Characterisation and undrained strength of amorphous clay

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This paper presents the physiochemical properties and relationship of saturated remoulded undrained shear strength, s_{ur} , against water content, w , for an amorphous organic clay, namely an alum water-treatment residue material derived from the production of potable water. The $\log w$ – $\log s_{ur}$ relationship was found to be strongly linear, and extended well beyond the measured plastic range. The effects of microstructure, and the shearing modes, rates and specimen confinement, are reported, along with the correspondence between s_{ur} measured in triaxial compression and that deduced from fall-cone and miniature vane tests. The mobilised strength exhibited high strain-rate dependence, increasing by $\sim 30\%/\log \dot{\epsilon}$ cycle increase. The bulk water-treatment residue material could be easily remoulded at water contents below the measured Casagrande plastic limit, indicating that the reported plastic range was notional and, furthermore, that the use of liquidity index as an indicator of the material's consistency is unreliable. The paper concludes by presenting a conceptual model that goes towards explaining the relatively high values of s_{ur} mobilised for this material at extremely high water contents.

Notation

A	water content for $h = 1$ mm
a	water content for $s_{ur} = 1$ kPa
B	gradient of $\log w$ – $\log h$ relationship
b	gradient of $\log w$ – $\log s_{ur}$ relationship
G_s	specific gravity of solids
h	cone penetration depth
K	cone factor
LOI	loss in dry mass on ignition
M	gradient of CSL in q – p' space
p'	mean effective stress
Q	vertical force
q	principal stress difference
R	ratio of strengths at plastic and liquid limits ($= s_{ur(PL)}/s_{ur(LL)}$)
r	regression coefficient
s_{ur}	saturated remoulded undrained shear strength
$s_{ur(LL)}$	value of s_{ur} at LL condition
$s_{ur(PL)}$	value of s_{ur} at PL condition
v	specific volume
w	water content
Γ	specific volume on CSL at $p' = 1$ kPa
$\dot{\epsilon}$	strain rate
λ	gradient of the isotropic compression line
σ_3	confining pressure

1. Introduction

Amorphous organic fine-grained soils are challenging geo-materials that include dewatered residues from municipal and

industrial treatment processes. For example, water-treatment residue material (O'Kelly, 2008; Wang *et al.*, 1992) is the organic slurry derived from the production of potable water at municipal works. These materials are characterised by high water content and plasticity, low specific gravity of solids, high compressibility and very low hydraulic conductivity. It is important to note that unlike peats (Mesri and Ajlouni, 2007), paper-mill sludge (Moo-Young and Zimmie, 1996) and to a lesser extent municipal sewage sludge (O'Kelly, 2006), the organic solids in the materials under consideration are predominantly colloidal in size (O'Kelly, 2008). Furthermore, these soils are generally in a saturated, remoulded condition during handling at the municipal or industrial works and subsequent disposal offsite. Hence their undrained shear strength–compressibility–water content relationships can be conveniently studied using critical-state soil mechanics, adopting the Cambridge stress-path parameters of mean effective stress (p') and principal stress difference (q) in this study. Also, since these relationships will be applied over a wide range of water content, owing to the high plasticity of these materials, it is appropriate to express the projection of the critical-state line (CSL) on the specific volume against mean effective stress plane (v – p' plane; Figure 1(a)) in the form (Butterfield, 1979)

$$1. \quad \log v = \log \Gamma - \lambda \log p'$$

where λ is the gradient of the CSL projection on the $\log v$ – $\log p'$ plane, and Γ is the CSL specific volume at $p' = 1$ kPa.

Figure 1. Relationships for saturated remoulded fine-grained soils: (a) specific volume against mean effective stress; (b) water content against undrained shear strength (Note: CSL, projection of the critical-state line; iso-NCL, isotropic normal compression line)

Given that the undrained strength in triaxial compression is equal to half of the deviator stress mobilised at failure for a normally consolidated or slightly overconsolidated soil, and with the gradient of the CSL projection on the p' - q plane given by the strength parameter M , the mean effective stress can be expressed in terms of the saturated remoulded undrained shear strength, s_{ur} , by

$$2. \quad p' = \frac{2s_{ur}}{M}$$

The specific volume of a saturated soil can be expressed in terms of its water content (w , as %) by

$$3. \quad v = 1 + \frac{G_s w}{100}$$

where G_s is the specific gravity of solids.

Hence, combining Equations 1–3, it is found that the $\log w$ – $\log s_{ur}$ relationship is also linear (Figure 1(b)), given by

$$4a. \quad \log w = \log a - b \log s_{ur}$$

or (Koumoto and Houlsby, 2001)

$$4b. \quad w = a s_{ur}^{-b}$$

where coefficient a is the water content (as %) corresponding to $s_{ur} = 1$ kPa, and coefficient b is the gradient of the $\log w$ – $\log s_{ur}$ relationship.

Although in practice one is more interested in the dependence of undrained strength on water content, the relationship is usually considered in either of the forms given by Equations 4a and 4b, since the coefficients a and b are closely related to the geotechnical properties, and their values can be readily determined using a number of approaches. The coefficient a , like the liquid limit (LL), is an indicator of the water-holding capacity of a soil, and its value depends on the grading, composition and mineralogy, shape, surface texture and activity of the clay fraction (Trauner *et al.*, 2005; Wood, 1990). The coefficient b relates to the soil compressibility, and is equal in value to the critical-state parameter λ (Figure 1). Furthermore, Koumoto and Houlsby (2001) have shown how the values of coefficients a and b can be determined from fall-cone data or from regression analysis of $\log w$ – $\log s_{ur}$ data, or alternatively may be calculated from the intrinsic parameters of the CSL projection determined from isotropic consolidated-undrained TC data. Trauner *et al.* (2005) also showed that, for inorganic fine-grained soils, the values of coefficients a and b can be determined from knowledge of the mineralogical properties alone, namely the mass portion and specific surface of the clay minerals.

All of the literature that reported the characteristics of remoulded undrained shear strength over the plastic range, including Koumoto and Houlsby (2001), Sharma and Bora (2003), Skempton and Northey (1953) and Wood (1990), would appear to concern fine-grained mineral soils, with a dearth of knowledge regarding organic soils. These experimental data indicate that the $\log w$ – $\log s_{ur}$ relationship is linear over the plastic range, apart from high-plasticity montmorillonite soils, which exhibit bilinear relationships near the LL condition, with this characteristic difference

in behaviour attributed to diffuse double-layer held water (Sharma and Bora, 2003, 2005).

There has also been a trend towards adopting the fall-cone and shear-vane methods as a quick means of determining shear strength in order to assess whether the materials have been adequately dewatered before leaving the municipal or industrial works and again, for example, by the landfill operator before accepting the dewatered cake for disposal. This raises the issue of the correspondence between s_{ur} measured in triaxial compression (TC) and that deduced from fall-cone and shear-vane tests.

2. Aims and scope

In this study, the physicochemical properties of and data for saturated remoulded undrained shear strength from fall-cone, shear-vane and TC tests performed on water-treatment residue (WTR) material are studied, with the following objectives.

- Establish whether the $\log w - \log s_{ur}$ relationship is linear, bilinear or otherwise over the plastic range, and in particular the correspondence between s_{ur} measured in TC and that deduced from fall-cone and shear-vane tests.
- Study the effects of microstructure and of the mode and rate of shearing in the different apparatus on the mobilised strength.
- Determine the values of s_{ur} corresponding to the Atterberg consistency limits, and hence the strength variation over the plastic range.

A review of the literature indicates that this study would appear to be one of the first to consider the relative significance of the factors listed in (b) above, specifically in terms of the coefficients a and b for organic clays. Hence, by using this approach in the present study, further insight will be gained regarding the factors influencing the values of coefficients a and b for amorphous organic clay. This study also demonstrates the application of conventional geotechnical laboratory testing and analysis to a challenging and unconventional geomaterial. The paper concludes by advancing a conceptual model towards explaining the relatively high shear strengths mobilised for high-water-content organic clays.

3. Experimental material

The WTR material considered in this study was a by-product of the chemically assisted purification of surface waters sourced from the Dublin and Wicklow mountains, an upland catchment of predominantly saturated peat overlying granite bedrock. The mineralogy and organic content of WTR, which is a reasonably homogeneous and isotropic material, depends on the catchment geology and hydrology, and also on the clarification processes used in the production of potable water at the municipal works. These processes included the addition of Chemifloc 4140® alum coagulant and Magnafloc® LT25 polyelectrolyte during the purification process, which also enhanced the dewatering efficiency of the WTR slurry. Further details of the catchment source

and the water-treatment works, which is located at Ballymore Eustace on the shore of Poulaphuca Reservoir (County Kildare), have been reported by O'Kelly (2008, 2010) and O'Kelly and Quille (2009, 2010).

The solids phase of the WTR was almost exclusively fine grained (Figure 2), comprising amorphous organic matter and clay mineral particles, with all of the solids passing the 425 μm sieve on wet-sieving the material.

Figure 3 shows data for counts against diffraction angle from X-ray diffraction analysis performed on both surface-dry and wet WTR specimens. There was an increased background and noise due to the significant organic fraction, especially for the wet specimen, with the high-intensity peaks interpreted as quartz and manganoan calcite (common catchment bedrock minerals that

Figure 2. Scanning electron micrographs at two different resolutions

Figure 3. X-ray diffraction analysis

were present as colloids in the source water), although there is also the likelihood of other trace minerals, albeit at concentrations of less than 1–2% by mass. The chemical additives of Chemifloc® alum and Magnafloc® polyelectrolyte did not feature in Figure 3, since the alum precipitate was present as amorphous aluminium hydroxide precipitates (with the WTR material itself comprising between 24% and 28% aluminium by dry mass), and the polyelectrolytes are organic molecules.

The WTR leachate was clear, with a pH of 8.6 and a specific gravity of 1.0025 at 20°C, similar to that of pure water, which has a density of 0.9982 g/cm³ at this temperature. The dissolved solids content of 548 mg/l was determined by oven-drying 50 ml of the leachate at a temperature of 105°C. The specific gravity of solids for the WTR material itself was 1.86.

Slurry specimens having water contents of ~500%, and nominally 20, 50 and 100 g in wet mass, were oven-dried at a temperature of 105°C over a period of 34 days. Figure 4 shows the percentage reduction of the 48 h specimen dry mass produced by further periods of oven-drying. Some of the solids were found to oxidise, but at an insignificant rate, since most of the organic fraction was already in a near-stable condition, and the polyelectrolyte additive became unstable only at temperatures above ~150°C. The Magnafloc® polyelectrolyte is a polyacrylamide, with a high molecular weight of 10–15 × 10⁶, and is anionic in aqueous solution (O'Kelly, 2011). For practical purposes, an oven-drying period of 48 h and temperature of 105°C were used for all water content determinations in the present study.

The material's loss-in-dry-mass on ignition (LD1) value of 57% for a temperature of 440°C is a good reflection of its gravimetric organic content, which includes the ~3.5% dry solids mass of polyelectrolyte additive, since the crystalline fraction remained stable at this ignition temperature, although the alum component may have degraded somewhat (O'Kelly and Quille, 2010). The ash from these ignition tests had an LL of 45%, determined using the 80 g–30° fall-cone LL method, and was non-plastic, indicating

Figure 4. Reduction in 48 h specimen dry mass produced by further oven drying at 105°C

that the high plasticity of the WTR material was associated with its organic fraction. The uniform paste for performing the fall-cone LL test was prepared by adding sufficient distilled water to the ash material, thoroughly remoulding, and allowing it to equilibrate over a period of 48 h. Furthermore, the LOI value was found to remain unchanged at 57% after the material had been stored at constant composition and ambient laboratory temperature and under anaerobic conditions over a period of 5 years, indicating that its organic fraction was not bioactive, at least under this environment. This is consistent with the findings of Elliott *et al.* (1990), who reported mineralisation rates of organic carbon and nitrogen in alum WTRs similar to those of natural soils.

The material was classified as amorphous organic clay, with extremely high values of LL and plastic limit (PL) determined using the 80 g–30° fall-cone LL apparatus and Casagrande thread-rolling method (BS 1377; BSI, 1990a). Note that the material used in the Atterberg limit tests had not been wet-sieved through the 425 µm size, since the proportion of coarser particles was insignificant and wet sieving would, in any event, have diluted or changed the chemistry of the pore liquid phase. Also, one of the aims of this study was to assess the correspondence between s_{ur} measured in TC and that deduced from fall-cone tests, without any pre-treatment of the test material. Figure 5 shows the relationships of water content against cone penetration depth (h) presented in a log–log plot for natural and blended WTR materials (with the latter prepared in a mini food blender over a period of 1 min), which can be expressed in the form (Koumoto and Houlsby, 2001)

$$5. \quad w = A h^B$$

with the data for the soil-dependent parameters A and B , LL determined for $h = 20$ mm, PL and plasticity index (PI) reported

Figure 5. Water content against penetration depth from fall-cone tests

in Table 1. Note that coefficient $b = B/2$ (Koumoto and Houlsby, 2001).

An important observation was that the bulk materials could be easily remoulded at water contents significantly below the measured PL values, which can be partly explained by scale effects for the Casagrande PL method (Barnes and O'Kelly, 2011), with the water content value at which crumbling occurs during rolling-out of the soil thread a function of the thread diameter. Hence the reported plastic range is notional, and, furthermore, the use of liquidity index as an indicator of the material's consistency is not reliable in practice. It can also be argued that the LL and PL conditions are defined for fine-grained mineral soils, with specific physical meaning, and that these Atterberg limits should not be applied to the WTR material, which comprised predominantly organic solids, albeit that these particles were almost exclusively colloidal in size. The difference between the natural and blended materials (Figure 5) indicated that the former had an inherent microstructure that was degraded somewhat by the blending action, with lower values of LL, PL and PI determined for the

Material	Fall-cone LL					PL		PI
	LL: %	A	B	n	r	PL: %	n	
Natural	513	148.2	0.415	7	0.998	268	2	245
Blended	474	146.2	0.393	7	0.990	254	2	220

n , number of tests; r , regression coefficient.

Table 1. Atterberg consistency limits

blended material, although the relative differences in these index values were not great overall.

4. Shear strength measurement

The undrained shear strength of the saturated freshly remoulded WTR material was determined from fall-cone, shear-vane and TC tests performed over a wide range of water contents in accordance with BS 1377 (BSI, 1990a, 1990b). In the fall-cone tests, s_{ur} was deduced from the measured cone penetration depth (h , mm)

$$6. \quad s_{urFC} = \frac{KQ}{h^2}$$

where Q is the vertical force of 0.785 N, and K is the cone factor.

Koumoto and Houlsby (2001) reported that, from theoretical analysis, $K = 1.33$ gave the dynamic s_{ur} corresponding to the average $\dot{\epsilon}$ of $\sim 1.67 \times 10^4 \%$ /min during penetration of the free-falling 80 g–30° cone used in this study. Karlsson (1981), Wood (1985) and Sharma and Bora (2003) have reported experimentally derived K values, in order, of 0.80, 0.85 and 0.82 using 30° cones with remoulded fine-grained mineral soils. Note that these experimental K values were calibrated against miniature vane data (Wood, 1985) and unconfined TC data (Sharma and Bora, 2003), for which the strain rate was approximately four orders of magnitude lower than that of the fall 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.

In the shear vane tests, a 25 mm by 25 mm cruciform vane was rotated under a vane-head rotation of 9°/min, which produced shear failure around a cylindrical surface enclosing the vane. The test specimen was laterally confined by the vane cup, but under no applied vertical stress, similar to that experienced by the fall-cone specimens. In the TC tests, specimens 38 mm in diameter by 76 mm long were sheared undrained under a confining pressure (σ_3) of 100 kPa at different strain rates ($\dot{\epsilon}$) of 0.0057, 2.0 and 7.8%/min. The shear strength values were determined as half of the peak deviator stress (Figure 6), which had been corrected for the restraining effect of the rubber membrane enclosing the specimen (BS 1377; BSI, 1990b). The triaxial specimens failed by general ductile bulging, with large specimen deformations required to mobilise the peak deviator stress, which is typical of organic soils.

5. Experimental results and analyses

The experimental data for water content and undrained shear strength from the fall-cone, shear-vane and TC tests are presented in a log–log plot in Figure 7. Note that for an initial assessment, dynamic fall-cone s_{ur} values were determined using $K = 1.33$ (Koumoto and Houlsby, 2001) in Equation 6. Also, the reported strength data are for the freshly remoulded material, since the WTR was thixotropic (O'Kelly, 2010; O'Kelly and Quille, 2010). For example, the vane strength was found to increase linearly

Figure 6. Triaxial compression for $\sigma_3 = 100$ kPa, unless otherwise stated

from 4.1 kPa for the remoulded material to 8.1 kPa after a curing period of 143 days (Figure 8), during which time the test material had been allowed to stand, undisturbed, at constant composition ($w \approx 390\%$) and at ambient laboratory temperature.

Unlike the bilinear relationships reported by Sharma and Bora (2003) for mineral soils with similarly high plasticity (bentonite soils with $LL = 210\text{--}460\%$), the $\log w\text{--}\log s_{ur}$ relationship for the WTR material under study was found to be linear, and extended well beyond the measured plastic range, albeit dependent on the method of shear strength measurement. The regression coefficient r values (Table 2) were very close to unity, indicating very strong correlations.

Figure 7. Water content against undrained shear strength from different test methods

Figure 8. Thixotropic behaviour of undisturbed WTR material

As expected, for a given water content, the deduced values of s_{ur} in fall cone and vane shear were different from those measured in TC on account of differences between the shearing modes and rates, applied confining pressure and specimen boundary conditions for the different apparatus. Considering that the WTR material was homogeneous and isotropic, it is reasonable to conclude that the TC s_{ur} was consistently marginally greater than the vane s_{ur} on account of the very different stress levels of the TC and shear vane tests, with a confining pressure of 100 kPa applied in the former. Furthermore, the dynamic s_{ur} deduced from the fall-cone tests was substantially greater than the measured TC s_{ur} on account of the significantly higher $\dot{\epsilon}$ in the fall-cone tests. This is substantiated by the unconfined TC s_{ur} data point plotting marginally below the s_{ur} trend line for the confined TC tests.

Test method	<i>n</i>	<i>w</i> : %	<i>a</i>	<i>b</i>	<i>r</i>
Fall cone (<i>K</i> = 1.33)	7	317–535	625.8	0.207	0.998
Fall cone (<i>K</i> = 0.60)	7	317–535	530.4	0.207	0.998
Fall cone (blended, <i>K</i> = 1.33)	7	340–529	572.6	0.196	0.990
Vane	14	383–581	496.8	0.183	0.991
Vane factored by 1.28	14	383–581	519.8	0.183	0.991
TC (100 kPa, 2%/min)	7	215–298	519.3	0.180	0.988
Vane and TC (100 kPa, 2%/min)	21	215–581	495.4	0.170	0.998

Table 2. Regression analysis of strength relationships

Also, the confined TC s_{ur} value for the higher $\dot{\epsilon}$ of 7.8%/min plotted marginally above the TC s_{ur} trend line for $\dot{\epsilon} = 2.0\%/min$ (Figure 7). The data points for confined TC for the very slow $\dot{\epsilon}$ of 0.0057%/min were also found to plot marginally above the TC s_{ur} trend line for $\dot{\epsilon} = 2.0\%/min$, which is most likely explained by the positive strength contribution due to thixotropic hardening over the course of these long-duration tests (with a time to failure of ~ 3 days) exceeding $\dot{\epsilon}$ effects.

The TC tests under $\dot{\epsilon} = 2.0\%/min$, and with $\sigma_3 = 100$ kPa, were adopted as the benchmark for comparison of the deduced values of s_{ur} in fall-cone and shear-vane tests. Under the specific test conditions in this study, the TC s_{ur} was found to be 1.28 times the deduced vane s_{ur} (Figure 9). Again, for the specific conditions in this study, the values of dynamic fall-cone s_{ur} deduced over the range of $h = 6.4$ – 22.0 mm, using $K = 1.33$ in Equation 6, were ~ 2.2 times the measured TC s_{ur} . The reported $\dot{\epsilon}$ range of 1.48 – $1.92 \times 10^4\%/min$ for $h = 15$ – 25 mm, with an average value of $\sim 1.67 \times 10^4\%/min$ (Koumoto and Houlsby, 2001), was approximately four orders of magnitude greater than that in the 2%/min

TC tests. Hence the factor of 2.2 corresponded approximately to a 30% increase in strength per tenfold increase in strain rate for the WTR material, which is significantly greater than the $\sim 10\%/log \dot{\epsilon}$ cycle typically associated with fine-grained mineral soils (Koumoto and Houlsby, 2001). Furthermore, the experimentally derived $K = 0.60$, necessary to achieve a one-to-one correspondence between the fall-cone data and the 2%/min TC s_{ur} trend line, was significantly lower than the experimental range of $K = 0.80$ – 0.85 (calibrated against either miniature vane or unconfined TC data) reported for the 30° fall cone in remoulded fine-grained mineral soils (Karlsson, 1981; Sharma and Bora, 2003; Wood, 1985).

The saturated remoulded undrained shear strengths, $s_{ur(LL)}$ and $s_{ur(PL)}$, corresponding to the LL and PL conditions respectively, were determined for the WTR material using Equation 7 and the values of coefficients *a* and *b* reported in Table 2.

$$7. \quad s_{ur} = \sqrt[b]{\frac{a}{w}}$$

Figure 9. Correspondence of fall cone (FC) and shear vane with triaxial compression (TC)

At the measured LL value of 513%, the vane $s_{ur(LL)} = 0.84$ kPa, which corresponds to a TC $s_{ur(LL)}$ of $0.84 \times 1.28 = 1.08$ kPa. At the PL value of 268%, the TC $s_{ur(PL)} \approx 39$ kPa for $\dot{\epsilon} = 2\%/min$ and with $\sigma_3 = 100$ kPa. Since the reproducibility of the Casagrande PL method is not as good as that of the fall-cone LL method (Wood, 1990), it is acknowledged that there may inevitably be some inaccuracy in determining the value of $s_{ur(PL)}$ using this approach. These strength values are significantly below the present best estimates of $s_{ur(LL)} \approx 1.7$ kPa (near the lower end of the reported range) and $s_{ur(PL)} = 110\text{--}170$ kPa given for fine-grained mineral soils (e.g. Sharma and Bora, 2003; Stone and Phan, 1995; Wood, 1990). However, the WTR values are consistent with the range of vane $s_{ur(LL)}$ reducing from about 1.9 to about 0.95 kPa, with increasing values of LL from 37% to about 120%, and vane $s_{ur(PL)} = 10\text{--}30$ kPa reported by Zentar *et al.* (2009) for four organic fine-grained soils, although their organic content (LOI = 6.7–9.7%) was significantly lower than that of the WTR material under study. The strength ratio ($R = s_{ur(PL)}/s_{ur(LL)}$) of ~ 36 over the plastic range is also significantly below $R \approx 100$, typically reported for fine-grained mineral soils (e.g. Sharma and Bora, 2003; Skempton and Northey, 1953; Wood, 1990).

6. Conceptual strength model for organic clays

A conceptual model is advanced towards explaining the relatively high values of shear strength mobilised for the WTR material at the extremely high water contents considered in this study, and for amorphous organic soils in general. The model is a development of one originally presented for municipal sewage sludge by Klein and Sarsby (2000), and encompasses the framework presented by Trauner *et al.* (2005) for inorganic fine-grained soils. Trauner *et al.* (2005) considered that the value of s_{ur} depended on the quantity of inter-grain water (comprising the 'free'/pore water and the adsorbed water layer around the external surface of clay mineral particles), but was independent of interlayer water associated with expanding clay minerals, since the latter water fraction is tightly tied between the unit layers of the mineral lattice structure. The model advanced in the present study makes a clear distinction between the influences of two different water fractions. Referring to Figure 10, the value of s_{ur} is considered to be

- dependent on the quantity of water located within the macro-pore spaces between the aggregate flocs (i.e. 'free'/pore water) as well as the adsorbed water layer around the outer surface of the aggregate flocs (these water fractions are collectively categorised as external water)
- independent of the quantity of (a) interstitial water located within the micro-channels and micro-pores of the solid organic matter itself, (b) adsorbed water held around the internal surfaces of the aggregate flocs and (c) chemically bound water as well as any water of hydration (these water fractions are collectively categorised as internal water).

All of the external and internal water (apart from the very small

Figure 10. Types of water in flocculated organic clay (Vesilind and Martel, 1990)

proportions of chemically bound water and water of hydration) evaporates at the standard oven-drying temperature of 105–110°C (O'Kelly, 2005) used for water content determinations. The internal water fraction was relatively high in the case of the WTR material, since high adsorption would have occurred around and within the aggregate floc, particularly on account of the very significant amounts of aluminium hydrolysis species derived from the Chemifloc® alum coagulant (Wang and Tseng, 1993). Hence, considering that the shear strength is exclusively associated with external water (and not the total water evaporated at the standard oven-drying temperature), relatively high values of s_{ur} can be mobilised at extremely high water contents, given that the internal water fraction was relatively high. This hypothesis is supported by the fact that the increase in external water, and corresponding decrease in internal water, achieved by blending the WTR slurry at a given water content value was found to produce a reduction in s_{ur} (Figure 7). However, only a portion of the interstitial water from the internal water fraction was actually released as 'free'/pore water by the mechanical action of the blender, considering the relative scale of the blades compared with the miniscule polymer-reinforced aggregate flocs (O'Kelly, 2011) that constituted the slurry material. A difficulty arises in trying to quantify the relative proportions of external and internal water fractions in organic soils and the changes in these proportions over time, caused by a change in effective stress, and further research is necessary in this regard.

7. Summary and conclusion

Alum WTR material is an amorphous, highly plastic soil comprising aggregate flocs of colloidal organic and clay mineral particles. The $\log w\text{--}\log s_{ur}$ relationship for this material was strongly linear, albeit dependent on the confining pressure (σ_3) and strain rate ($\dot{\epsilon}$), and extended well beyond the measured plastic range. At a given water content, the s_{ur} measured in TC was consistently marginally greater than that deduced in vane shear, with the mobilised strength increasing in value for higher σ_3 or $\dot{\epsilon}$.

Scaling the miniature vane s_{ur} values by 1.28 and using a cone factor $K = 0.60$ for the 30° fall-cone apparatus were found to produce a one-to-one correspondence between the s_{ur} values deduced by fall cone and shear vane with the measured values in TC for $\dot{\epsilon} = 2\%/min$ and with $\sigma_3 = 100$ kPa. This experimental cone-factor value is considerably lower compared with the previously reported range of $K = 0.80$ – 0.85 for similar cones in remoulded fine-grained mineral soils.

The mobilised strength exhibited a high $\dot{\epsilon}$ dependence, with the strength increasing by $\sim 30\%/log \dot{\epsilon}$ cycle increase, significantly greater than the $\sim 10\%$ increase typically associated with fine-grained mineral soils.

The TC s_{ur} values mobilised at the LL and PL conditions were 1.08 and 39 kPa respectively, giving a strength ratio R of ~ 36 over the measured plastic range. These values are substantially below the present best estimates for fine-grained mineral soils. An important observation was that the bulk WTR material could be easily remoulded at water contents significantly below the measured Casagrande PL, indicating that the reported plastic range was notional and, furthermore, that the use of liquidity index as an indicator of this material's consistency is unreliable.

The relatively high s_{ur} values mobilised for the WTR material at extremely high values of water content were explained by considering that the shear strength was governed exclusively by the water fractions located between and around the constituent aggregate flocs, as opposed to the total amount of water that evaporates at the standard oven-drying temperature used for water content determinations.

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