Geotechnical Engineering

Undrained shear strength–water content relationship for sewage sludge
O'Kelly

ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/geng.11.00016
Paper 1100016
Received 03/02/2012   Accepted 13/03/2012
Keywords: geotechnical engineering/sewage treatment & disposal/strength & testing of materials

ice
Institution of Civil Engineers
publishing

Undrained shear strength–water content relationship for sewage sludge

Brendan C. O'Kelly MEngSc, PhD, FTCD, CEng, CEnv, MICE, FIEI
Associate Professor, Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland

Micro-fibrous organic clays include sludges and residues derived from municipal and industrial treatment processes. This paper studies the relationship of water content w against remoulded undrained shear strength s_{ur} of one such material, namely sewage sludge (biosolids), and the factors affecting the coefficients a and b in the equation $w = as^{-b}{}_{ur}$. Data for s_{ur} in fall-cone, vane shear and triaxial compression (TC) tests were examined, considering the material's mineralogical, physiochemical and biological properties. The effects of the different shearing modes, rates and confinement pressure on the mobilised strength were studied, since the different apparatuses approach the estimation of strength in different ways. The scalar relating the deduced s_{ur} values in vane shear to TC was not singular, but was particularly sensitive to the confining pressure (σ_3) applied in TC tests, and also to the difference in strain rate between the different tests. The deduced s_{ur} from the miniature vane was between 1·19 and 1·40 times that mobilised in quick-undrained TC of 38 mm diameter specimens under σ_3 of 100 kPa. New methods of analysis are presented to estimate the strength contribution of the gel-like pore fluid to the mobilised s_{ur}, and also to determine more accurately the water content corresponding to the fall-cone liquid limit condition.

Notation

A	gas voids content
a	water content for $s_{ur} = 1$ kPa
b	gradient of log w against log s_{ur} relationship
C	torsional stiffness
D	vane diameter
F	adjustment factor
H	vane height
h	penetration depth of fall cone
I_L	liquidity index
K	cone factor
M	gradient of critical state line in q–p′ space
Q	vertical force
S_r	degree of saturation
s_{ur}	remoulded undrained shear strength
t_f	time to failure
w	water content
Γ	specific volume on critical state line at p′ = 1 kPa
$\dot{\gamma}$	rate of shear strain
θ_f	angular deflection of spring at failure
λ	gradient of the isotropic compression line
σ_3	confining pressure
ϕ_u	angle of shearing resistance under undrained conditions

1. Introduction

The relationship between the water content w and the remoulded undrained shear strength s_{ur} of fine-grained inorganic soil is given by (Koumoto and Houlsby, 2001)

$$w = as_{ur}^{-b} \tag{1}$$

where the coefficient a (%) is determined as the water content corresponding to $s_{ur} = 1$ kPa, and the coefficient b is given by the gradient of the linear function relating the logarithm of the water content (%) to the logarithm of the undrained shear strength (kPa) (Figure 1).

The coefficient a is an indicator of the water-holding capacity of the soil, and its value depends on the grading, composition and mineralogical properties, particularly those of the clay fraction (Trauner *et al.*, 2005; Wood, 1990). The coefficient b, which relates to the soil compressibility, is equal in value to the critical-state parameter λ for isotropic consolidation. Koumoto and Houlsby (2001) have shown how the values of the coefficients a and b can be determined from

- fall-cone data covering a sufficiently wide range of water contents
- regression analysis of $\log w : \log s_{ur}$ data, usually obtained by miniature vane tests
- the measured values of the critical-state strength parameter M, and isotropic compressibility parameters λ and Γ.

Micro-fibrous organic clays include amorphous peat, and organic sludges and residues derived from municipal and industrial treatment processes. For example, sewage sludge (biosolids) material is the thick slurry by-product derived from chemical and biological treatment of wastewater at municipal works. These

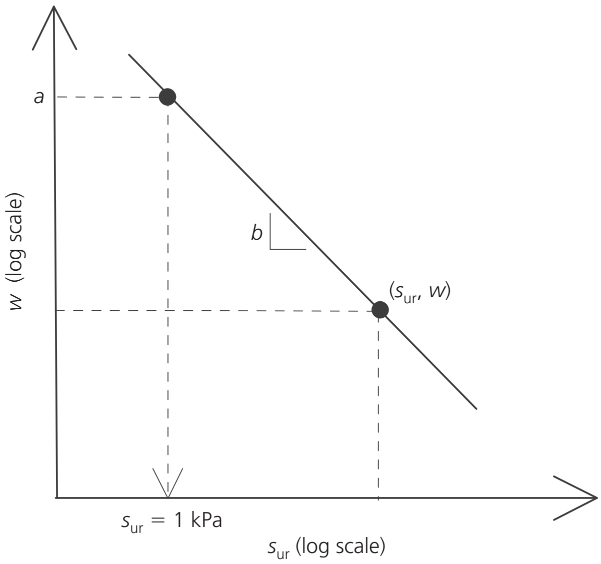

Figure 1. Water content against remoulded undrained shear strength for fine-grained mineral soil

high-plasticity materials consist mainly of aggregate flocs of clay mineral and micro-fibrous organic particles (O'Kelly, 2006). Strength determinations on sewage sludge material are particularly challenging on account of its viscous pore fluid, which is more akin to a gel than to water (Klein and Sarsby, 2000; O'Kelly, 2008), and the material is also normally in an active state of biodegradation. Hence the composition and geotechnical properties of sewage sludge change over time, and the rate and intensity of this change are governed largely by geoenvironmental conditions.

An assessment of the strength and consolidation properties of these unconventional soils is more complex for the reasons outlined above, particularly for material of slurry or very soft consistency, on account of the relative contribution of the viscous gel-like pore fluid to the shear strength of the material. Note that material of slurry consistency is at a water content greater than the liquid limit (LL) condition. Hence the interpretation of s_{ur} data from, for example, fall-cone (FC) or shear-vane tests may not be straightforward. In particular, Klein and Sarsby (2000) reported that the calibration of the FC method with respect to sewage sludge was not known. However, considering the viscous gel-like nature of the pore fluid, the s_{ur} values mobilised for water contents at or near the LL condition could be considerably greater than the contributions of shear resistance arising directly from friction and bonding between the solids and also entanglement of the organic fibres. The value of the coefficient a determined from regression analysis of $\log w : \log s_{ur}$ data obtained from fall-cone LL tests could also be artificially high.

Furthermore, there has been a trend towards adopting the FC method as a quick means of determining the value of s_{ur}, although in light of the concerns raised above, the reliability of such data for gelatinous slurry may be open to question. Furthermore, the conventional definition of the LL condition relates to fine-grained mineral soils in which the shear strength is mobilised by friction and bonding between the solids alone. Hence standard analysis of fall-cone LL data that does not take into account the component of shear resistance mobilised by the viscous gel-like pore fluid could also give artificially high values of water content corresponding to the LL condition and, moreover, the use of the liquidity index as an indicator of the material consistency may not be fully reliable.

The mobilised strength depends on the test method, the rate of shear strain, the nature of the material forming the test specimen and ageing effects caused by internal reactions (chemical change, decomposition and accumulation of biogas, particularly for undrained conditions) brought about over time by ongoing microbial activity. A review of the literature suggests that only two studies have specifically considered the effect of the different shearing modes in shear vane and TC tests on the values of s_{ur} mobilised for sewage sludge. O'Kelly (2005b, 2006) reported that, for material of soft to very stiff consistency, higher s_{ur} values were mobilised for the 12·7 × 12·7 mm vane under a vane-head rotation of 9·0°/min compared with 38 mm diameter specimens sheared in undrained triaxial compression at a strain rate of 1·2%/min. These data indicated that the deduced vane s_{ur} increased from 1·19 to 1·40 times s_{ur} mobilised in TC, with decreasing water content over the range of 150% to 80%. Second, Koenig and Bari (2001) reported that s_{ur} values mobilised by the pocket shear-meter were ~27% greater than for the miniature vane, presumably because the mobilised s_{ur} is dependent on the vane size, aspect ratio and time to failure. A small proportion of coarse fibrous material would also affect smaller size vanes to a greater extent, potentially recording unconservative values, particularly for higher shear strength material. More research has been performed on sewage sludge mixed with different admixtures (many of which were pozzolanic in nature, e.g. lime, fly ash, cement and slag) in order to improve geotechnical properties, although the shear strength behaviour of these mixtures and of their pore fluid phase is significantly different from that of the unamended sewage sludge.

All of the literature that has studied the variation in s_{ur} over the plastic range (including Koumoto and Houlsby, 2001; Sharma and Bora, 2003; Skempton and Northey, 1953; Wood, 1990) would appear to concern only mineral soils in which the constituent solids are inert and incompressible, for practical purposes, over the stress range of engineering interest. The experimental data in these studies indicated that the $\log w : \log s_{ur}$ relationship for fine-grained mineral soil was linear over the full plastic range, with one known exception: a bilinear relationship occurs for montmorillonite soils, owing to the characteristic difference in behaviour caused by the diffuse double-layer held water (Sharma and Bora, 2003, 2005).

2. Aims and scope

A database of s_{ur} values for freshly remoulded and compacted sewage sludge comprising miniature vane and triaxial compression tests reported by O'Kelly (2004b, 2005b, 2006), along with original fall-cone and triaxial compression tests presented in this study, is re-examined in the light of recent knowledge gained with respect to the mineralogical, physicochemical and biological properties of the material, with the following objectives.

(*a*) Determine whether the $\log w : \log s_{ur}$ relationship is linear, bilinear or otherwise over the plastic range, and in particular the correlation of s_{ur} in vane shear to triaxial compression.
(*b*) Study the effects of the mode and rate of shearing, degree of specimen saturation and the pore liquid.
(*c*) Estimate the component of shear resistance mobilised by the pore fluid for water contents at, near and above the LL condition.
(*d*) Develop a more reliable method of analysis for determining the water content value corresponding to the fall-cone LL condition for gelatinous fine-grained soils.

A review of the literature indicates that this paper would appear to be one of the first to specifically consider the affects and relative significance of the factors listed in (b) above in terms of the coefficients *a* and *b* for organic clays. Hence, by using this approach, further insight will be gained regarding the factors that influence the coefficients *a* and *b* for micro-fibrous organic clays in general, and gelatinous organic clay in particular.

3. Experimental material

The sewage sludge material considered in this study had been moderately degraded by naturally occurring bacteria at the municipal wastewater works, conditioned with dilute Magnafloc® LT25 polyelectrolyte solution for a better dewatering efficiency, and mechanically dewatered using a belt-filter press to produce a sludge residue with $w \approx 700\%$ (O'Kelly, 2006). Each batch of treated sludge material from the municipal works is reasonably homogeneous and isotropic, although the properties from one batch to the next can change periodically, depending on the relative domestic and industrial compositions of the wastewater and the level of treatment achieved at the municipal works. From wet sieve analysis, ~90% of the material by dry mass passed the 425 μm sieve, with the retained material composed mainly of plant fibres (cellulose, hemicellulose and lignin) along with a small proportion of animal hair strands. Loss-on-ignition tests on dry pulverised material at a temperature of 440°C indicated a gravimetric organic content (OC) of ~70%, which includes the Magnafloc® additive, for material sourced directly from the municipal treatment works. Hence the material composition by total dry mass was ~30% inert (i.e. mineral), ~14% coarse fibrous, and the remaining ~56% comprising micro-fibres and colloidal organic matter. Scanning electron micrographs reported by O'Kelly (2005a) indicated that the solids phase comprised aggregate flocs of clay mineral particles, randomly entangled coarse and micro-fibres, colloidal organic matter (carbohydrates, proteins and lipids; Raunkjaer *et al.*, 1994), and pathogenic organisms that were responsible for ongoing anaerobic decomposition of the material. Hence the composition and viscosity of the pore fluid change over time, with the generation of new microbial cells, fatty acids and polymers. The leachate had a mildly high pH of 8·0, and the gaseous phase of occluded bubbles comprised largely methane and carbon dioxide (O'Kelly, 2005a). The high intensity peaks from X-ray diffraction analysis of the mineral solids were interpreted as quartz, calcite and kaolinite, although there was also the likelihood of other trace minerals, albeit at concentrations of less than 1–2% by mass, which could not be detected, owing to increased background and noise in the data caused by the amorphous body.

It is important to note that although a significant amount of the solid organic matter in sewage sludge is fibrous, the individual fibres are predominantly very short in length (i.e. micro-fibrous), unlike fibrous peat or paper-mill sludge (Mesri and Ajlouni, 2007; Moo-Young and Zimmie, 1996). Klein and Sarsby (2000) reported that the micro-fibres in sewage sludge are not really in intimate contact with one another, but are separated by the pore fluid. Furthermore, Klein and Sarsby (2000), Sarsby (2005) and O'Kelly (2008) reported that the pore fluid has a viscous gel-like nature, caused by the high concentration of dissolved solids, high bonding or adsorption of the liquid phase within and around the aggregate flocs, and some form of biological coagulation between the pore fluid and organic solids.

Liquid limit (LL) and plastic limit (PL) values of 314% and 53·3% respectively were determined for the 90% fraction of the sewage sludge material that passed the 425 μm sieve using the 80 g–30° fall-cone and Casagrande thread-rolling methods in accordance with BS 1377 (BSI, 1990a). These Atterberg limit values are within the range of calcium montmorillonite clay minerals. Considering the reproducibility of the thread-rolling method, which has been criticised in some of the literature, including Sivakumar *et al.* (2009), the PL value of 53·3% and standard deviation of 2·1% were determined from the results of five PL tests repeated on the sludge material. The material had a high toughness, and became very stiff to hard on nearing the PL condition during the rolling-out procedure, with between 15 and 20 cycles (instead of the usual 5 to 10 cycles) required to reduce the soil thread from 6·0 mm to 3·0 mm in diameter, under uniform hand-rolling pressure. The very high plasticity (plasticity index of 261%) was attributed largely to the organic fraction, but also to the kaolinite component. The high organic content accounts for the high water content, low specific gravity of solids value of 1·55 (similar to that reported for cellulose fibres), and very low bulk density and dry density values.

In this paper, the reported values of water content were calculated on the basis that the liquid phase corresponded to the volatile fraction after oven-drying the test specimens over a four-day period at a temperature of 60°C, instead of the standard oven-drying temperature of 105–110°C conventionally used for mineral soils (BS 1377; BSI, 1990a). The lower drying temperature was adopted in order to limit experimental errors arising from the loss in dry solids mass associated with the removal of some water of hydration, as well as some oxidation of organic matter and other volatile chemicals. O'Kelly (2004a, 2005c) presented data that showed that these effects became significant for the sewage sludge material at temperatures of greater than approximately 80°C.

4. Remoulded undrained shear strength data

A large database of s_{ur} values for water contents at near the plastic limit to greater than the liquid limit (liquidity index, $I_L = 0{\cdot}01 - 1{\cdot}84$) has been reported for this sewage sludge material in vane shear and quick-undrained triaxial compression (O'Kelly, 2004b, 2005b, 2006). These data have been complemented by FC and additional TC tests performed at higher cell-confining pressures as part of this study. Figure 2 shows data for dry density against water content for all of the vane and TC specimens considered in this study.

All the shear strength tests were performed in accordance with BSI (1990b) in a temperature-controlled environment at 21°C, considering that the values of coefficients a and b may also be influenced by temperature (Trauner *et al.*, 2005). The specimens were sheared directly after preparation, and the time to failure was short (a maximum of 12·5 min and 22 min in TC and vane-shear tests respectively) in order to determine the remoulded values of undrained shear strength. Otherwise, had the specimens been allowed to stand for any extended period of time, they would have undergone a reduction in the degree of saturation, and of the effective confinement pressure in TC tests, because of the slow but steady accumulation of biogas generated internally by anaerobic microbial activity.

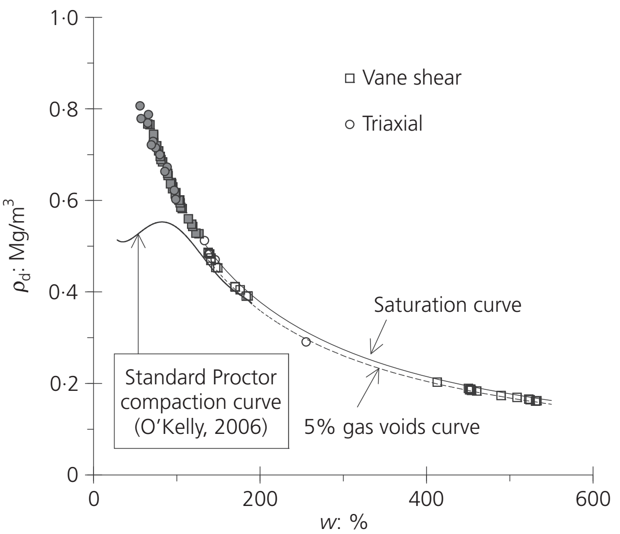

Figure 2. Dry density against water content for sewage sludge, including data of O'Kelly (2004b, 2006) (hollow symbols, material of slurry and soft consistencies; solid symbols, compacted air-dried material)

In the FC tests, an 80 g–30° fall-cone LL apparatus (BS 1377; BSI, 1990a) was used as an implicit strength-measurement device to determine the $\log w : \log s_{ur}$ relationship for the freshly remoulded material over a band of water content about the LL condition. The slurry material could not be prepared to a fully saturated state, since occluded bubbles of biogas remained trapped within the material, even after vigorous agitation.

The shear strength tests reported by O'Kelly (2004b, 2005b, 2006) had been performed on very soft and soft specimens of freshly remoulded material, and also on standard Proctor-compacted material that had been allowed to air-dry over different periods in a fume cupboard at ambient temperature, thereby reducing the water content by different amounts over the plastic range.

In the shear vane tests, a 12·7 mm by 12·7 mm cruciform vane was pushed vertically into the specimens, and the vane head was rotated by the drive motor at an angular rotation of 9·0°/min, which was deemed sufficiently fast to maintain an undrained shear condition. In the TC tests, specimens 38 mm in diameter by 76 mm long were confined under a cell pressure, σ_3, of 100 kPa, and sheared quickly in an undrained condition at a strain rate of 1·2%/min. Additional TC data were determined in this study for σ_3 of 300 kPa in order to study the effect of confinement pressure on the coefficients a and b for unsaturated sludge material. It could be argued that lower confining pressures, in line with typical field-overburden conditions, should have been used in these TC tests; nevertheless, the study will allow the general effect of a change in confining (overburden) pressure to be deduced. Furthermore, although some dissipation of the excess pore-liquid pressure could have occurred to the pore gas voids during shearing of the compacted specimens, the relatively quick strain rates, along with the material's very low coefficient of permeability, of the order of 10^{-9} to 10^{-11} m/s (O'Kelly, 2008), meant that although some of the specimens were in a partially saturated state, they had been essentially sheared in a fully undrained condition.

The degree of saturation (S_r) of 10 freshly prepared specimens of slurry material ($I_L = 1{\cdot}38 - 1{\cdot}84$) tested in vane shear was 95·3–97·0%, indicating that fully saturated specimens could not be prepared, because of trapped biogas bubbles ($A = 2{\cdot}6 - 4{\cdot}2\%$, where A is the gas voids content). The 17 very soft and soft specimens ($I_L = 0{\cdot}30 - 0{\cdot}50$) tested in vane shear and TC had values of $S_r = 94{\cdot}1 - 97{\cdot}4\%$ and $A = 1{\cdot}8 - 4{\cdot}1\%$. The effect of anaerobic microbial activity (including loss of organic solids and associated biogas, and additional pore-liquid generation) on the shear strength response of the slurry, very soft and soft specimens was not significant at ambient laboratory temperature, since it was possible to prepare and shear these specimens over a relatively short period of time, and, moreover, the optimum temperature for anaerobic mesophilic digestion of sewage sludge occurs at 35°C (Metcalf & Eddy, Inc., 2003).

In contrast, specimens prepared by standard Proctor compaction of material that had been air-dried beforehand over different periods were also susceptible to aerobic decomposition, the intensity of which depended on the length of the drying period necessary to reduce the water content to the desired value. However, the effect of aerobic decomposition on the geotechnical properties of the test material was not measured directly. Mean S_r and A values were calculated as 100·9% and −0·49% respectively for the 22 compacted vane specimens ($I_L = 0{\cdot}04$–$0{\cdot}30$), and 99·4% and 0·27% respectively for the 13 compacted TC specimens ($I_L = 0{\cdot}01$–$0{\cdot}18$), based on the specific gravity of solids value of 1·55 that had been measured for the original sludge material (OC = 70%). Considering standard Proctor-compaction at wet of the optimum water content for compaction of 90% for the sludge material produced $A \approx 3$–5% (see Figure 2); the calculated gas voids contents of −0·49% and 0·27% for the compacted vane and TC specimens respectively indicated that the specific gravity of solids value most likely increased for the air-dried material, because of further decomposition occurring under aerobic conditions, which had caused a knock-on effect in overestimation of the degree of saturation and underestimation of the gas voids content. This is supported by the fact that the specific gravity of solids for this sludge material increased linearly from 1·55 to 1·80 with a reduction in organic content from 70% to 50% (O'Kelly, 2006, 2008). However, the actual values of S_r and A cannot be determined for the compacted air-dried specimens, since the level of aerobic decomposition (reduction in organic content) and the resulting increase in the specific gravity of solids were not measured directly in the present study.

5. Experimental results and analyses

5.1 Data for $\log w : \log s_{ur}$

The data for $\log w : \log s_{ur}$ from the strength tests on the sludge material are shown in Figures 3–5. The data for dynamic s_{ur} for slurry material in Figure 3 were determined from the measured penetration depth (h, mm) of the fall cone, from

$$s_{ur} = \frac{KQ}{h^2} \tag{2}$$

where K is the cone factor as defined by Hansbo (1957), with $K = 1{\cdot}33$ determined from theoretical studies (Koumoto and Houlsby, 2001), and Q is the vertical force of 0·785 N for the 80 g–30° cone. The failure mechanism involved general shearing as the free-falling cone displaced the soil out of the way before coming to a stationary position.

The vane s_{ur} data in Figure 4 were calculated from the torsional shear resistance mobilised by the specimen. The vane was located centrally at the mid-height of the 34 mm deep specimen cup, and

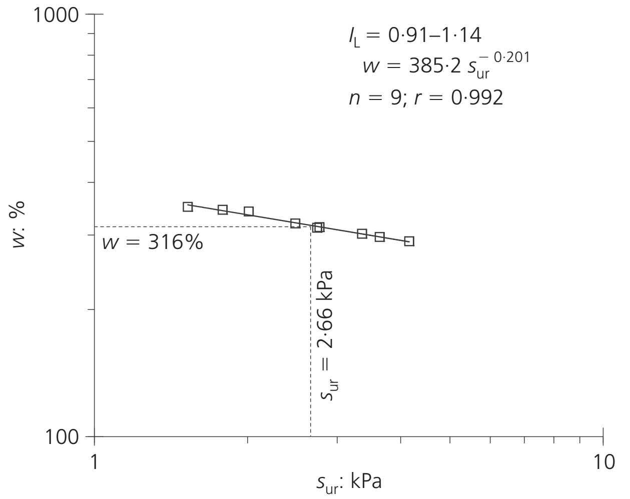

Figure 3. Water content against dynamic shear strength from fall-cone tests (n, number of data points; r, regression coefficient)

produced a shear failure around a cylindrical surface enclosing the vane. The failure mechanism was confirmed for material of soft and firmer consistency from preliminary tests in which the cruciform vane had been embedded just flush with the top surface of the specimen, and the development of the cylindrical failure surface was observed under the rotation of the vane. Four calibrated springs of different torsional stiffness ($C = 1{\cdot}0$, 1·9, 3·3 or 5·8 kN/m²) were used in performing the vane tests, depending on the consistency of the test material, according to

$$s_{ur\ vane} = \frac{C\theta_f}{\pi D^2 (H/2 + D/6)} \tag{3}$$

where θ_f is the angular deflection of the spring at shear failure (degrees); and H and D are the vane height and diameter respectively (i.e. 12·7 mm).

The data for s_{ur} in TC shown in Figure 5 were calculated as half of the deviator stress, which has been corrected for the restraining effect of the enclosing rubber membrane on the specimen deformation response. The triaxial specimens failed by general ductile bulging, except for water contents at near the PL condition, in which case a well-defined failure plane formed at typically 45–50° to the horizontal. Large specimen deformations were required to mobilise s_{ur} fully in both the vane and TC tests. Note that the deviator stress values mobilised in TC often increased monotonically beyond 20% axial strain (typical of organic soils). The limiting 20% strain criterion, traditionally used in such circumstances, was applied in determining the values of TC s_{ur} for further analysis later in this study.

5.2 Interpretation of strength data

As expected, Figures 3–5 show that different s_{ur} values were mobilised by the sludge material for a given water content value,

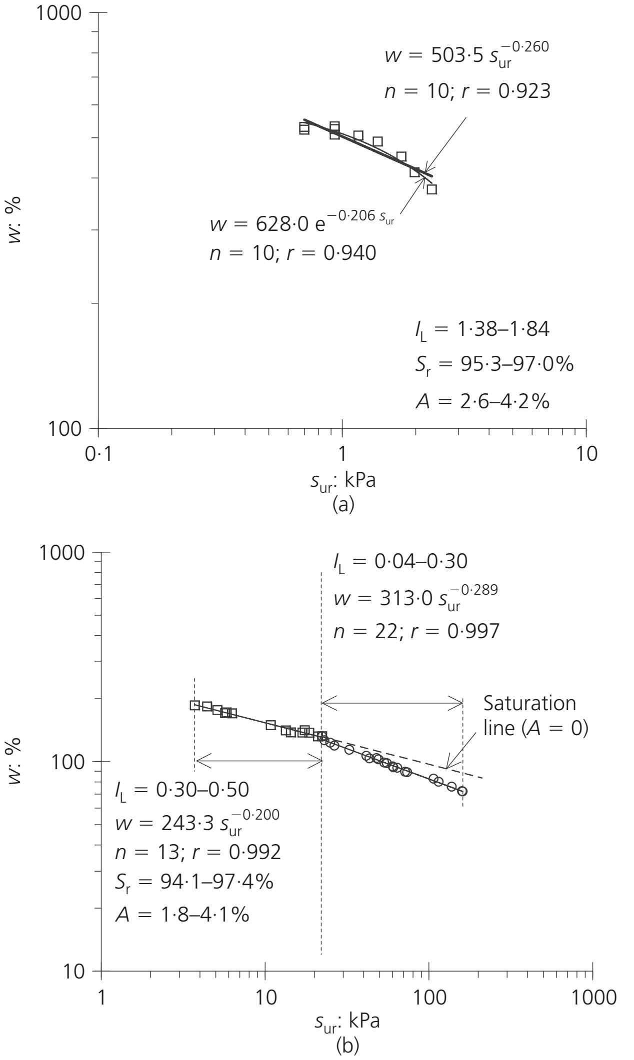

Figure 4. Water content against strength in vane shear: (a) slurry material; (b) plastic material

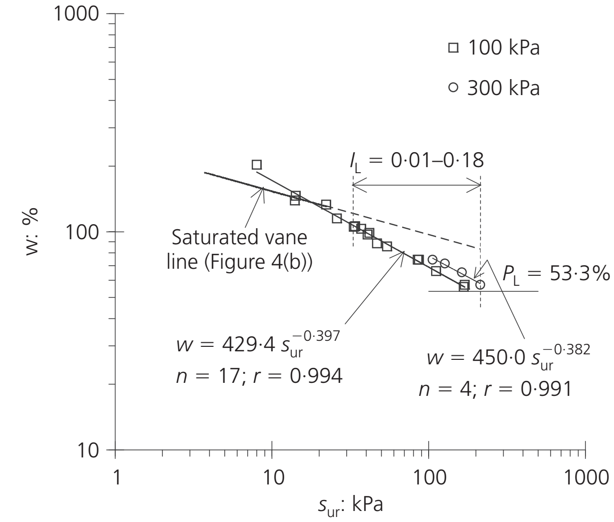

Figure 5. Water content against undrained strength in triaxial compression under cell pressures of 100 and 300 kPa

owing to differences in the test methods (shearing modes, stress and boundary conditions), rates of shear strain, degree of saturation, and aerobic decomposition. For example, Figures 4(b) and 5 indicate that the vane s_{ur} for the compacted specimens was consistently greater than that in TC under $\sigma_3 = 100$ kPa for $w > 160\%$. Furthermore, the interpretation of the FC and vane data for water contents at near the LL condition was complicated by the significant difference in strain rates between these tests, with higher s_{ur} values mobilised for higher rates of shear strain for the former. It is also postulated that a significant contribution of the mobilised shear strength for sewage sludge of slurry and very soft consistencies ($s_{ur} < \sim 4$ kPa) arises from its viscous pore fluid. Klein and Sarsby (2000) and Sarsby (2005) reported that this viscous behaviour can be attributed to the 'cellular biomass' (highly viscous non-Newtonian fluid phase composed of polysaccharide) that encloses the solids, and which behaves more like a gel than like water.

5.3 Comparison of shear vane and triaxial compression strengths

A theoretically rigorous and direct method of determining the relationship between s_{ur} mobilised in vane shear and TC does not exist. A further complication arises regarding the rate of shear strain (i.e. time to failure, t_f). In TC tests, the t_f value is predetermined in adopting the limiting strain at failure criterion, whereas the t_f value in vane shear is a function of the torsional stiffness of the spring, the speed of the drive motor to the vane shaft and the undrained shear strength of the test material itself (Figure 6).

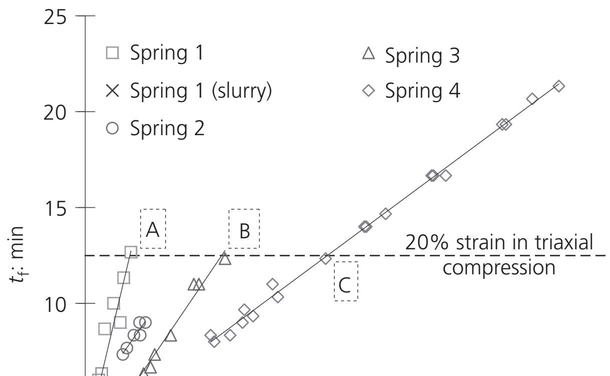

Figure 6. Time to failure in vane shear for different water contents and torsion springs (stiffness of springs in order 1 to 4 was 1·0, 1·9, 3·3 and 5·8 kN/m²)

A significantly slower rate of vane-head rotation could result in a partially drained condition occurring, as distinct from the fully undrained condition provided by the enclosing specimen membrane in TC tests. The effects of the different modes and rates of shear around the cylindrical failure surface in vane tests and general ductile bulging in TC were studied by considering the s_{ur} values deduced for a given water content from the different apparatus. In the TC tests, t_f was preset at 12·5 min, given that these tests had been performed at a strain rate of 1·2%/min, with specimen failure deemed to have occurred by 20% axial strain. The speed of the drive motor for the vane apparatus was also fixed, producing a vane-head rotation of 9·0°/min. Hence the author took the approach of shearing specimens prepared at the same water content but using different torsion springs, in order to achieve different times to failure and hence strain rates. As expected, Figure 7 shows that the deduced vane s_{ur} values for a given water content increased with decreasing t_f. The trend in the data suggests that the strain-rate dependence was greater for higher values of water content.

The t_f value for three of the 65 vane tests performed in total (specimens A–C, Figure 6) happened to coincide with the t_f of 12·5 min in TC, and the constitutive behaviour of these specimens is compared with that of TC specimens at the same water content in Figure 8. The behaviour in vane shear and TC was distinctly different. The shear resistance developed over the cylindrical failure surface in vane shear was proportional to the torque applied at the vane head, which was controlled by the fixed angular rotation of the drive motor, and gave rise to the approximately linear perfectly plastic response evident in vane shear. It could be argued that the applied vane loading was, in a way, stress controlled. The measured angular rotation of the vane (i.e. relative slip around the cylindrical surface) at failure was 39°, 41·5° and 43° for specimens A, B and C in combination with springs 1, 3 and 4 respectively. For a given spring, the angular rotation at failure increased with increasing strength: for example, from 33° to 60° for deduced s_{ur} of 50 kPa to 180 kPa determined using spring 4. The TC specimens deformed by general ductile bulging under the constant rate of axial deformation.

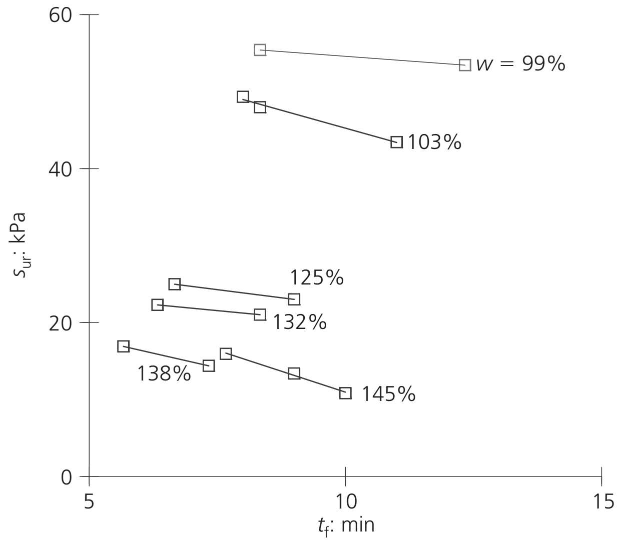

Figure 7. Vane s_{ur} mobilised for different times to failure

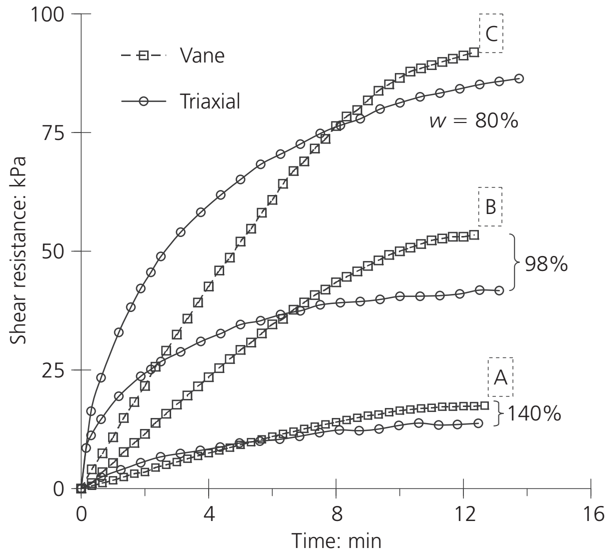

Figure 8. Response of identical specimen pairs in vane shear and TC (TC specimens deemed to have failed after a period of 12·5 min, corresponding to 20% axial strain)

Figure 9 shows 11 pairs of shear vane and TC tests performed at the same water content and sheared over similar periods, with $t_f = 10–14$ min and 12·5 min respectively. Figure 9(a) shows excellent agreement between the values of dry density achieved for the vane and TC specimen preparation methods (maximum difference of 3% in water content recorded for specimen pairs). Figure 9(b) shows that the s_{ur} values mobilised in vane shear were consistently greater than those in TC under $\sigma_3 = 100$ kPa by a scalar, F, of 1·21. A different confining pressure applied in TC produced a different scalar value. It must also be noted that the mobilised strengths in vane shear were peak values, whereas the strengths in TC generally corresponded to 20% axial strain, with marginally higher s_{ur} values often mobilised for larger strains in TC, which if taken into account would reduce the scalar value somewhat. When all of the w–s_{ur} database was considered (with generally different t_f values in vane shear and TC), this scalar was found to increase from about 1·19 to 1·40 (mean value of 1·30) with decreasing water content over the range of 150% to 80% ($I_L = 0·10–0·37$), in agreement with earlier work reported by the author (O'Kelly, 2005b, 2006). This indicates that the scalar is not governed exclusively by the relative difference in the strain rate achieved during the vane and TC tests. Hence there must be other significant factors (e.g. perhaps specimen confinement) at play, since, intuitively, the scalar would have been expected to decrease in value with decreasing water content

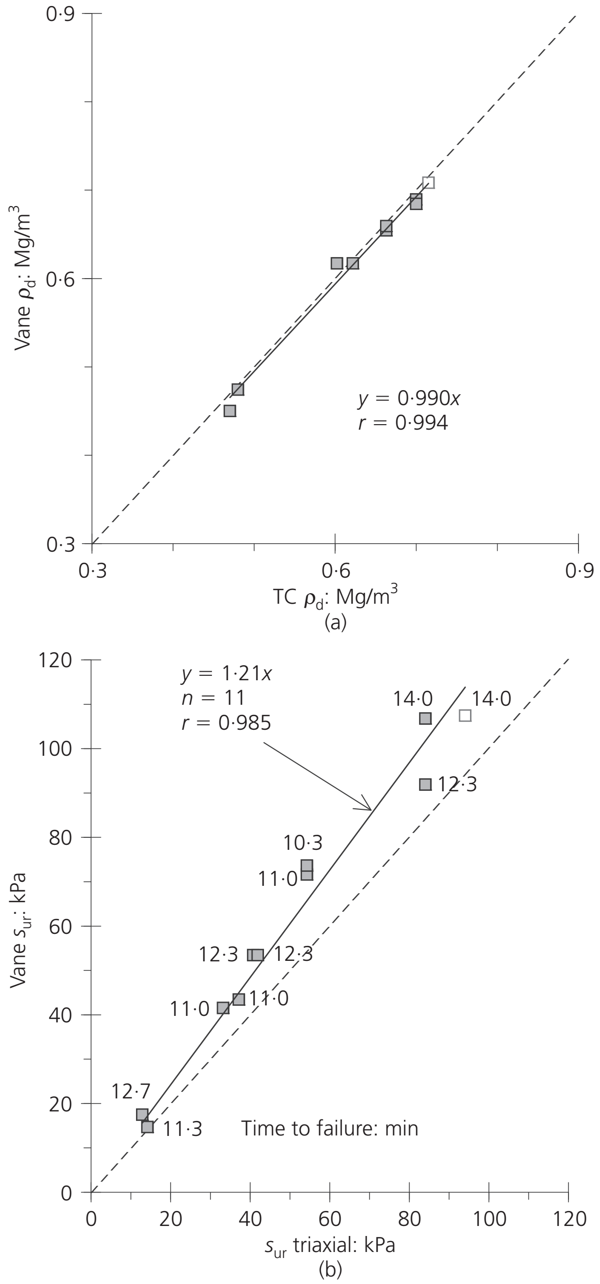

Figure 9. Effect of shearing mode on deduced strength: (a) dry density; (b) remoulded strength

because of the comparatively greater times to failure (reduced strain rates) in vane shear (see Figure 6).

The effect of the different test methods was also considered in terms of the coefficients a and b by comparing the correlations of $\log w : \log s_{ur}$ for the compacted specimens in vane shear and TC (Figures 4(b) and 5). The trend in these correlations suggests that the coefficients a and b depend on the test method, with both coefficients a and b for the test material greater in TC. For example, the coefficient b value for the compacted material in TC was greater than that in vane shear by a factor of 1·37. This again indicates that the value of the scalar F relating s_{ur} in vane shear to that in TC is dependent on the water content value.

5.4 The $\log w : \log s_{ur}$ relationship

5.4.1 Linearity of relationship

The values of the coefficients a and b in Figures 3–5 were determined from regression analysis of the $\log w : \log s_{ur}$ data over different water content bands, each defined in terms of a range of liquidity index. The regression coefficient, r, values were very close to unity, indicating very strong correlations. The saturation trend line in Figure 4(b) is an approximation (since these specimens could not be prepared to full saturation), and was determined from the data for freshly prepared very soft to soft specimens ($S_r = 94{\cdot}1–97{\cdot}4\%$). However, the trends in these experimental data indicate that the $\log w : \log s_{ur}$ relationship is linear over the plastic range, albeit dependent on the degree of saturation, decomposition and also the test method.

Sharma and Bora (2003) reported that the $\log w : \log s_{ur}$ relationships determined for 55 inorganic soils using the FC method were linear over the full plastic range, and, furthermore, the relationship extended to water contents greater than the LL condition. However, the vane data in Figure 4 indicate that the linear relationship does not extend to water contents greater than the LL condition in the case of the sludge material: for example, coefficient $b = 0{\cdot}200$ and $0{\cdot}260$ for $I_L = 0{\cdot}30–0{\cdot}50$ and $1{\cdot}38–1{\cdot}84$ respectively.

5.4.2 Effect of degree of saturation

The effect of the degree of saturation on coefficients a and b was considered by comparing the vane correlations of $\log w : \log s_{ur}$ in Figure 4(b) for the nearly saturated remoulded specimens ($I_L = 0{\cdot}30–0{\cdot}50$; $S_r = 94{\cdot}1–97{\cdot}4\%$) and the compacted air-dried specimens ($I_L = 0{\cdot}04–0{\cdot}30$). The trend in these correlations suggests that an increase in S_r causes a reduction in both coefficients a and b. For example, the values of coefficient b for the compacted and almost saturated sludge materials in vane shear were in the ratio of 1·45 to 1·0. This is intuitively correct, since the coefficient b relates to compressibility, and soil with a higher gas voids content (lower S_r) is more compressible for a given water content.

5.4.3 Effect of confining pressure in triaxial compression

The effect of confining pressure on the coefficients a and b was considered by comparing the correlations of $\log w : \log s_{ur}$ for compacted sludge specimens tested at the same strain rate but under different σ_3 values of 100 kPa and 300 kPa in TC (Figure 5). The s_{ur} value (and hence coefficients a and b) for a saturated fine-grained soil having the same stress history is independent of the confinement pressure. However, the sludge material was unsaturated, owing to trapped biogas generated from internal reactions, and hence its Mohr–Coulomb envelope to the Mohr circles of stress at failure had a concave curvature, becoming progressively less steep under higher confinement pressure.

Consequently, the trend in the experimental data in Figure 5 indicates that an increase in confinement pressure causes an increase in the coefficient a, with $a = 429{\cdot}4$ and $450{\cdot}0$ for sludge under σ_3 of 100 and 300 kPa respectively, although the coefficient b would appear to be practically independent of confinement pressure.

Hence undrained sewage sludge does not behave as a $\phi_\mathrm{u} = 0$ material, with a progressive increase in undrained strength occurring under increasing confinement pressure. Also, the scalar F relating deduced values of s_ur in vane shear to TC was particularly sensitive to the applied confining pressure for the latter (Section 5.3). Furthermore, of more significance to municipal engineers concerned with efficient handling, transportation and disposal of the sludge material (e.g. to landfill; O'Kelly, 2004b) would be its unconfined compressive strength.

5.4.4 Effect of strain rate in fall-cone and vane shear

Similar boundary conditions and confinement are provided by the specimen cups during FC and shear vane tests. Hence the difference in deduced s_ur values between these test methods was largely due to their significantly different rates of shear strain. The FC and vane data in Figures 3 and 4(b) for very soft material indicate that the coefficient a is strongly dependent on the rate of shear strain, whereas coefficient b appears to be independent of it. The strain rate during FC tests is not constant, since the cone initially accelerates as it penetrates into the specimen, and then decelerates to a stationary position. However, the average strain rate of approximately $4{\cdot}2 \times 10^4$%/min (Koumoto and Houlsby, 2001) for cone penetration depths of between 15 and 25 mm was approximately four orders of magnitude greater than that in the vane tests. Figure 10 shows data for $\log w : \log s_\mathrm{ur}$ for these almost saturated specimens, in which the deduced vane s_ur values have been increased by 40%, following Equation 4, whereby the s_ur of fine-grained soil increases in value by approximately 10% for every tenfold increase in the rate of shear strain $\dot{\gamma}$ (Koumoto and Houlsby, 2001).

$$\frac{s_\mathrm{ur}}{s_\mathrm{ur}(1\%/h)} = 1{\cdot}0 + 0{\cdot}1 \log_{10} \dot{\gamma} \tag{4}$$

where $\dot{\gamma}$ is in %/h.

Note that the coefficient b value of 0·200 remained unchanged after applying this adjustment, again suggesting that b is practically independent of the strain rate (Koumoto and Houlsby, 2001). However, Figure 10 indicates that the difference in strain rate can only partially account for the significant difference in the coefficient a values of 385·2 and 243·3 deduced from the FC and vane data respectively.

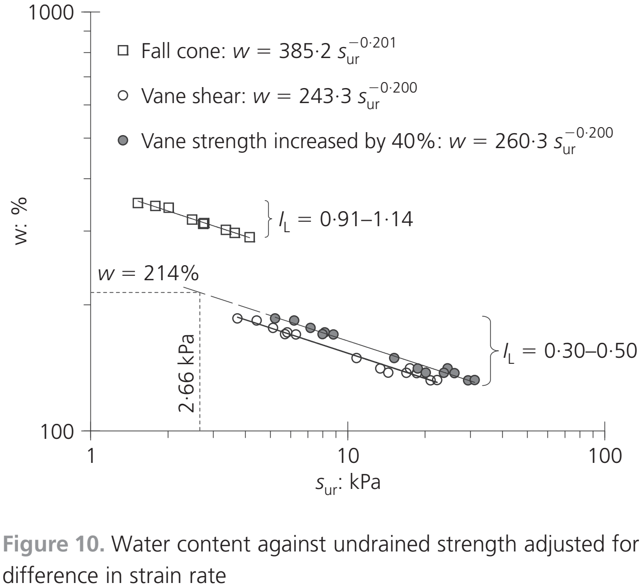

Figure 10. Water content against undrained strength adjusted for difference in strain rate

5.4.5 Effect of viscous pore fluid phase

Although a detailed characterisation of the gel-like pore fluid itself is not presented, it is postulated that the FC trend line for slurry material ($I_\mathrm{L} = 0{\cdot}91$–$1{\cdot}14$; Figure 10) includes a significant shear resistance contribution from the pore fluid, and furthermore the vane trend line for very soft material ($I_\mathrm{L} = 0{\cdot}30$–$0{\cdot}50$) represents almost exclusively the shear resistance mobilised in friction, intertwining and bonding between the solids. The latter seems reasonable, since the relative contribution of the pore fluid to the mobilised strength would be minor over this lower liquidity index range.

Hence the values of the coefficient a and of the LL determined from FC data for slurry material could be artificially high, and the value of the former could also be unrepresentative of material in the plastic state. Artificially high fall-cone LL values measured for the sludge material would give rise to unreliable I_L values: for example, visual observations of bulk material confirmed that the sewage sludge under consideration in the present study was almost liquid for $I_\mathrm{L} > \sim 0{\cdot}6$. Extrapolation of s_ur data determined (e.g. using Equation 1) for a narrow band of water content about the LL condition could also result in the shear strength being significantly overestimated over the wider plastic range. Note that the liquidity index values reported in this study were calculated on the basis of the measured fall-cone LL value of 314%.

6. Discussion

6.1 Determination of LL value for gelatinous soil

6.1.1 Fall-cone method

The LL condition as determined by the fall-cone LL method for saturated fine-grained mineral soil having a pore water phase is implicitly defined as the water content corresponding to a predefined s_ur, the value of which depends on the cone characteristics and penetration depth specified for the LL condition. The British Standard defines the LL condition by a 20 mm penetration depth of the 80 g–30° fall cone (BS 1377; BSI, 1990a), which corresponds to a dynamic s_ur of 2·66 kPa, mobilised in friction and bonding between the mineral particles under an average strain rate of $4{\cdot}2 \times 10^4$%/min (Koumoto and Houlsby, 2001).

However, in the case of gelatinous fine-grained soil, the additional shear resistance mobilised by its pore fluid may be significant, as has been alluded to for the sludge material in this study, and may constitute the bulk of the shear strength mobilised for slurry material. Hence, for consistency, it is suggested that the LL condition for gelatinous fine-grained soil should be defined in terms of the shear resistance mobilised in friction and bonding between the solids (also including intertwining of fibres in the case of micro-fibrous clays) rather than the mobilised shear strength, with the latter possibly including a significant strength contribution from the gel-like pore fluid.

Previous studies on saturated fine-grained mineral soils (Koumoto and Houlsby, 2001; Sharma and Bora, 2003) have shown that, apart from montmorillonite soils (Sharma and Bora, 2003, 2005), the $\log w : \log s_{ur}$ relationship is linear over the full plastic range, and extends to water contents greater than the LL condition. The data for the very soft and soft sludge material in Figure 4(b) indicate that the $\log w : \log s_{ur}$ relationship was also linear within the plastic range ($I_L = 0{\cdot}30$–$0{\cdot}50$). It has been suggested in Section 5.4.5 that over this I_L range: (a) s_{ur} is mobilised almost exclusively in friction, intertwining and bonding between the solids; and (b) the non-linearity in the $\log w : \log s_{ur}$ relationship for water contents at near and above the LL condition arises from the contribution of the gel-like pore fluid.

Hence it is postulated that the water content corresponding to the LL condition (now redefined specifically in terms of the shear resistance mobilised in friction, intertwining and bonding between the solids) can be calculated using Equation 1 with input values of coefficients a and b determined from regression analysis of $\log w : \log s_{ur}$ data for remoulded material of soft or firmer consistency (i.e. for which the relative contribution of the pore fluid is insignificant). In this manner, the value of LL and hence of the liquidity and plasticity indices could be defined more precisely. For example, values of $a = 260{\cdot}3$ and $b = 0{\cdot}200$ ($I_L = 0{\cdot}30$–$0{\cdot}50$; Figure 10) were determined for the plastic sludge by adjusting the vane s_{ur} data in line with the dynamic strain rate of the FC tests. Substituting these coefficient a and b values along with a dynamic shear resistance of 2·66 kPa in Equation 1 would give a reduced value of LL = 214% for the sludge material. The water content of 214% corresponds to an I_L of 0·62 (based on the measured fall-cone LL and PL values of 314% and 53% respectively). Hence the redefined LL condition, which occurred for a water content of 214%, would appear to be consistent with visual observations that the bulk sludge material was almost liquid for $I_L > \sim 0{\cdot}6$.

A further observation concerns standard practice for determining the fall-cone LL value. Given that the fall-cone LL value is implicitly defined in codes and standards in terms of remoulded undrained shear strength, it would appear more appropriate to determine the LL value from analysis of the FC $\log w : \log s_{ur}$ data rather than the standard practice of analysing the near-linear relationship of cone penetration depth against specimen water content. The FC s_{ur} values for different specimen water contents can be calculated from the measured cone penetration depth using Equation 2. Nevertheless, the associated error generally appears to be very small, since the fall-cone LL test is performed over a relatively narrow band of water content. For example, in the case of the sewage sludge material, regression analysis of the experimental FC data ($n = 9$) of penetration depth against specimen water content gave a fall-cone LL value of 314%, compared with 316% derived from regression analysis of the $\log w : \log s_{ur}$ data and applying s_{ur} of 2·66 kPa at LL for the 80 g–30° fall cone (Figure 3).

6.1.2 Casagrande percussion method

The controlling mechanisms in the fall cone and Casagrande percussion methods for the determination of the liquid limit of fine-grained soils are quite different: friction between the solids and viscous shear resistance of double-layer-held water respectively (Prakash, 2005). Hence the Casagrande percussion method may be a more appropriate means of determining the water content value corresponding to the LL condition in the case of gelatinous soils. Undrained shear strengths of up to 5·6 kPa have been reported for the Casagrande LL condition (e.g. Wasti and Bezirci, 1986; White, 1982). This encompasses the vane s_{ur} of 5·2 kPa inferred for the sewage sludge material by extrapolation of the best-fit correlation in Figure 4(a) to a water content of 214%, which was established in Section 6.1.1 as being more representative of this phase transition. However, further research is recommended in this regard.

6.2 Contribution of gel-like pore fluid to shear strength

It was argued in Section 6.1.1 that the non-linear $\log w : \log s_{ur}$ relationship for water contents at near and above the LL condition in the case of gelatinous fine-grained soil may be attributed to additional shear resistance provided by its pore fluid. For example, referring to Figure 11, it is suggested that the dynamic s_{ur} of 2·66 kPa mobilised at $w = 314\%$ comprised 0·38 kPa due to friction, intertwining and bonding between the solids and a further 2·28 kPa (i.e. 86% of the mobilised s_{ur}) due to the shear resistance of the pore fluid.

The vane data for water contents about the LL condition and very soft to soft material are shown on the normal w–s_{ur} plot in Figure 12. Also included is the fall-cone LL value of 314% and corresponding vane s_{ur} of 2·42 kPa, which was determined as follows: the FC s_{ur} of 2·66 kPa at LL was reduced by a factor of 1·43 (following from Equation 4) and then multiplied by the mean adjustment factor F of 1·30 (Section 5.3) in order, first, to reconcile the dynamic FC s_{ur} value with the strain rate in TC and, second, to account for the effect of the different shearing mode. The 10% adjustment in s_{ur} per tenfold difference in strain rate

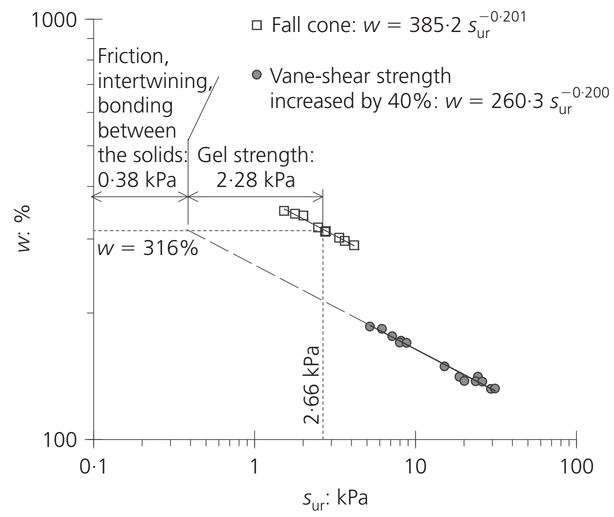

Figure 11. Fall-cone and vane data adjusted for difference in strain rate

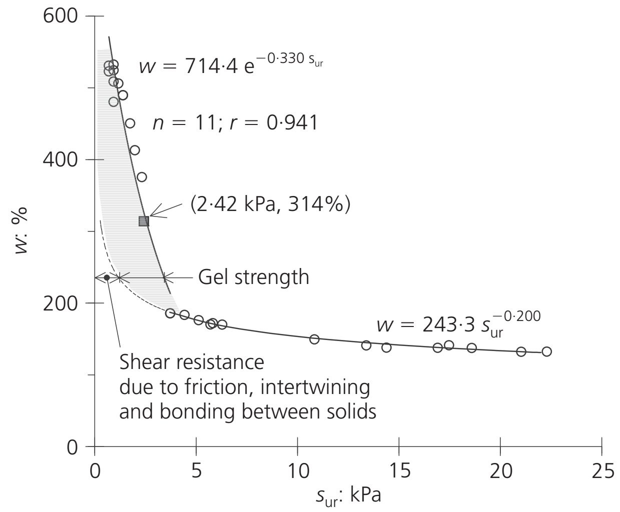

Figure 12. Water content against vane strength for material of slurry to soft consistency

(Equation 4) brought the fall-cone LL data point into good agreement with the vane correlation curve for the slurry material.

Figure 12 indicates that the w–s_{ur} relationship for slurry material was approximately linear, although best defined by an exponential relationship ($r = 0{\cdot}941$), and the following explanations are proposed.

- For $w >> $ LL, the viscosity of the thick suspension increases with reducing water content, owing to the increase in solids concentration. It is suggested that greater chemical bonding and biological coagulation between the solids and pore liquid also gives the slurry material gel-like characteristics.
- The shear resistance mobilised in friction, intertwining and bonding between the solids gradually builds up as the solids begin to come into closer contact with further reductions in water content.
- The relative contribution of shear resistance provided by the pore fluid to the mobilised strength would decrease for water contents nearing the LL condition, which has been redefined in the present study exclusively in terms of the shear resistance mobilised in friction, intertwining and bonding between the solids for gelatinous soils.
- The s_{ur} value is almost entirely mobilised in friction, intertwining and bonding between the solids for very soft or firmer material ($w \leqslant 185\%$; Figure 12).

It is speculated that, in common with gels, any shear resistance arising from the pore fluid of sewage sludge is likely to decrease with increasing temperature. The relative contribution of the pore fluid to the mobilised s_{ur} value decreases with decreasing water content below the LL condition (Figure 12). Hence, following from point 3 above, it is postulated that the coefficient b for gelatinous soil of slurry or very soft consistency may also be affected by changes in temperature, that is, decreasing marginally in value with increasing temperature.

6.3 Remoulded undrained shear strength and PL condition

Three of the sewage sludge specimens that had been prepared by standard Proctor compaction at wet of the optimum water content were subsequently allowed to slowly air dry close to the PL value of 53·3% before shearing in TC tests (Figure 5). Two of these specimens were sheared under $\sigma_3 = 100$ kPa and mobilised s_{ur} of 168 kPa and 170 kPa ($w = 57\%$ and 56% respectively); the third specimen was sheared under $\sigma_3 = 300$ kPa and mobilised a higher s_{ur} of 214 kPa ($w = 57{\cdot}2\%$). Two vane tests performed on material that had been slowly air-dried to above the PL condition mobilised s_{ur} of 171 kPa and 181 kPa ($w = 68\%$ and 65% respectively). These s_{ur} values in TC and vane shear are on the high side compared with other highly organic soils, but are consistent with $s_{ur} \approx 170$ kPa reported for fine-grained mineral soil at the PL condition (e.g. Sharma and Bora, 2003; Stone and Phan, 1995; Wood, 1990), and also with the very stiff to hard consistency of the soil thread observed in performing the Casagrande rolling-out procedure on the sludge material. Note that the Atterberg limit tests were performed on the fraction passing the 425 μm sieve, in accordance with BS 1377 (BSI, 1990a).

The relatively high s_{ur} values mobilised for the sewage sludge material can be explained, at least in part, by the entangled fibres (of which ~17% by total dry mass were coarse) and Magnafloc® LT25 polyelectrolyte that had been added at the municipal treatment works. O'Kelly (2011) reported that chemical conditioning of water treatment residue (a colloidal organic clay) with Magnafloc® had the effect of increasing its TC s_{ur} by 10–20%, owing to interparticle bridging and intertwining phenomena that occurred in the presence of the polyelectrolyte during floc formation and growth. It is postulated that significant reinforcement was also provided by the coarse fibrous fraction, consisting mainly of plant fibres but also of animal hairs. The latter are one of the strongest natural fibres, with an ultimate tensile strength of ~380 MPa (about as strong as structural steel of the same diameter), and can strain by up to 50% in a wet condition before breaking.

7. Summary and conclusion

Sewage sludge is a relatively homogeneous, isotropic, three-phase material comprising aggregate flocs of clay mineral and mainly micro-fibrous organic particles, and a gel-like pore fluid that includes occluded bubbles produced internally as the material biodegrades. Freshly remoulded material cannot be prepared to a fully saturated state, with the degree of saturation reducing over time, owing to the steady accumulation of biogas generated internally, so that undrained sewage sludge does not behave as a $\phi_u = 0$ material.

The $\log w : \log s_{ur}$ relationship for the sewage sludge was found to be strongly linear over the plastic range, albeit dependent on the degree of saturation and aerobic decomposition (for specimens prepared by compaction of air-dried material) and also on the method of shear strength measurement. The trends in the data of $\log w : \log s_{ur}$ suggest the following conclusions.

- The coefficients *a* and *b* both reduce in value with an increase in the degree of saturation.
- The coefficient *a* increases with an increase in the rate of shear strain, and for unsaturated material with an increase in confinement pressure, whereas the coefficient *b* remains practically unchanged.

The scalar relating the deduced vane s_{ur} to that mobilised in TC depends on: the material and its physical state (water content, degree of saturation); the dimensions of the cruciform vane and triaxial specimen; the time to failure; and the specimen boundary conditions and confinement pressure. Hence the scalar value was not singular, even under the specific test conditions in vane shear and TC considered in the study. For example, the deduced s_{ur} from miniature vane tests was between 1·19 and 1·40 times greater than that mobilised in quick-undrained TC of 38 mm diameter specimens under $\sigma_3 = 100$ kPa over the water content range of 80–150%, with a scalar value of 1·21 corresponding to similar times to failure of ~12·5 min for both tests.

Although a detailed characterisation of the pore fluid itself was not presented, it was found that, unlike fine-grained mineral soil, the $\log w : \log s_{ur}$ relationship for sewage sludge of slurry consistency was non-linear, and it was postulated that this deviation occurred because of the gel-like nature of the pore fluid. Hence it was suggested that the LL value determined from FC data was likely to be artificially high. It was proposed that, in the case of gelatinous clay, the LL condition should be specifically defined only in terms of the shear resistance mobilised in friction, intertwining (where fibres are present) and bonding between the solids, rather than the mobilised shear strength, since the latter may also include a significant shear resistance contribution from the pore fluid.

The TC s_{ur} value of compacted sludge material at the PL condition was in good agreement with the value of ~170 kPa reported in the literature for inorganic fine-grained soil.

REFERENCES

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

BSI (1990b) BS 1377: Part 7. Methods of test for soils for civil engineering purposes (shear strength tests (total stress)). BSI, Milton Keynes, UK.

Hansbo S (1957) A new approach to the determination of the shear strength of clay by the fall-cone test. *Proceedings of the Royal Swedish Geotechnical Institute* **14**: 1–48.

Klein A and Sarsby RW (2000) Problems in defining the geotechnical behaviour of wastewater sludges. In *Geotechnics of High Water Content Materials* ASTM STP 1374 (Edil TB and Fox PJ (eds)). American Society for Testing and Materials, Philadelphia, PA, USA, pp. 74–87.

Koenig A and Bari QH (2001) Vane shear strength of dewatered sludge from Hong Kong. *Water Science and Technology* **44(2–3)**: 389–397.

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

Mesri G and Ajlouni M (2007) Engineering properties of fibrous peats. *Geotechnical and Geoenvironmental Engineering* **133(7)**: 850–866.

Metcalf & Eddy, Inc. (2003) *Wastewater Engineering, Treatment and Reuse*, 4th edn. McGraw-Hill, New York, NY, USA.

Moo-Young HK and Zimmie TF (1996) Geotechnical properties of paper mill sludges for use in landfill covers. *ASCE Journal of Geotechnical Engineering* **122(9)**: 768–775.

O'Kelly BC (2004a) Accurate determination of moisture content of organic soils using the oven drying method. *Drying Technology* **22(7)**: 1767–1776.

O'Kelly BC (2004b) Geotechnical aspects of sewage sludge monofills. *Proceedings of the Institution of Civil Engineers – Municipal Engineer* **157(3)**: 193–197.

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

O'Kelly BC (2005b) Mechanical properties of dewatered sewage sludge. *Waste Management* **25(1)**: 47–52.

O'Kelly BC (2005c) New method to determine the true water content of organic soils. *Geotechnical Testing Journal* **28(4)**: 365–369.

O'Kelly BC (2006) Geotechnical properties of municipal sewage sludge. *Geotechnical and Geological Engineering* **24(4)**: 833–850.

O'Kelly BC (2008) Effect of biodegradation on the consolidation properties of a dewatered municipal sewage sludge. *Waste Management* **28(8)**: 1395–1405.

O'Kelly BC (2011) Effects of aluminum sulfate and polyelectrolyte solutions on the geotechnical properties of organic clay. *Soils and Foundations* **51(2)**: 359–367.

Prakash K (2005) Discussion on 'Plastic limit, liquid limit, and undrained shear strength of soil: Reappraisal'. *Geotechnical and Geoenvironmental Engineering* **131(3)**: 402.

Raunkjaer K, Hvitved-Jacobsen T and Nielsen PH (1994) Measurement of pools of protein, carbohydrate and lipid in domestic wastewater. *Water Research* **28(2)**: 251–262.

Sarsby RW (2005) Geotechnical properties of sewage sludge. *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan*, vol. 4, pp. 2327–2330.

Sharma B and Bora PK (2003) Plastic limit, liquid limit and undrained shear strength of soil: Reappraisal. *Geotechnical and Geoenvironmental Engineering* **129(8)**: 774–777.

Sharma B and Bora PK (2005) Closure to 'Plastic limit, liquid limit and undrained shear strength of soil: Reappraisal'. *Geotechnical and Geoenvironmental Engineering* **131(3)**: 403.

Sivakumar V, Glynn D, Cairns P and Black JA (2009) A new method of measuring plastic limit of fine materials. *Géotechnique* **59(10)**: 813–823.

Skempton AW and Northey RD (1953) The sensitivity of clays. *Géotechnique* **3(1)**: 30–53.

Stone KJL and Phan CD (1995) Cone penetration tests near the plastic limit. *Géotechnique* **45(1)**: 155–158.

Trauner L, Dolinar B and Misic M (2005) Relationship between the undrained shear strength, water content, and mineralogical properties of fine-grained soils. *International Journal of Geomechanics, ASCE* **5(4)**: 350–355.

Wasti Y and Bezirci MH (1986) Determination of consistency limits of soils by the fall cone test. *Canadian Geotechnical Journal* **23(2)**: 241–246.

White IL (1982) Soil plasticity and strength: a new approach using extrusion. *Ground Engineering* **15(1)**: 16–24.

Wood DM (1990) *Soil Behaviour and Critical State Soil Mechanics*. Cambridge University Press, New York, NY, USA.