proportion and larger sizes of peat fibres present in test material P_r (see O'Kelly and Zhang, 2013).

Although the PL and unconfined compression tests are entirely different test procedures, based on different mechanisms and affected by different parameters, it would seem reasonable to expect some general match between the brittle–ductile transitions observed in these tests. However, from the evidence presented, there is no association between the observations made and results obtained from the PL tests and unconfined compression tests with regard to the limit of workability. In other words, the P_r and $P_{b\text{-}s}$ materials exhibited plastic behaviour at water contents significantly below their measured PL values. Similar experimental findings have been reported by O'Kelly (2014) for water-treatment residue material (LOI = 57%, with all of its solid particles finer than 425 μm in size), which exhibited a general ductile response in unconfined compression when tested for water contents in the range of 215–300%, despite having a measured PL of 268%.

Discussion

The sample preparation method for Atterberg limit testing of mineral soil given in British Standard BS EN 1377–2:1990 (BSI, 1990) is generally also adopted for testing of peat and was the procedure used in preparing material P_r in the present study. Some researchers

Figure 6. Failure condition of the soil threads. (a) Specimen A at PL (d = 3 mm; F = 0·5; w = 578%); (b) specimen B at 'PL' (d = 6 mm; F = 0·5; w = 85%); (c) specimen C at 'PL' (d = 10 mm; F = 0·5; w = 597%); (d) specimen D (d = 16 mm; F = 0·2; w = 628%); (e) specimen E at 'PL' (d = 18 mm; F = 0·1; w = 616%). Note: d, thread diameter at crumbling condition; F, reduction in diameter achieved at failure of the thread, expressed as a fraction of its starting diameter; w, water content

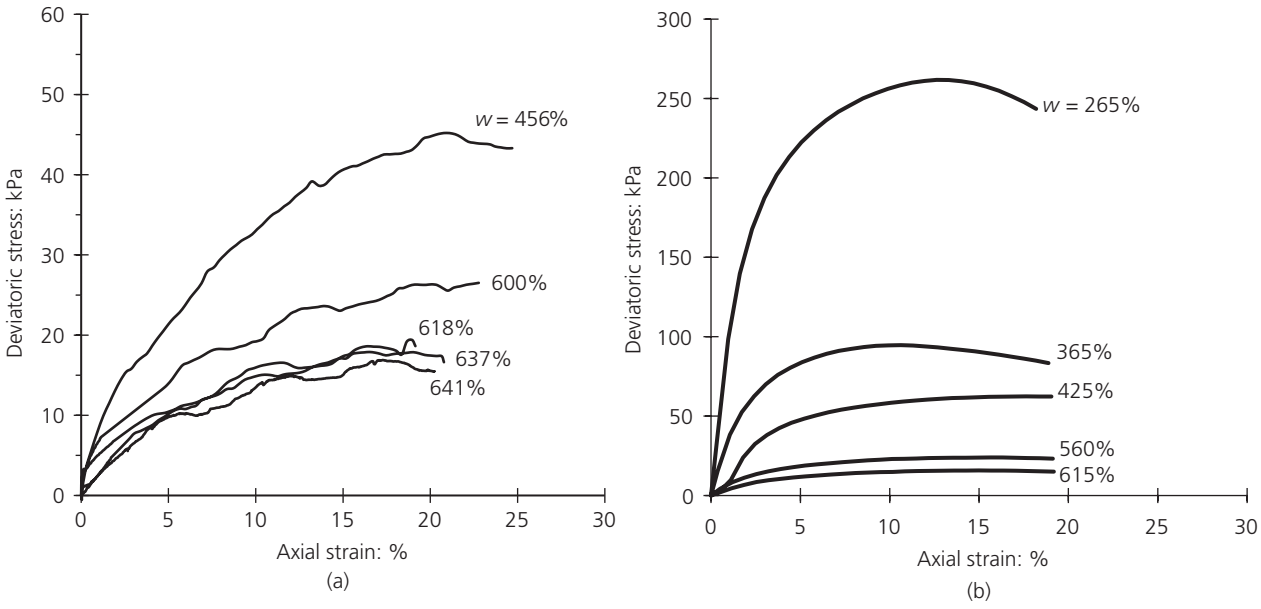

Figure 7. Unconfined compression tests performed at 2% axial strain/min: (a) material P_r; (b) material $P_{b\text{-}s}$

have reported on the use of domestic liquidisers to prepare the peat test material (Hobbs, 1986; O'Kelly and Zhang, 2013), although for the slightly decomposed peat investigated, this approach was found to produce material having significantly different fabric and structure. As demonstrated in the present study, unsurprisingly, different sample preparation methods can produce considerable disparity in interpolated LL and PL values, which, on a basic level, would invariably compromise the ability of researchers to meaningfully compare tests results.

Compressibility is possibly the main issue with peaty soils, and as reported by Hobbs (1986), this may be linked to LL and other governing decomposition characteristics of such materials. This supposition is tentatively supported by the fact that the LL value of test material $P_{b\text{-}s}$ (762%) was marginally greater than that measured for material $P_{b\text{-}s\text{-}w}$ (712%). The only difference in the testing procedure for the identical starting materials was that the $P_{b\text{-}s\text{-}w}$ material had been consolidated to a mean effective stress of ~30 kPa before preparing the LL test material. In other words, the preloading effect for material $P_{b\text{-}s\text{-}w}$, which had produced a volumetric strain of 40% (see Figure 4), resulted in a lower LL value, although its effect could be considered marginal given the significant preconsolidation stress applied, compared with that for most peat deposits.

Apart from highly humified peat, the test material used in the determination of the Atterberg limits bears little relation to the natural (intact) peat material; they have distinctly different mechanical and hydraulic properties. It is difficult, then, to see how the deduced LL and PL values can be meaningfully correlated with mechanical behaviour to any great extent. Further, the LL has been reported as a useful indicator of the peat morphology (its initial cation-exchange ability depends on the type of plant detritus) and also its degree of humification (Hobbs, 1986), although peat classification systems (e.g. modified von Post system, see Landva and Pheeney (1980)) can arguably fulfil these roles with equal or better effect.

As evidenced from observations made for the peat material investigated in the present study, the water content at the PL determined for crumbling of the soil thread at 3 mm (or greater) in diameter did not define the brittle–ductile transition for the different test materials, but some higher water content value. There is a scale effect related to the peat fibres, but this alone cannot account for the excessively high PL water contents measured, compared with the water content at the material's brittle–ductile transition. Since the measured PLs did not represent the limit of workability for the processed peat materials, the deduced plastic ranges were notional and calculated liquidity index values would not be reliable indicators of their consistency. Further, unlike fine mineral soils, the measured PLs (and to a lesser extent, measured LLs) of the peat material are not expected to meaningfully correlate to any great extent with fundamental soil parameters.

To demonstrate this point further, and broaden the discussion to include other fine-grained organic soils, Table 2 lists the saturated remoulded undrained shear strength values deduced for the PLs ($s_{ur(LP)}$) of the P_r and $P_{b\text{-}s}$ test materials, and also reported PLs for four marine sediments (Zentar *et al.*, 2009) and a water-treatment residue material (O'Kelly, 2014). The very soft or soft consistency (inferred $s_{ur(LP)}$ range of 9·1–30·5 kPa) implied for the reported PLs

Property	Test material		WTR[b]	F5[c]	F6[c]	F12[c]	F13[c]
	P_r[a]	$P_{b\text{-}s}$[a]					
LL: %	1064	762	513	128·29[d]	113·92[d]	101·92[d]	92·98[d]
PL: %	578	446	268	48·4	47·2	46·4	43·6
PI: %	486	316	245	79·93	66·73	55·53	49·39
LOI: %	98·6	98·6	57	9·7	9·3	7·0	6·7
Coefficient *a*	1238	1179	519·3	127·54	112·74	97·681	90·269
Coefficient *b*	0·315	0·304	0·180	0·296	0·292	0·289	0·330
Deduced $s_{ur(PL)}$: kPa	11·2 (UC)	24·3 (UC)	30·5 (TC)	26·5 (vane)	19·7 (vane)	13·2 (vane)	9·1 (vane)

[a] Present investigation.
[b] O'Kelly (2014).
[c] Zentar *et al*. (2009).
[d] Casagrande LL.
UC and TC, unconfined and triaxial compressions respectively; WTR, water-treatment residue material; F5, F6, F12 and F13, marine sediments; coefficients *a* and *b* relate to the water content (w) against remoulded undrained strength (s_{ur}) relationship of $w = as_{ur}^{-b}$, after Koumoto and Houlsby (2001).

Table 2. Remoulded undrained strengths $s_{ur(PL)}$ deduced for measured PLs of some fine organic soils

of these fine-grained organic soils is considered unrealistically low. Further, compared with the two peat materials, the four marine sediments had significantly lower LOI values ranging between 6·7 and 9·7%. This would suggest that research is warranted to investigate the appropriateness and value of PL testing applied to low organic content soils.

Another viewpoint is that, as per the soil classification systems presented in ASTM (2011), BSI (2015) and many other standards, the ranges of LL and PI considered for classification purposes are limited to 100/120% and 60/70%, respectively. The peat materials considered in the present study, and peaty soils in general, have measured LLs and PIs far greater than these values and hence cannot be placed on the standard plasticity chart. Extrapolation of the plasticity chart for higher plasticity characteristics is usually not attempted since the A-line criteria may not be satisfied. Hence, for such materials, one should not use the criteria set out for natural fine-grained soils, which have been classified based on very specific characteristics (i.e. maximum values of LL of 120% and PI of 70%). In other words, taking this viewpoint, the conventional experimental soil mechanics approach for the determination of the consistency limits is not applicable for such materials.

In conclusion, Atterberg limit testing of peat does not produce meaningful results in that the deduced plastic range for the test material is notional and calculated liquidity index values are not reliable indicators of its consistency. In other words, Atterberg limit concepts are generally not appropriate for peat and other highly organic soils. These findings concur with Hobbs (1986), who reported that 'the plasticity properties of peat, where obtainable, throw little useful light on its character and consequently there is little point in completing plastic limit determinations on peat soils'.

A more useful suite of index tests for assessing the geotechnical behaviour of peat is its natural water content, organic content (usually determined from LOI tests), fibre content and degree of humification. According to Edil and Wang (2000), this suite of tests should be routinely performed (instead of LL and PL tests) on organic soils for engineering purposes. For correlations with strength and compressibility parameters, Dutch organic soil practice has found that water content and bulk density (unit weight) are usually sufficient for peat (den Haan and Feddema, 2012). Description of the in situ (undisturbed) peat material and its morphology are most beneficial in interpretations of geotechnical parameter values. Magnified images are also beneficial in identifying the peat morphology, fabric and microstructure. A discussion on these tests and other techniques, including imaging, has been presented by O'Kelly (2015).

Summary and conclusions

There are fundamental issues making the Atterberg limit concepts not appropriate for peat soils. For both the LL and PL tests, scale and reinforcement effects related to the peat fibres can be significant, especially for less humified peat material. It was found that using larger soil thread diameters of up to 20 mm for the crumbling diameter requirement during the rolling-out procedure did not overcome these effects. The nature of the solid particles in the peat material is another significant factor, evidenced by the fact that PL testing of the (blended) peat material passing the 425 μm sieve also did not produce results consistent with the water content corresponding to this material's brittle–ductile transition.

Measured LL and PL values are generally strongly dependent on the sample preparation method adopted, which itself can be subject to operator-dependent variations. Greater mechanical breakdown of the peat material during preparation of the test material produces greater reductions in measured consistency limit values and also a reduced plasticity index value. Unlike mineral soils, preloading is another determining factor, producing a lower LL value for the peat, in that its organic solids retained some stress history because of their compressible nature.

On the basis of the experimental observations for the peat test material, PL testing does not produce meaningful results so that the deduced plastic range is notional and, hence, calculated liquidity index values are not reliable indicators of its consistency. Research is warranted to investigate the appropriateness and value of PL testing for soils having low organic content.

For peats and other highly organic soils, a more useful suite of index tests for assessing their geotechnical behaviour is natural water content, organic content, fibre content and degree of humification, along with a description of the in situ deposit and its morphology.

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REFERENCES

Adams JI (1964) A comparison of field and laboratory measurement of peat. In *Proceedings of the Ninth Muskeg Research Conference, Québec* (Butler J and MacFarlane IC (eds)). National Research Council of Canada, Ottawa, ON, Canada, Technical memorandum 81, pp. 117–135.

Asadi A, Huat BBK, Hanafi MM, Mohamed TA and Shariatmadari N (2011) Chemico-geomechanical sensitivities of tropical peat to pore fluid pH related to controlling electrokinetic environment. *Journal of the Chinese Institute of Engineers* **34(4)**: 481–487.

ASTM (2010) D 4318-10e1: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA, USA.

ASTM (2011) D 2487-11: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, USA.

ASTM (2013) D 1997-13: Standard test method for laboratory determination of the fiber content of peat samples by dry mass. ASTM International, West Conshohocken, PA, USA.

Barnes GE (2013) *The Plastic Limit and Workability of Soils*. PhD thesis, University of Manchester, Manchester, UK.

Berry PL and Poskitt TJ (1972) The consolidation of peat. *Géotechnique* **22(1)**: 27–52.

BSI (1990) BS EN 1377:1990: Part 2. Methods of test for soils for civil engineering purposes: classification tests. BSI, London, UK.

BSI (2015) BS 5930:2015: Code of practice for ground investigations. BSI, London, UK.

den Haan EJ (1996) A compression model for non-brittle soft clays and peat. *Géotechnique* **46(1)**: 1–16.

den Haan EJ and Edil TB (1994) Secondary and tertiary compression of peat. In *Proceedings of the International Workshop on Advances in Understanding and Modelling the Mechanical Behaviour of Peat, Delft, the Netherlands* (den Haan E, Termaat R and Edil TB (eds)). Balkema, Rotterdam, the Netherlands, pp. 49–60.

den Haan E and Feddema A (2012) Deformation and strength of embankments on soft Dutch soil. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **166(3)**: 239–252, http://dx.doi.org/10.1680/geng.9.00086.

Dhowian AW and Edil TB (1980) Consolidation behavior of peats. *Geotechnical Testing Journal* **3(3)**: 105–114.

Edil TB and Wang X (2000) Shear strength and K_0 of peats and organic soils. In *Geotechnics of High Water Content Materials* (Edil TB and Fox PJ (eds)). ASTM International, West Conshohocken, PA, USA, ASTM STP 1374, pp. 193–198.

Haigh SK, Vardanega PJ, Bolton MD and Barnes GE (2014) Discussion: The plastic limit of clays. *Géotechnique* **64(7)**: 584–586.

Hanrahan ET, Dunne JM and Sodha VG (1967) Shear strength of peat. *Proceedings of the Geotechnical Conference, Oslo, Norway*, vol. 1, pp. 193–198.

Hobbs NB (1986) Mire morphology and the properties and behaviour of some British and foreign peats. *Quarterly Journal of Engineering Geology* **19(1)**: 7–80.

Koumoto T and Houlsby GT (2001) Theory and practice of the fall cone test. *Géotechnique* **51(8)**: 701–712.

Landva AO and Pheeney PE (1980) Peat fabric and structure. *Canadian Geotechnical Journal* **17(3)**: 416–435.

Landva AO, Pheeney PE, La Rochelle P and Briaud JL (1986) Structures on peatland – geotechnical investigations. In *Proceedings of the Advances in Peatlands Engineering Conference, Ottawa, Canada*. National Research Council of Canada, Ottawa, ON, Canada, pp. 31–52.

O'Kelly BC (2005) Consolidation properties of a dewatered municipal sewage sludge. *Canadian Geotechnical Journal* **42(5)**: 1350–1358.

O'Kelly BC (2014) Characterisation and undrained strength of amorphous clay. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **167(3)**: 311–320, http://dx.doi.org/10.1680/geng.11.00025.

O'Kelly BC (2015) Atterberg limits and peat. *Environmental Geotechnics*, http://dx.doi.org/10.1680/envgeo.15.00003.

O'Kelly BC and Orr TLL (2014) Briefing: Effective-stress strength of peat in triaxial compression. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **167(5)**: 417–420, http://dx.doi.org/10.1680/geng.13.00143.

O'Kelly BC and Sivakumar V (2014) Water content determinations for peat and other organic soils using the oven-drying method. *Drying Technology* **32(6)**: 631–643.

O'Kelly BC and Zhang L (2013) Consolidated-drained triaxial compression testing of peat. *Geotechnical Testing Journal* **36(3)**: 310–321.

Prakash K, Sridharan A and Prasanna HS (2009) A note on the determination of plastic limit of fine-grained soils. *Geotechnical Testing Journal* **32(4)**: 372–375.

Skempton AW and Petley DJ (1970) Ignition loss and other properties of peats and clays from Avonmouth, King's Lynn and Cranberry Moss. *Géotechnique* **20(4)**: 343–356.

Yang J and Dykes AP (2006) The liquid limit of peat and its application to the understanding of Irish blanket bog failures. *Landslides* **3(3)**: 205–216.

Zentar R, Abriak NE and Dubois V (2009) Fall cone test to characterize shear strength of organic sediments. *Geotechnical and Geoenvironmental Engineering* **135(1)**: 153–157.

Zhang L and O'Kelly BC (2014) The principle of effective stress and triaxial compression testing of peat. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **167(1)**: 40–50, http://dx.doi.org/10.1680/geng.12.00038.

Zhang L and O'Kelly BC (2015) Effect of salt grain additions on fibrous peat consolidation. *Proceedings of the Institution of Civil Engineers – Ground Improvement* **168(1)**: 14–21, http://dx.doi.org/10.1680/grim.12.00034.

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