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ASSESSING THE SHEAR STRENGTH OF MUNICIPAL SLUDGES AND RESIDUES FOR LANDFILL DISPOSAL

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ABSTRACT: This paper describes various issues from a geotechnical standpoint concerning the strength of biosolids (sewage sludge) and water-treatment residue (WTR) materials for landfill (monofill) disposal. These materials must be sufficiently dewatered at the municipal works to reduce transportation and landfill-disposal costs, to provide adequate shear strength for efficient handling, placement and trafficability requirements at the landfill site, and for geotechnical stability of the landfill slopes. Topics covered in this paper include: (i) the characteristic behavior and properties of these challenging geomaterials; (ii) undrained strength requirements for landfilling; (iii) in-situ and laboratory strength measurement techniques and interpolation of the strength data; (iv) strength predictions using existing undrained strength–water content correlations. Since these correlations are material specific, with the geotechnical properties of biosolids and WTR materials varying between treatment plants, they generally cannot be applied more widely with confidence. A new (different) approach, which uses a power-law relationship to predict values of remolded undrained strength mobilized for different water contents, is presented.

KEYWORDS: dewatering, landfill, monofill, sludge disposal, strength, water content

1. INTRODUCTION

The principal disposal options for biosolids (sewage sludge) and water-treatment residue (WTR) materials in many parts of the world are: indefinite storage in lagoons (Klein and Sarsby, 2000; Lin et al. 2014; Zhan et al., 2014); volume reduction by mechanical and (or) thermal means followed by landfilling, either at single-purpose monofills (O'Kelly, 2004, 2005b, 2010; Oettle et al., 2016) or co-disposal at municipal solid waste (MSW) landfill sites (Koenig et al., 1996; Lo et al., 2002). Other options include land application as agricultural fertilizer, for composting to produce a humus-like product resembling soil, soil re-development in mine reclamation, in forestry, reuse as a fill material, and as daily cover for landfills. These are challenging and unconventional geomaterials, with very high water and organic contents, low specific gravity of solids (particle density), and exhibit extremely high plasticity, very high

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shrinkage, compressibility and swelling potential, and have very to extremely low hydraulic conductivity (O’Kelly, 2005a, 2006, 2008a, 2016; O’Kelly and Quille, 2009, 2010).

The landfill-disposal route is subject to stringent environmental controls, coupled with rising landfill-gate costs and difficulties in sourcing new landfill sites. Pertinent regulations, including the Council of the European Communities Landfill and Waste Management Directives (1999; 2006), have mainly tended to focus on ensuring that no harmful substances from these landfills reach the biosphere or hydrosphere in unacceptable quantities; hence, the importance of efficient well-maintained landfill biogas-control and leachate-drainage systems. However, landfill disposal of large volumes of these materials may also lead to geotechnical problems, including: (i) excessive differential settlements that may damage the landfill capping layer; (ii) slope instability problems. As discussed by O’Kelly (2004, 2005b, 2010), from a geotechnical standpoint, the biosolids and WTR materials must be adequately dewatered at the municipal works to reduce transportation and landfill-disposal costs and to achieve sufficient shear strength for efficient handling, placement and trafficability requirements at the landfill site, and for geotechnical stability of the landfill slopes.

The dewatered sludge and residue materials are soil-like, and as such, their behavior in lagoons, monofills or MSW landfill sites can be assessed using soil mechanics theory (Wang et al., 1992; Klein and Sarsby, 2000; O’Kelly 2004, 2006, 2010). For instance, the factor of safety against slope instability for the short-term condition (generally critical case) is dependent, among other factors, on the undrained shear strength (s_u) of the in-situ material. The effect of ongoing biodegradation on the engineering behavior of the landfilled materials can be significant and must also be considered (O’Kelly, 2006, 2008a, 2013b).

Provided excess pore-water and pore-gas pressures generated within the landfill body can readily dissipate, the factor of safety value on slope instability generally increases with elapsed time due to the gain in shear strength as a result of thixotropic hardening (Wang et al., 1992; O’Kelly, 2010; O’Kelly and Quille, 2010) and consolidation of the landfilled material (O’Kelly, 2005a, 2008a). For example, Cao et al. (2006) reported that the values of undrained shear strength of a sewage sludge material of slurry consistency that was allowed to stand undisturbed for periods of 5 and 15 days before performing the strength tests were ~ 2 kN/m^2 and 14 kN/m^2, respectively. The intermediate and long-term factors of safety against geotechnical instability are assessed using an effective-stress slope stability analysis.

2. CRITERIA FOR LANDFILLING OF BIOSOLIDS AND WTR MATERIALS FROM GEOTECHNICAL STANDPOINT

Pertinent guidelines (e.g. Council of the European Communities Landfill and Waste Management Directives 1999, 2006) preclude MSW landfill operators from accepting sludge materials having a gravimetric water content greater than 300% (solids content, SC < 25%); set as an indirect guide to the minimum shear strength required for efficient handling, placement of the material in a landfill and its geotechnical stability. The water content affects the size of the treatment and disposal facilities necessary, transportation costs, the size and life span of the landfill (monofill), and the amount of leachate formation in the landfill.

The water content, used in the geotechnical literature, is defined as the mass of the pore water to the mass of the dry solids, expressed as a percentage. The solids content, defined as the mass of the dry solids to the bulk mass, can be related to the water content (w, as %) by:

$$\text{SC (as \%)} = \frac{100}{1 + w/100} \tag{1}$$

The definitive method for the determination of the water content (or SC) of a representative test-specimen is the oven-drying method, with standardized oven-drying temperature ranges of 105–110°C (ASTM, 2007) or 105±5°C (BSI, 1990a). O'Kelly (2014b) and O'Kelly and Sivakumar (2104) discussed the pros and cons of adopting lower oven-drying temperatures in the range 35−90°C (instead of the standardized temperature ranges) for water content determinations on organic soils, including municipal sludge and residue materials, in order to prevent possible charring, oxidation and (or) vaporization of substances other than water from the test specimen. From a comprehensive experimental investigation, they concluded that for routine water content determinations on these materials, the standardized oven-drying temperature range of 105–110°C or 105±5°C should be consistently used in conjunction with a 24-h drying period and a minimum wet specimen mass of 50 g.

In practice, the maximum 300% water content requirement (SC < 25%) is generally an unreliable guide to the minimum shear strength for landfilling from a geotechnical standpoint (O'Kelly, 2010, 2013c; O'Kelly and Quille, 2010). As discussed in O'Kelly (2010) and O'Kelly and Quille (2010), no universal relationship exists for geomaterials between the water content and the undrained shear strength, which is also dependent on a range of other factors. For biosolids and WTR materials, these include:

- Natural differences in the composition of the suspended solids in the raw (source) waters which effect the mineralogical composition and organic content of the sludge/residue by-product (O'Kelly, 2006, 2010; O'Kelly and Quille, 2009, 2010);
- The types and levels of treatments, including amounts of chemicals (coagulants, polyelectrolytes and conditioners) added (O'Kelly, 2011), to separate out the sludge/residue by-product at the municipal works;
- The method of strength measurement (O'Kelly, 2013b, 2013c, 2014a).

For example, from a review of the undrained strength against water content data presented by Novak and Calkins (1975), Wang et al. (1992), Wichmann and Riehl (1997) and O'Kelly (2008b), O'Kelly and Quille (2010) found that the undrained shear strength of alum-coagulated WTR materials can range between 6 and 80 kPa at the limiting 300% water content value requirement for landfilling.

Hence, it is widely acknowledged that landfill operators specify a minimum undrained shear strength value based on sound geotechnical considerations, rather than the requirement for a maximum water content value of 300%, in determining the acceptance of sludge and residue materials for landfill disposal (Wichmann and Riehl, 1997; O'Kelly, 2004, 2005b, 2010; O'Kelly and Quille, 2010; Environment Agency (UK), 2010).

From a geotechnical standpoint, minimum shear strengths of 20 kPa (Loll, 1991) and 25 kPa (Siedlungsabfall, 1993; Wichmann and Riehl, 1997) have been recommended in the past for municipal sludge and residue materials co-disposed at MSW landfills. These materials were typically placed in thin layers and mixed and scarified in-situ with the MSW material, which had the effect of reducing their water content, thereby increasing their shear strength. For dedicated monofills, higher undrained shear strength of typically 50 kPa have been recommended for trafficability requirements (landfill compactors and dump trucks) and to achieve an adequate factor of safety against instability of the landfill slopes (O'Kelly, 2004, 2005b, 2010; O'Kelly and Quille, 2010). Increasingly, there is a tendency to require a minimum in-situ undrained strength value of 50 kPa (Environment Agency (UK), 2010) for these materials in order to meet both environmental and geotechnical considerations.

As described by O'Kelly (2010) and O'Kelly and Quille (2010), the required level of dewatering necessary to achieve these strength values can be produced at the treatment works using recessed-plate filter press and belt-dryer devices. In general, the belt press device cannot by itself reduce the water content sufficiently. The belt-dryer device mechanically dewaters the slurry material under an applied stress of 800–1000 kPa, followed by full or partial drying of the pressed cake at low temperatures. Alternatively, thermal treatment or soil-conditioning techniques (Kayser et al., 2011; Disfani et al., 2015) may be used to dewater very soft biosolids and WTR materials sufficiently and expeditiously.

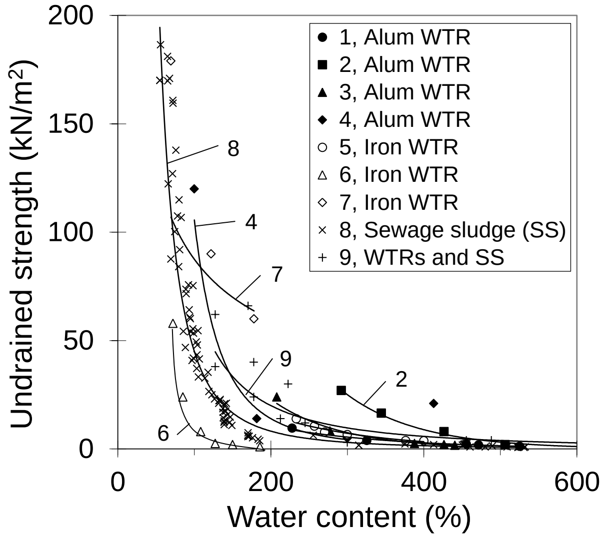
The principal approaches for the determination of the shear strength of dewatered sludge and residue materials employ fall cone, vane shear, pocket penetrometer, direct shear, and triaxial compression apparatuses. The shear vane and fall-cone apparatus (see BSI (1990a, b)) are particularly attractive for operators of municipal water/wastewater treatment works and landfills since these mechanical tests can be performed relatively quickly, both in laboratory (Klein and Sarsby, 2000; Kayser et al., 2011; O'Kelly, 2006, 2013c, 2014a) and field (Voß, 1993; Zhan et al., 2014) settings, to produce reasonably accurate results (O'Kelly, 2006; O'Kelly and Quille, 2010). The field vane is particularly useful in determining the in-situ strength profile with depth of the deposit (Zhan et al., 2014).

However, relating the strength values determined using different apparatus, and for different test conditions, is often not straightforward (O'Kelly, 2013b, 2013c, 2014a; Oettle et al., 2016) since the different strength measurement apparatus approach the estimation of strength in different ways. For instance, in vane shear, the mobilized strength value is dependent on the vane size, its aspect ratio and the time to reach shear failure, which is a function of the torsional stiffness of the spring in the vane apparatus, the speed of the drive motor to the vane shaft and the undrained shear strength of the test material (O'Kelly, 2013b, 2013c). The effects of differences in the shearing mode, strain rate, specimen confinement pressure and boundary conditions on the mobilized strength value have been investigated for biosolids materials by Kayser et al. (2011) and O'Kelly (2013b, 2013c) and for WTR materials by O'Kelly (2010, 2014a). Compared with inorganic soils, biosolids and WTR materials typically have much higher strain rate dependence (Kayser et al., 2011; O'Kelly, 2014a).

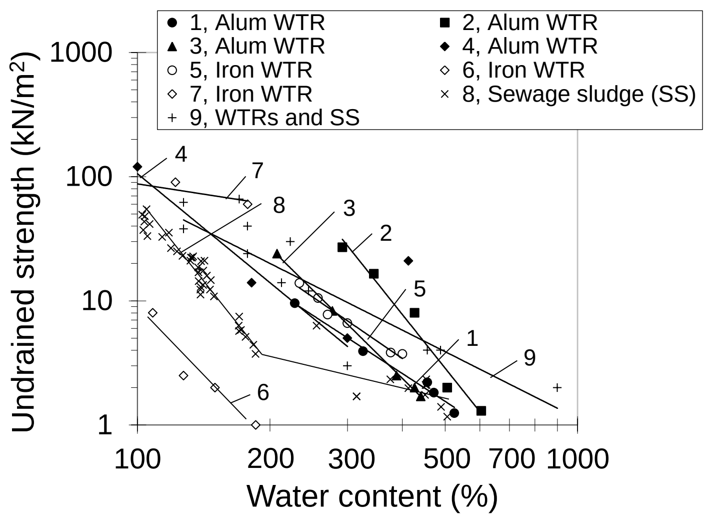
Further, a significant feature of the strength properties of biosolids (sewage sludge) material of slurry and very soft consistencies is its viscous gel-like pore fluid, caused by the high concentration of dissolved solids, high bonding or adsorption of the liquid phase within and around the aggregate flocs, and some form of biological coagulation between the pore fluid and organic solids (Klein and Sarsby, 2000; Sarsby, 2005; O'Kelly, 2008a, 2013c). Hence, the interpretation of fall-cone data for undrained strength measurement may not be straightforward, particularly for biosolids material of slurry consistency (Klein and Sarsby, 2000), on account of the very high strain rates produced during the strength test by the falling cone.

3. UNDRAINED STRENGTH–WATER CONTENT RELATIONSHIPS

Various relationships have been proposed for estimating the remolded undrained shear strength from measured values of water content, often in combination with the liquid limit (LL) and plastic limit (PL) values, with the principal relationships reviewed by O'Kelly (2013a). Many of them assume a one-hundredfold strength variation between the water content values corresponding to the LL and PL conditions, but O'Kelly (2013a) emphasized that there is no theoretical basis for this; rather the value of the strength gain with reducing water content between the LL and PL has been shown to vary over a wide range when many different soils are considered (Nagaraj et al., 2012; Haigh et al., 2013; O'Kelly, 2013a, 2015a). This is particularly true for organic soils, including the municipal sludge and residue materials under consideration in this paper, for which the value of the strength gain between the LL and PL has been found to be significantly less than the assumed value of 100 (Zentar et al., 2009; O'Kelly, 2013a, 2014a, 2015a). Hence, when applied to organic soils, these type of correlations would significantly overestimate the undrained strength.



(a) Adopted from O'Kelly B.C. (2010). Landfill disposal of alum water treatment residues: some pertinent geoengineering properties. Residuals Science and Technology, 7(2): 95–113.



(b) Adopted from O'Kelly B.C. and Quille M.E. (2010). Shear strength properties of water treatment residues. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, 163(1): 23–35.

Figure 1. Undrained shear strength–water content correlations for municipal sludges and residues: 1 and 5, Novak and Calkins (1975); 2, 3 and 6, Wang et al. (1992); 4 and 7, Wichmann and Riehl (1997); 8, O'Kelly (2006); 9, Geuzens and Dieltjens (1991).

Undrained shear strength–water content correlations have been presented by numerous researchers for specific biosolids (sewage sludge) and WTR materials tested (see Figure 1). However, as evident from Figure 1, these correlations generally cannot be applied more widely with confidence to other biosolids and WTR materials since their geotechnical properties (undrained strength) are dependent on natural differences in the composition of the suspended solids in the raw (source) waters, which effect the mineralogical composition and organic content of the sludge/residue by-product as well as the types and levels of treatments, including amounts of chemicals added, to separate out the sludge/residue by-product at the municipal works (O'Kelly, 2006, 2010; 2011, 2013b, 2013c, 2014a; O'Kelly and Quille, 2009, 2010).

Further, as described in O'Kelly (2013a), it has been well documented that for geomaterials, the undrained strength against water content (see Figure 1(a)) and logarithm of undrained strength against water content relationships are both highly non-linear, exhibiting concave curvatures. However, when plotted on a bi-logarithmic plot (see Figure 1(b)), the undrained strength against water content relationship has been shown to be linear over the full plastic range, including for organic soils (Zentar et al. 2009; O'Kelly 2014a).

Voß (1993) presented an empirical relationship (Equation 2) between in-situ vane shear strength (s_u, in kN/m^2) and the bulk density (ρ, in Mg/m^3) for monofilled sewage sludge materials, which predicts strengths in the general range of 1 to 50 kN/m^2 as the bulk density of the material increases from 1.0 to 1.25 Mg/m^3.

$$s_u = 2.09 \times 10^{-8} \exp^{17.5\,\rho} \qquad (2)$$

Klein and Sarsby (2000), citing the work of Voß (1993), reported that Equation (2) gave a reasonable representation of laboratory vane strength data they obtained for 'fresh', very high water content, sewage sludge material (i.e. very soft to soft in consistency). [Note that this equation was not reported correctly in the Klein and Sarsby paper]. They concluded that bulk density appeared to be a better indicator of the shear strength behavior for soft sewage sludge material (than using just water content or fiber/solid ratio) since it encompasses the effects of both void ratio (its pore fluid has essentially zero shear strength) and fiber/solids content (the fibers provided little frictional shear strength at very high water content). However, using laboratory vane strength data reported in O'Kelly (2006) for sewage sludge material (having an LL of 315%, PL of 55%, particle density (specific gravity of solids) of 1.55 Mg/m^3 and total volatile solids value of 70%), the author has found that apart from $s_u < 7$ kN/m^2, Equation 2 does not give a reasonable representation of the data, significantly under-predicting the mobilized strength values (see Figure 2). Again, this demonstrates that undrained strength–water content correlations derived for specific sewage sludge (biosolids) or WTR materials generally cannot be applied with confidence to other sewage sludge and WTR materials, for the reasons explained earlier in the paper.

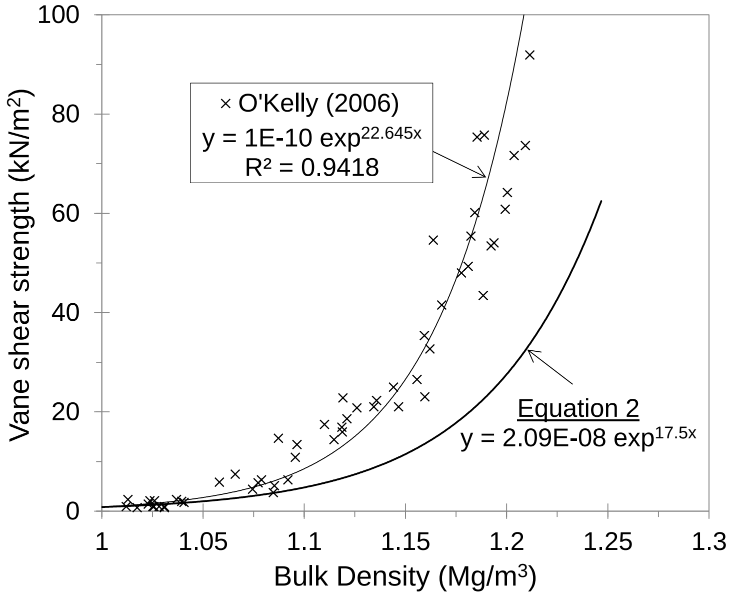


Figure 2. Laboratory vane-shear strength – bulk density correlation for sewage sludge material. Adopted from O'Kelly B.C. (2006) Geotechnical properties of municipal sewage sludge. Geotechnical and Geological Engineering, 24(4): 833–850.

O'Kelly (2013a) presented a new (different) approach in which a power-law relationship is used to predict values of remolded undrained strength mobilized for different water contents. This approach does not have the inherent limitations of many of the existing undrained strength–water content relationships; namely, it does not rely on empirical strength values associated with the LL and PL conditions, nor does it rely on a predetermined (fixed) value for the strength variation that occurs over the plastic range, which has been shown to be a fallacy when considering a range of different soils (Nagaraj et al., 2012; Haigh et al., 2013; O'Kelly, 2013a, 2015a).

As described by O'Kelly (2013a), in applying the new method to predict the undrained shear strength of a specific soil material at different water content values, control data are obtained for the specific soil under examination from direct strength measurements (e.g. using shear-vane apparatus) of two test-specimens prepared at different water contents, but ideally close to the LL and PL conditions, so as to cover a wider range of water contents. From the strength and corresponding water content measurements for these two test-specimens, the remolded undrained shear strength (s_{ur}) value of this soil material can be deduced for any particular value of water content (w_n) within the plastic range, as:

$$\log s_{ur} = (1 - W_{LN})\left(\log \frac{s_{ur2}}{s_{ur1}}\right) + \log s_{ur1} \qquad (3)$$

where s_{ur1} and s_{ur2} are the measured undrained strength values (with corresponding water content values of w_1 and w_2) and W_{LN} is the relative water-content parameter given by:

$$W_{LN} = \frac{\log w_n - \log w_2}{\log w_1 - \log w_2} \qquad (4)$$

Full details on the development of this method and its application in determining the remolded undrained strength of geomaterials are presented in O'Kelly (2013a).

4. SUMMARY AND CONCLUSIONS

Biosolids (sewage sludge) and WTR materials are difficult, challenging and unconventional geomaterials. Since biosolids and WTR materials obtained from different treatment plants exhibit different geotechnical behavior and properties, experimental undrained strength–water content correlations determined for a specific biosolids or WTR material cannot generally be applied more widely with confidence.

Further, the undrained strength of these materials can vary widely (e.g. from 6 to 80 kN/m2 for a range of different alum WTR materials considered in the present study) at the 300% maximum water content value specified in some landfill guidelines, such that this requirement also cannot generally be used with confidence in establishing threshold strength values for various geotechnical reasons. Hence, landfill operators should specify minimum values of undrained shear strength based on sound geotechnical considerations (rather than maximum water content) in determining the acceptance of sludge and residue materials for landfill disposal.

A new (different) approach to predicting values of remolded undrained strength mobilized for different water contents was presented. In assessing a specific soil material, the method requires two pairs of strength and water content measurements (these act as controls), and once these have been obtained, the remolded undrained strength corresponding to different (measured) water contents can be predicted, with confidence, using the power-law relationship employed.

REFERENCES

ASTM (2007). Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils, D2974-07a. ASTM International, West Conshohocken, PA, USA.

BSI (1990a). BS EN 1377: Part 2. Methods of Test for Soils for Civil Engineering Purposes (Classification Tests). British Standards Institution, Milton Keynes, UK.

BSI (1990b). BS EN 1377: Part 7. Methods of Test for Soils for Civil Engineering Purposes — Shear Strength Tests (Total Stress). British Standards Institution, Milton Keynes, UK.

Cao Y.H., Yan S.W. and Yang C.M. (2006). Test on methods to solidify wastewater sludge (in Chinese). Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/Journal of Tianjin University Science and Technology, vol. 39, n. 2, pp. 199–203.

Council of the European Communities (1999). Council Directive 1999/31/EC of 26th April 1999 on the Landfill of Waste. Official Journal of the European Communities, 1999, L182, pp. 1–19.

Council of the European Communities (2006). Council Directive 2006/12/EC of the Council of 5th April 2006 on Waste. Official Journal of the European Communities, 2006, L114, pp. 1–13.

Disfani M.M., Arulrajah A., Maghoolpilehrood F., Bo M.W. and Narsilio G.A. (2015). Geotechnical characteristics of stabilised aged biosolids. Proceedings of the Institution of Civil Engineers – Environmental Geotechnics, vol. 2, n. 5, pp. 269–279.

Environment Agency (UK) (2010). Waste Acceptance at Landfills. Environment Agency, Bristol, UK. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296422/geho1110btew-e-e.pdf (accessed 16/10/2015).

Geuzens P. and Dieltjens W. (1991). Mechanical strength determination of cohesive sludges: a Belgian research project on sludge consistency. In Recent Developments in Sewage Sludge Processing, Colin, Newman and Puolanne (Eds), Elsevier, London, pp. 14–23.

Haigh S.K., Vardanega P.J. and Bolton M.D. (2013). The plastic limit of clays. Géotechnique, vol. 63, n. 6, pp. 435–440.

Kayser C., Larkin T. and Singhal N. (2011). Enhancement of the shear strength of wastewater residuals using industrial waste by-products, Journal of Environmental Engineering, ASCE, vol. 137, n. 11, pp. 1002–1011.

Klein A. and Sarsby R.W. (2000). Problems in defining the geotechnical behaviour of wastewater sludges. In Geotechnics of High Water Content Materials, Edil and Fox (Eds), ASTM, West Conshohocken, PA, USA, ASTM STP 1374, pp. 74–87.

Koenig A., Kay J.N., Wan I.M. (1996). Physical properties of dewatered wastewater sludge for landfilling, Water Science and Technology, vol. 34, n. 3–4, pp. 533–540.

Lin W., Zhan X., Zhan T.L., Chen Y., Jin Y. and Jiang J. (2014). Effect of FeCl3-conditioning on consolidation property of sewage sludge and vacuum preloading test with integrated PVDs at the Changan landfill, China. Geotextiles and Geomembranes, vol. 42, n. 3, pp. 181–190.

Lo I.M.C., Zhou W.W. and Lee K.M. (2002). Geotechnical characterization of dewatered sewage sludge for landfill disposal. Canadian Geotechnical Journal, vol. 39, n. 5, pp. 1139–1149.

Loll U. (1991). Measurement of laboratory vane shear strength as community standard or reference method for testing the suitability of dewatered sludges for use as landfill. In Treatment and Use of Sewage Sludge and Liquid Agricultural Wastes, L'Hermite (Ed.), Elsevier, London, pp. 310–315.

Nagaraj H.B., Sridharan A. and Mallikarjuna H.M. (2012). Re-examination of undrained strength at Atterberg limits water contents. Geotechnical and Geological Engineering, vol. 30, n. 4, pp. 727–736.

Novak J.T. and Calkins D.C. (1975). Sludge dewatering and its physical properties. Journal of the American Water Works Association, vol. 67, n. 1, pp. 42–45.

Oettle N.K., O'Kelly B.C. and Ramos J.A. (2016). Shear strength of biosolids for monofill design. Waste Management (under review for possible publication).

O'Kelly B.C. (2004). Geotechnical aspects of sewage sludge monofills. Proceedings of the Institution of Civil Engineers – Municipal Engineer, vol. 157, n. 3, pp. 193–197.

O'Kelly B.C. (2005a). Consolidation properties of a dewatered municipal sewage sludge. Canadian Geotechnical Journal, vol. 42, n. 5, pp. 1350–1358.

O'Kelly B.C. (2005b). Sewage sludge to landfill: some pertinent engineering properties. Journal of the Air and Waste Management Association, vol. 55, n. 6, pp. 765–771.

O'Kelly B.C. (2006). Geotechnical properties of municipal sewage sludge. Geotechnical and Geological Engineering, vol. 24, n. 4, pp. 833–850.

O'Kelly B.C. (2008a). Effect of biodegradation on the consolidation properties of a dewatered municipal sewage sludge. Waste Management, vol. 28, n. 8, pp. 1395–1405.

O’Kelly B.C. (2008b). Geotechnical properties of a municipal water treatment sludge incorporating a coagulant. Canadian Geotechnical Journal, vol. 45, n. 5, pp. 715–725.

O’Kelly B.C. and Quille M.E. (2009). Compressibility and consolidation of water treatment residues. Proceedings of the Institution of Civil Engineers – Waste and Resource Management, vol. 162, n. 2, pp. 85–97.

O’Kelly B.C. (2010). Landfill disposal of alum water treatment residues: some pertinent geoengineering properties. Residuals Science and Technology, vol. 7, n. 2, pp. 95–113.

O’Kelly B.C. and Quille M.E. (2010). Shear strength properties of water treatment residues. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, vol. 163, n. 1, pp. 23–35.

O’Kelly B.C. (2011). Effects of aluminum sulfate and polyelectrolyte solutions on the geotechnical properties of organic clay. Soils and Foundations, vol. 51, n. 2, pp. 359–367.

O’Kelly B.C. (2013a). Atterberg limits and remolded shear strength–water content relationships. Geotechnical Testing Journal, vol. 36, n. 6, pp. 939–947.

O’Kelly B.C. (2013b). Discussion of “Enhancement of the shear strength of wastewater residuals using industrial waste by-products”. Journal of Environmental Engineering, ASCE, vol. 139, n. 2, pp. 312–315.

O’Kelly B.C. (2013c). Undrained shear strength–water content relationship for sewage sludge. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, vol. 166, n. 6, 576–588.

O'Kelly B.C. (2014a). Characterisation and undrained strength of amorphous clay. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, vol. 167, n. 3, pp. 311–320.

O’Kelly B.C. (2014b). Drying temperature and water content–strength correlations. Proceedings of the Institution of Civil Engineers – Environmental Geotechnics, vol. 1, n. 2, pp. 81–95.

O’Kelly B.C. and Sivakumar V. (2014). Water content determinations for peat and other organic soils using the oven-drying method. Drying Technology, vol. 32, n. 6, pp. 631–643.

O’Kelly, B.C. (2015a). Atterberg limits are not appropriate for peat soils. Proceedings of the Institution of Civil Engineers – Geotechnical Research, vol. 2, n. 3, pp. 123–134.

O'Kelly BC (2016) Laboratory permeability determinations for biosolids. Proceedings of the Institution of Civil Engineers, Environmental Geotechnics, vol. 3, n. 3, pp. 132–139.

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

Siedlungsabfall T.A. (1993). Dritte Allgemeine Verwaltungsvorschrift zum Abfallgesetz. Bundesanzeiger (Third General Administrative Provision on the Waste Management Act. Federal Gazette), Munich, Germany.

Voß T. (1993). Beitrag zur Festigkeitsentwicklung von Klärschlämmen in Monodeponien (Contribution to the Strength Development of Sludges in Mono-Disposal Sites). PhD thesis, Kassel University, Kassel, Germany.

Wang M.C., Hull J.Q., Jao M., Dempsey B.A. and Cornwell D.A. (1992). Engineering behavior of water treatment sludge. Journal of Environmental Engineering, ASCE, vol. 118, n. 6, pp. 848– 864.

Wichmann K. and Riehl A. (1997). Mechanical properties of waterwork sludges — shear strength. Water Science and Technology, vol. 36, n. 11, pp. 43–50.

Zentar R., Abriak N.-E. and Dubois V. (2009). Fall cone test to characterize shear strength of organic sediments. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, vol. 135, n. 1, pp. 153–157.

Zhan T.L., Zhan Z., Lin W., Luo X. and Chen Y. (2014). Field and laboratory investigation on geotechnical properties of sewage sludge disposed in a pit at Changan landfill, Chengdu, China. Engineering Geology, vol. 170, pp. 24–32.