Landfill Disposal of Alum Water Treatment Residues: Some Pertinent Geoengineering Properties

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ABSTRACT: This paper presents the geoengineering properties of the alum water treatment residues derived from the production of potable water at three different municipal works, including the effects of catchment geology; chemical additives; and thixotropic hardening phenomena, with reducing water content (increasing solids content) from the viscous slurry state to the semisolid state. The geoengineering behavior was akin to that of high-plasticity organic clays, with low values of bulk and dry density and high compressibility, although the consolidation rate was low (hydraulic conductivity of the order of 10^{-4}–10^{-6} m/day). The data presented in this paper can be used to determine the level of dewatering necessary for more efficient landfill disposal, including the anticipated amounts and rates of settlement and the factor of safety against geotechnical instability of the residue slopes for the short- and long-term conditions. It is recommended that sludge and residues should be dewatered to achieve minimum shear strengths of 20 and 50 kPa for geotechnical stability at municipal landfills and dedicated monofills, respectively.

INTRODUCTION

WATER treatment residues (WTRs) are the gelatinous slurry by-products from the treatment processes used in the production of potable water at municipal works. The WTRs comprise sand, silt and clay particles, colloidal organic matter, and chemicals (coagulants, polyelectrolytes and conditioners) that have been added to the source water during the treatment processes. Chemical coagulation using ferric chloride, or more generally using aluminum sulfate (alum), causes the colloidal particles (i.e. less than 1 μm in size) that are suspended in the water entering the treatment plant to aggregate into flocs that settle out more readily under gravity. The residue is characterized as alum or iron WTR depending on the coagulant type used. Polyelectrolytes are synthetic long-chained organic molecules that act as binding agents, thereby increasing the inherent shear strength of the newly-formed flocs, and hence the viscosity of the slurry residue [1,2]. Conditioners including sulfuric acid, bentonite, calcium or sodium hydroxide, and sodium silicate may also be added, depending on the nature of the source water, in order to improve the polyelectrolyte performance.

Increasing quantities of WTRs are being produced worldwide annually due to the increasing demand for potable water and more stringent regulations: for example, the European Union Drinking Water Directive [3]. Currently, the principal disposal options are: (1) storage, often over an indefinite period, in sludge lagoons; (2) dewatering by mechanical and/or thermal means, followed by landfilling of the residue cake, either at dedicated monofills or co-disposal at municipal landfills; (3) incineration. However, more stringent regulation (for example by the US EPA [4] and the European Union [5,6]) has placed greater restrictions on these disposal options, principally to minimize environmental impacts. Landfill disposal of large volumes of soft residues may also lead to geotechnical problems, including slope instability and excessive differential settlement that may damage the landfill capping layer. Hence, the slurry residue must be adequately dewatered at the municipal works by mechanical and/or thermal means, or by allowing the slurry to dry naturally in drying beds.

In this paper, the amount of water within the pore space of the residue materials was quantified in terms of the water content (w), defined in the geotechnical literature as the mass of the pore water to the mass of the dry solids, expressed as a percentage. The water content is one of the most commonly determined parameters in

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characterizing geoengineering behavior and is generally determined using the oven drying method, with the dry solids mass corresponding to the residual mass after oven drying the test specimen at 105 ± 5°C for a period of 24 h. Oven drying removes the free water in the pore space between the flocs; the internal water in the micro-channels within the flocs; and the pores within the constituent solid particles themselves [7]. Bound water in the form of water of hydration and adsorbed water held on the surface of the solid particles by electrical attraction are considered to be part of the solids and can not be removed by oven drying. The solids contents (*SC*), defined in the water-treatment literature as the mass of the dry solids fraction expressed as a percentage of the bulk wet mass, can be related to the water content by

$$SC = \frac{100}{1 + \left(\frac{w}{100}\right)} \tag{1}$$

Geoengineering Properties of Alum WTRs from the Literature

Table 1 lists some typical geoengineering data reported for alum WTRs in the literature [8–16]. Alum WTRs have very high Atterberg liquid and plastic limits; a relatively low specific gravity of solids; high total volatile solids (*TVS*); and are classified as high-plasticity organic clays. The wet residue, direct from the treatment works, has a low bulk density of 1.0–1.2 tonne/m^3.

Figure 1 shows data for shear strength against water content for some alum and iron WTRs, and also municipal sewage sludge. There is a significant variation in the shear strength value of these materials at a given water content, which is expected, due to the natural variability of the source waters and hence the mineralogy and organic content of the suspended solids. Different types and levels of chemical treatment, and also biological treatment in the case of the sewage sludge, had been applied in order to separate the residue by-products at the municipal works. In general, alum WTR tends to have slightly higher shear strength than iron WTR at a given water content, and both alum and iron WTRs tend to have higher shear strengths than sewage sludge.

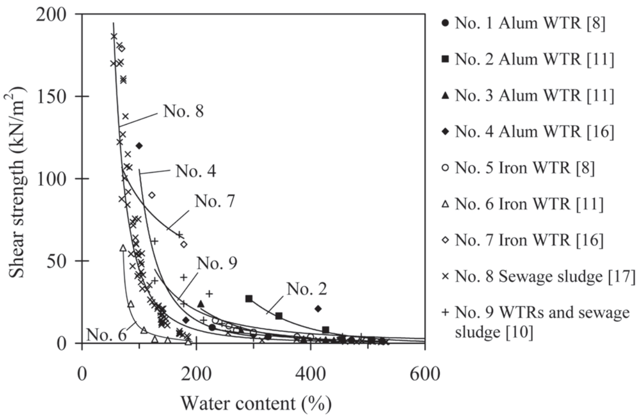


Figure 1. *Shear strength against water content data for WTR and sewage sludge materials.*

Table 1. Typical Geoengineering Properties of Alum WTRs.

Parameter	Value
Liquid limit, %	100–550
Plastic limit, %	80–250
Specific gravity of solids	1.8–2.2
Total volatile soilds, %	10–60
Bulk density, tonne/m^3	1.0–1.2
Dry density, tonne/m^3	0.12–0.36
Effective cohesion, kPa	0
Effective angle of shearing resistance, degree	28–44

Wet alum WTR is thixotropic, with Wang et al. [11] reporting strength gains (ratio of the shear strength measured after a specified curing period to the remolded shear strength, under constant external conditions and specimen composition) of 5.7–8.0 achieved after a ten-week curing period and for *SC* = 10–20%. The effective angle of shearing resistance (ϕ') values of 28–44° reported for alum WTRs are towards the upper end of the range normally associated with high-plasticity organic clays, although consistent with $\phi' = 32–37°$ reported for municipal sewage sludge (*TVS* = 70–50%) [17,18].

Alum WTR has a very low hydraulic conductivity, which reduces in value from typically 10^{-4} to 10^{-6} m/day, with increasing effective stress from 2 to 540 kPa [12]. Note that the effective stress (σ'), which acts across the contacts between the solid particles, is defined as the difference between the total/applied stress (σ) and the excess pore water pressure in the saturated pore voids.

Volume Change Theory

Residues and sludge are soil-like materials and, as such, their settlement behavior in lagoons, monofills or dedicated deposition areas at municipal landfills can be assessed using soil mechanics theory [18], and a more comprehensive explanation of the following can be obtained in undergraduate soil mechanics textbooks, including Craig [19].

The settlement due to a change in the state of effective stress comprises two components: primary consolidation (ΔH_c) and secondary compression (ΔH_s). Primary consolidation can be described by classical 1–D consolidation theory, whereby the change in the residue volume corresponds to the change in the volume of the pore water, assuming fully saturated conditions. The void ratio (*e*) is defined as the volume of the pore voids to the volume of the solids and, referring to Figure 2, the change in the void ratio (*e*) can be predicted by

$$\Delta e = C_c \log \frac{\sigma'_{vo} + \Delta\sigma'_v}{\sigma'_{vo}} \tag{2}$$

where

C_c = compression index (gradient of the void ratio against logarithm of effective stress curve)
σ'_{vo} = initial vertical effective stress
σ'_v = increase in vertical effective stress (i.e. applied stress)

Wet alum WTR is highly compressible. For example, very high compression index values of C_c = 5.3–6.7 were reported for alum WTR that had been dewatered using a centrifuge and sand-drying method [11]. The primary consolidation settlement, which is due to the dissipation of the excess pore water pressure, can be estimated as

$$\Delta H_c = H_o \frac{\Delta e}{1 + e_o} = H_o \frac{C_c}{1 + e_o} \log \frac{\sigma'_{vo} + \sigma'_v}{\sigma'_{vo}} \tag{3}$$

where

e_o = initial void ratio
H_o = initial thickness of the saturated residue layer

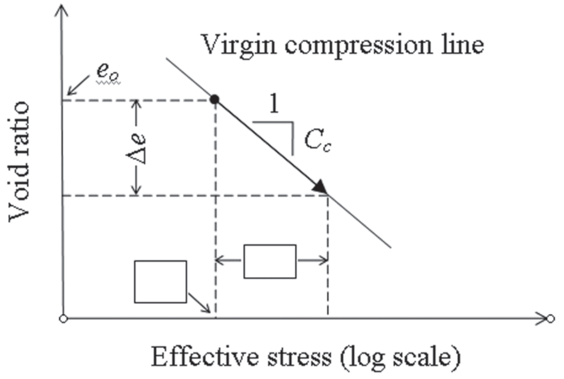


Figure 2. *Theoretical consolidation plot.* Note: e_O, *initial void ratio;* σ'_{vo}, *initial vertical effective stress;* Δe, *change in void ratio due to a change in the vertical effective stress,* $\Delta\sigma'_v$; C_C, *compression index.*

Secondary compression (creep) settlement, which is due to the gradual rearrangement and compression of the solids (residue flocs) into a more stable configuration under the increased effective stress, is a time dependent process that can be expressed by

$$\Delta H_s = H_o C_{\text{sec}} \log \frac{t_1}{t_2} \tag{4}$$

where

C_{sec} = coefficient of secondary compression
t_1 = time period to achieve substantial completion of the primary consolidation phase
t_2 = time period that extends into the secondary compression phase ($t_2 > t_1$).

Objectives of this Study

The objectives of this paper are to study the geoengineering and hydraulic properties of alum WTRs derived from different catchments, and in particular to study the effects of several influencing factors: catchment geology; chemical additives; and thixotropic hardening phenomena. Geotechnical recommendations are made regarding the safe and efficient disposal of these residues in engineered landfills. In addition, pertinent data are presented that can be used to calculate the factor of safety against instability of the landfill slopes and the time-dependent settlement response.

TEST MATERIALS

Alum WTRs were sourced from three of the larger municipal water treatment plants in Ireland: the Ballymore Eustace and Leixlip works in County Kildare, and the Clareville works in County Limerick, which produce about 91, 73 and 62 Mm^3 of potable water per annum respectively, and taken together account for almost 30% of the potable water produced in Ireland. The raw water entering these treatment plants is sourced from three different catchments, thereby providing a good overall representation of the alum WTRs produced in the country. The residues are coagulated at these municipal works using Chemifloc 4140® alum, supplied in its hydrated form [i.e. $Al_2(SO_4)_3 \cdot 14H_2O$], and Magnafloc LT25® polyelectrolyte, which are manufactured by Allied Colloids and Ciba Zietag. The combined dosages (given as mg/l source water) that had been added during the different treatment processes are

Table 2. Chemicals Added During the Treatment Processes.

	Hydrated Alum	Polyelectrolyte		Dry H_2SO_4
Residue	mg/l	mg/l	Mean % Dry Residue Mass	mg/l
WTR 1	40–65	0.6–1.5	3.5	0
WTR 2a	60–100	0.8–2.0	4.8	0.5
WTR 2b	0	0	0	0
Control	40–60	0.2–1.0	1.6	0

listed in Table 2, with the range of values reflecting the necessary adjustments to the dosage appropriate to the level of turbidity of the incoming source water. These dosages were broadly similar and are at the higher end of the ranges normally used in practice, since the source waters were all medium high in turbidity. Also listed in Table 2 are the polyelectrolyte concentrations, expressed as a percentage dry solids mass of the residue by-product at the different works. These mean concentration values were calculated on the basis of the annual production of potable water, the mass of dry solids residue produced per annum, and the mean polyelectrolyte dosages as mg/l source water at the different works, assuming that all of the polyelectrolyte additives were retained in the residues.

Alum WTR 1 Sample

The alum residue from the Ballymore Eustace works (WTR 1) was derived from the treatment of medium color, medium-turbidity water sourced from the Dublin and Wicklow mountains (upland catchment of peat over granite bedrock) and which had been stored in Poulaphouca reservoir, County Wicklow, prior to its treatment. The slurry residue was dewatered using a recessed-plate filter press device under an applied stress of 1500 kPa, with about 1200 tonnes of the wet alum residue ($SC = 23\%$) produced at the treatment works in 2007. Samples of the pressed residue cake were obtained from the skip containers at the end of the dewatering process at the treatment works in November 2005.

Alum WTR 2a Sample

The alum residue from the Clareville works (WTR 2a) was derived from the treatment of high color, turbid water (typically 20–25 NTU) sourced from the lower Shannon, Ireland's longest river, draining the central lowland area of about 15700 km^2. The Shannon is a low gradient river, about 260 km in length with a mean annual discharge of 186 m^3/s, which runs for much of its course through karstified limestone overlain by raised and riverine bogs, many of which has been harvested for peat over the years. Much of the turbidity and color in the water is likely to be attributed to the organic material associated with the peat.

The raw water is delivered upstream of the Ardnacrusha dam through an open channel to the Clareville treatment works. After the initial screening process, the turbid water passes through 8.0-m deep primary sedimentation (holding) tanks, before the coagulation process, where a high alum dosage of 60–100 mg/l raw water was added owing to its high turbidity. Sulfuric acid was also added to adjust the pH in order to improve the polyelectrolyte performance.

At the end of the treatment process, the slurry residue was consolidated to about 700% water content under an applied stress of 800–1000 kPa using a belt-press device, and the pressed material was then allowed to dry naturally in drying beds, with about 900 tonnes of the wet alum residue ($SC = 15\%$) produced at the treatment works in 2006. Residue samples were obtained from the drying beds for geotechnical laboratory testing in October 2006.

Residue WTR 2b Sample

Samples of the turbid water were withdrawn from the mid-height of the primary sedimentation tanks at the Clareville works using 22.5 liter drums in February 2008. These drum samples were allowed to evaporate and settle out over a period of about four weeks at ambient laboratory temperature of 20°C. The thickened slurry residue formed (WTR 2b) was poured from the drums into shallow trays and the water content was allowed to reduce further by fan-assisted evaporation, again at ambient temperature, before the saturated slurry residue was mechanically dewatered using a consolidometer press. Although the solids in the drum samples were more than 40% volatile, the fact that the catchment source mainly comprised natural saturated peat meant that the bulk of these solids were already in a near stable condition. Hence, any biological activity that may have occurred during the course of settling and dewatering the drum samples in the laboratory would not have significantly altered the characteristics of the solids in residue WTR 2b.

One of the objectives of this study was to determine the effect of the chemical additives on the geoengineering and hydraulic properties, which was achieved by comparing the behaviors of alum WTR 2a and this non-chemically treated residue WTR 2b. These materials were identical in composition apart from the chemical additives in WTR 2a.

Alum WTR 3 Sample

The alum residue from the Leixlip works (WTR 3) was derived from the treatment of medium color, medium-turbidity water sourced from the river Liffey (upland catchment of limestone bedrock). The residue was dewatered using a recessed-plate filter press device under an applied stress of 1500 kPa, with about 1100 tonnes of the wet alum residue ($SC = 25\%$) produced at the treatment works in 2007. Samples of the pressed residue cake were obtained from the skip containers at the end of the dewatering process at the treatment works in November 2006.

PHYSIOCHEMICAL PROPERTIES

Table 3 lists the physiochemical properties which were determined using standard geotechnical-laboratory tests [20,21] carried out on fresh residue specimens obtained directly from the treatment works.

The water content values were determined using the oven drying method and are an accurate measure of the combined amounts of free and internal water within the pore space of the residue materials [7]. The degree of oxidation of the volatile solids was not significant at the oven drying temperature of 105 ± 5°C since the bulk of the organic material was already in a near stable condition and the polyelectrolyte additives only become unstable above about 150°C. The aluminum hydroxide precipitate degrades at higher temperatures of 180–600°C, with further calcination occurring above 1000°C.

Table 3. Properties of the Residue Materials Direct from the Treatment Works.

Parameter	WTR 1	WTR 2a	WTR 2b	WTR 3
Water content, %	340	570	–	300
Solids content, %	23	15	–	25
Bulk density, tonne/m^3	1.08	1.06	–	1.10
Dry density, tonne/m^3	0.25	0.18	–	0.26
Void ratio	6.3	11.3	–	5.7
Liquid limit, %	490	550	550	430
Plastic limit, %	240	260	280	220
Plasticity index	250	290	270	210
Total volatile soilds, %	57	45	41	46
Specific gravity of solids	1.86	1.99	1.83	1.90
Adhesion limit, %	240	365	355	345
Linear shrinkage, %	47	45	38	48
Free swell, %	35	10	10	40
pH	8.6	7.1	7.9	7.2

WTR 1, WTR 2a and WTR 3 are alum water treatment residues; WTR 2b is a non-chemically treated residue.

The Atterberg liquid and plastic limits, defined as the water content values at the transitions from the liquid state to the plastic state and from the plastic state to the semisolid state respectively, were determined using the fall-cone penetrometer and Casagrande thread-rolling methods [20]. The plasticity index was calculated as the numeric difference between the liquid limit and plastic limit values. The residues had very high liquid limit (430–550%) and plasticity index (210–290) values. The adhesion limit, determined as the lowest water content at which the solids adhered to a clean dry spatula, was also very high; in excess of 240% water content. The bulk density (ρ) and the dry density (ρ_d) were calculated as the wet mass and the dry solids mass per unit volume respectively [20], with the dry density given by

$$\rho_d = \frac{100\rho}{100 + w} \qquad (5)$$

where

$w =$ water content (as %)

The dewatered residue samples from the treatment works had low bulk and dry density values (1.06–1.10 and 0.18–0.26 tonne/m^3, respectively) and a wide range of water contents, and hence void ratio values, due to inherent differences in their consolidation properties and also differences in the drainage conditions and confining pressures that had been applied by the recessed-plate filter press and belt press devices. WTR 2a was of slurry consistency (water content greater than the liquid limit value, where the liquid limit condition corresponds to undrained shear strengths of about 1.7 kPa). WTR 1 and WTR 3 were soft to firm in consistency due to greater level of dewatering that had been achieved under the higher confining pressure of 1500 kPa applied by the recessed-plate filter press device. Nevertheless, their void ratio values of 5.7 and 6.3 were still very high.

X-ray diffraction analysis indicated that the crystalline fraction of the residues comprised quartz and manganoan calcite; both common bedrock minerals that are present as colloidal particles in the source waters. The chemical additives in the alum WTRs did not feature in the analysis since the alum was present in its aluminum hydroxide form (disordered and without any definable crystalline structure), and the polyelectrolytes are organic molecules. Inductively-coupled plasma analysis was also carried out on six specimens of alum WTR 2a over the water content range of 120% to 1100%, which indicated that this residue comprised 24–28% aluminum by dry mass, in line with the range of 29.7 ± 13.3% reported for alum WTRs [22].

The total volatile solids (*TVS*) values of 41–57% were determined by heating dry powered residue specimens in a muffle furnace at a temperature of 440°C [21], which oxidizes both the polyelectrolytes and the organic solids. The polyelectrolytes, which are unstable above 150°C, typically comprised 3.3% dry solids mass (range 1.6–4.8% dry solids mass) for alum WTRs 1, 2a and 3 (Table 2). Nevertheless, the TVS value is a good reflection of the gravimetric organic content since the crystalline fraction remains stable at the ignition temperature of 440°C. For example, calcination to form lime occurs at a much higher temperature of about 850°C. The 4% higher TVS value measured for alum WTR 2a, compared to the non-chemically treated residue WTR 2b, is most likely due to the 4.8% polyelectrolyte by dry solids mass basis that had been added during the treatment processes at the municipal works, and which was ultimately retained in alum WTR 2a. Some natural variations could also be expected in the composition of the suspended solids in the source water since WTR 2a and WTR 2b had been sampled in October and February, respectively. Organic matter in soil is generally responsible for high plasticity; low specific gravity of solids; high shrinkage; high compressibility; and low hydraulic conductivity [23]. Note that the organic fractions of WTR and sewage sludge materials mainly comprise colloidal-size particles (i.e. non fibrous), although the organic fraction of the WTRs is usually in a near stable condition whereas sewage sludge is bioactive, with the organics usually at moderate to strong levels of biodegradation [17,18,24]. The specific gravity of solids values of 1.83–1.99, which were measured using the small picnometer method [20], were relatively low, and consistent with the high organic contents. Note that the specific gravity of solids for mineral soils is typically in the range 2.5–2.7.

Linear shrinkage was calculated as the percentage reduction in the length of a bar of the wet residue material, which had been prepared at the liquid limit condition using a mold 130 mm in length, and oven dried at a temperature of 105 ± 5°C [20]. The linear shrinkage values of 38–48% were very high, indicating substantial reductions in volume would occur on drying the wet residue materials. The free swell values, defined as the maximum volumetric expansion that would occur on full re-saturation of the powered oven-dried residue materials, of 10–40% were also high, although consistent with the high plasticity index values. The pH of the residues was determined using an electrometric method [21] and, as expected, the pH was slightly alkaline due to the chemical conditioning of the water during the treatment processes.

The water content of the wet residue samples was reduced over time in the geotechnical laboratory by allowing thin layers of the wet material to dry naturally in trays at ambient temperature of 20°C.

COMPACTION PROPERTIES

Ordinary Proctor compaction tests were conducted in the one-liter compaction mold [25] on the wet alum WTR samples that had been allowed to dry naturally over different periods, with regular remolding, thereby obtaining a range of uniform materials with different water content values. The samples were regularly mixed during the drying process, and any clumps were disaggregated to pass the 20.0 mm sieve size prior to the compaction tests. Sets of three cylindrical sub-specimens (38 mm in diameter and 76 mm high) were also prepared from the wet ordinary Proctor compacted specimens. The wet mass, bulk volume and water content values of these sub-specimens were measured after they had been allowed to slowly air-dry further, and shrink without cracking, at ambient laboratory temperature. The bulk density was calculated as the wet mass per unit volume, from which the dry density was calculated using Equation (5).

Figure 3(a) shows the density values achieved by ordinary Proctor compaction alone. Figure 3(b) shows the density values achieved by allowing the sub-specimens that had been prepared from the wet ordinary Proctor compacted specimens to reduce in water content by natural air drying. Note that the zero air voids curve included in Figure 3 corresponds to the fully saturated condition and therefore represents an upper bound for the dry density values. The zero air voids curve was determined from the measured specific gravity of solids values [19].

The bulk and dry density values of 0.96–1.13 and 0.21–0.36 tonne/m^3 respectively, achieved by ordinary Proctor compaction [Figure 3(a)] were very low com-

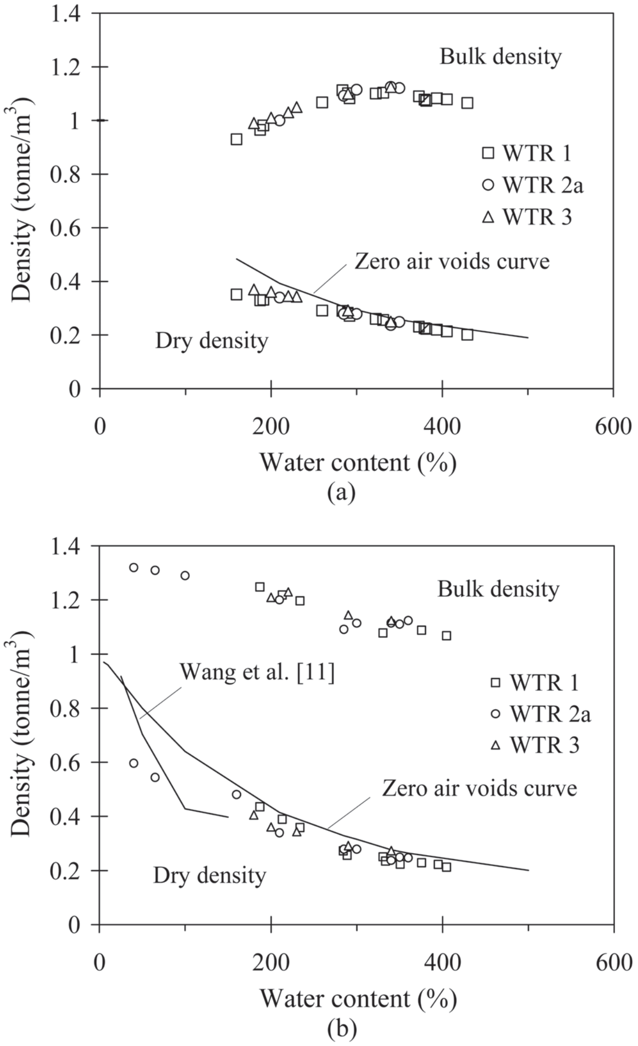


Figure 3. *Ordinary Proctor compaction; (a) Compaction alone, (b) Compaction followed by air drying.*

pared with mineral soils, although in line with the high water content of 200–400% and the low specific gravity of solids values. Furthermore, the dry density against water content curve in Figure 3(a) was relatively flat over the test range, which is a distinctive characteristic of these residue materials, with the dry density decreasing marginally in value with increasing water content, since the pore water constitutes an increasing proportion of the residue volume. The optimum water content to achieve the maximum dry density for ordinary Proctor compaction did not occur within the water content range tested, and this trend in the dry density data is consistent with Wang et al. [11].

Figure 3(b) shows that below 200% water content, the bulk and dry density values achieved by allowing the compacted alum WTR material to air-dry naturally were consistently greater than those achieved by ordinary Proctor compaction alone at the reduced water content value. Controlled drying and shrinkage without cracking of the wet sub-specimens had produced lower air voids contents ($A = 2.5$–3%), compared with those achieved by ordinary Proctor compaction alone of the dried alum WTRs ($A = 3.5$–5%). Note that the air voids content is defined as the ratio of the volume of the pore air voids to the bulk volume, given as a percentage. The residue materials were brittle below about 160% water content and crushed to a dust under the impact of the compaction rammer.

Hence, field compaction of these alum WTRs would be most efficiently carried out over the water content range of 200–240% owing to the tendency for these residues to stick to machine plant above the adhesion limit value of 240%. *Insitu* air drying and shrinkage of the compacted residues subsequently produce higher dry density values than achieved by compaction alone of material placed below 200% water content, thereby increasing the storage capacity of the monofill. Ordinary Proctor compactive effort was also found to be excessive for these alum WTRs, evident by some swelling of the compacted specimens at a constant water content, and it is suggested that a lighter field-compactive energy of about one-third ordinary Proctor compactive effort should be adequate in the case of residue monofills, following from the recommendations by Loll [26] and O'Kelly [27]. Hence, residues for landfilling should not be dried beforehand below 160% water content since they would easily crush to a dust under the action of the compaction roller, raising additional environmental concerns.

SHEAR STRENGTH PROPERTIES

The undrained shear strength of the ordinary Proctor-compacted residue specimens was measured as a function of their water content using quick-undrained triaxial compression tests [28]. These data are pertinent to the placement and trafficability of the residues in monofills, and achieving an adequate factor of safety against short-term geotechnical instability of the monofill slopes. The thixotropic hardening behavior was studied by carrying out laboratory vane and triaxial compression tests [28] on specimens of alum WTR 2a that had been allowed to cure, undisturbed at a constant composition, over different periods.

The effective stress shear strength properties, which are used in determining the factor of safety against instability of the monofill slopes for the intermediate and long-term conditions, were measured using isotropic consolidated-undrained triaxial compression tests, and with continuous measurement of the pore water pressure response [29].

Undrained Shear Strength

Quick-undrained triaxial compression tests were carried out on the partially saturated specimens (38 mm in diameter and 76 mm high) that had been prepared from the one-liter ordinary Proctor compacted specimens which had air voids contents of 3.5–5%. Some of these triaxial specimens were allowed to air-dry slowly over different periods prior to shearing in order to simulate the strength gain that would occur due to air drying of the residue used, for example, as daily cover on a municipal landfill. A cell confining pressure of 100 kPa was applied to the triaxial specimens, which were then sheared quickly at 2% axial strain/min in an undrained condition. Specimen failure was deemed to have occurred at a limiting 20% axial strain, unless the measured shear stress value had reached a maximum at a lower strain value. Figure 4 shows data for shear stress against axial strain for pairs of WTR 2a and WTR 2b specimens that had been sheared at similar water contents.

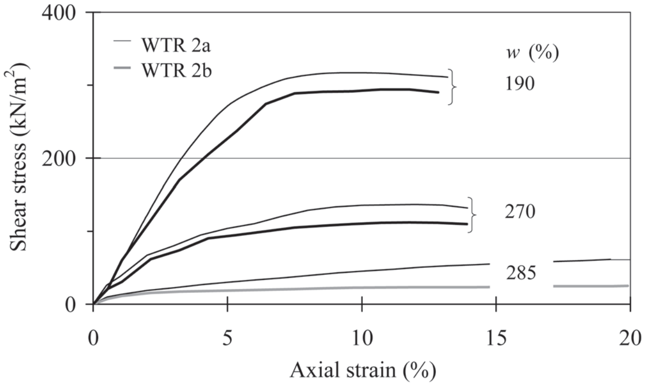


Figure 4. *Shear stress against strain for WTR 2a and WTR 2b (chemically and non-chemically treated residues, respectively) under triaxial compression.*

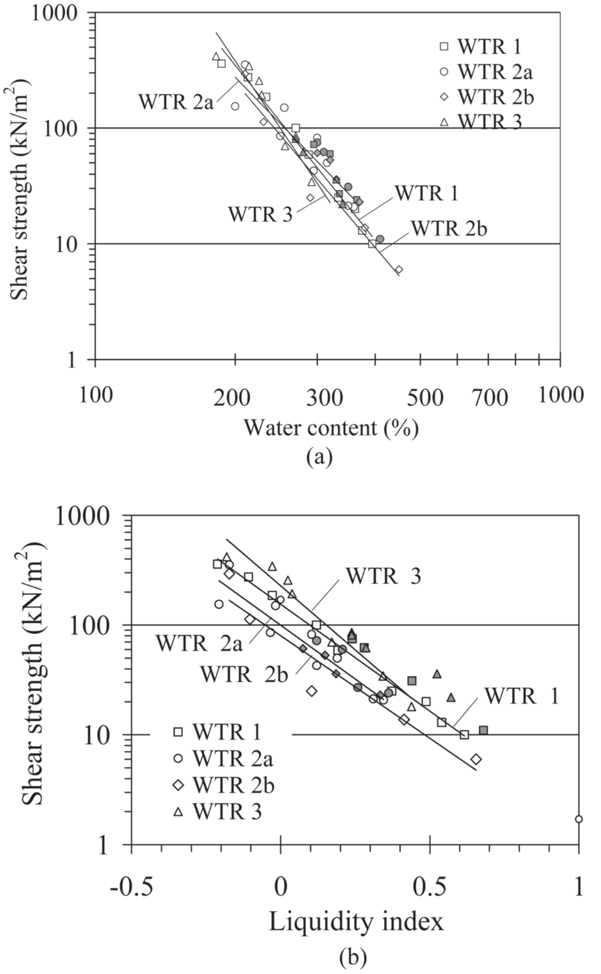


Figure 5. *Undrained shear strength data. Hollow and shaded symbols denote quick-undrained and consolidated-undrained triaxial compression tests, respectively; (a) Against water content, (b) Against liquidity index.*

Figure 5(a) shows the data for triaxial undrained shear strength against water content on a logarithm–logarithm plot. Figure 5(b) shows the water content values scaled in terms of the liquidity index [I_L, Equation (6)]. Overall, the shear strength values for the three alum WTRs were in good agreement, and consistently greater than that measured for the non-chemically treated residue WTR 2b, with the shear strength approximately inversely related to the water content and the liquidity index on logarithm–logarithm and logarithm–linear plots, respectively. Note that I_L values of unity and zero correspond to the Atterberg liquid limit and plastic limit conditions respectively, and $I_L < 0$ indicates that the material is in a semisolid state.

$$I_L = \frac{w - w_P}{w_L - w_P} \tag{6}$$

where

w = water content
w_L = liquid limit
w_P = plastic limit

Thixotropy Effects

Laboratory Vane

Saturated alum WTR 2a material prepared at 365% and 520% water content (I_L = 0.36 and 0.90, respectively) was pressed into molds, 70 mm square in plan and 70 mm high, taking care to avoid trapping air voids, and hermetically sealed by wrapping in cling film. The vane undrained shear strength of these specimens was measured [28] after standing periods of up to four weeks at ambient laboratory temperature of 20°C. The specimens were sheared quickly using a miniature cruciform vane, 25 mm in both width and length, which was rotated at 0.1 rev/min. Figures 6(a) and 6(b) show data for the increase in vane shear strength and the strength gain ratio against the standing period. For example, the vane shear strength measured for $I_L = 0.90$ (i.e. near the liquid limit condition) was found to increase from 3 kPa in the remolded state to about 7 kPa after a nine-day curing period, with a strength gain ratio of 3.3 achieved by the end of the four-week test period. The higher strength gain ratios of 5.7 to 8.0 that have been reported for alum WTRs by Wang et al. [11] correspond to a ten-week standing period, and for higher liquidity index values of 1.6–2.0, which is in line with the expected trend of increasing thixotropy effects with increasing standing times and liquidity index values.

Triaxial Compression

Three physically-identical triaxial specimens A–C, each 38 mm in diameter and 76 mm high, were prepared from a saturated cake of alum WTR 2a that had been consolidated one-dimensionally from the slurry state under an applied vertical stress of 60 kPa to a water content near its plastic limit value ($I_L = 0.14$) using a large consolidometer press developed by O'Kelly [30,31]. The triaxial specimens A, B and C were allowed to cure, undisturbed and at a constant composition, for periods of 0, 5 and 12 days, respectively.

An isotropic cell confining pressure of 260 kPa was then applied to these triaxial specimens under undrained conditions, thereby mobilizing an effective isotropic confining pressure (σ'_c) of about 60 kPa, which had been approximately achieved under the applied vertical stress of 60 kPa and 1–D consolidation conditions in the consolidometer press. Next, the triaxial specimens were sheared in an undrained condition at $3.3 \times 10^{-5}\%$ axial strain/min, which was sufficiently slow to allow full equalization of the pore water pressures to occur throughout the specimens at failure.

Similar stress–strain behavior and shear strength values were measured for the triaxial specimens A–C [Figure 6(c)], indicating that negligible thixotropic strength gain had occurred over the curing period of up to 12 days, which was expected, since the specimen water content was near the plastic limit condition. Seed and Chan [32] reported that the effect of thixotropic hardening decreases with decreasing liquidity index, and that the plastic limit represents a lower bound water content value for thixotropic behavior.

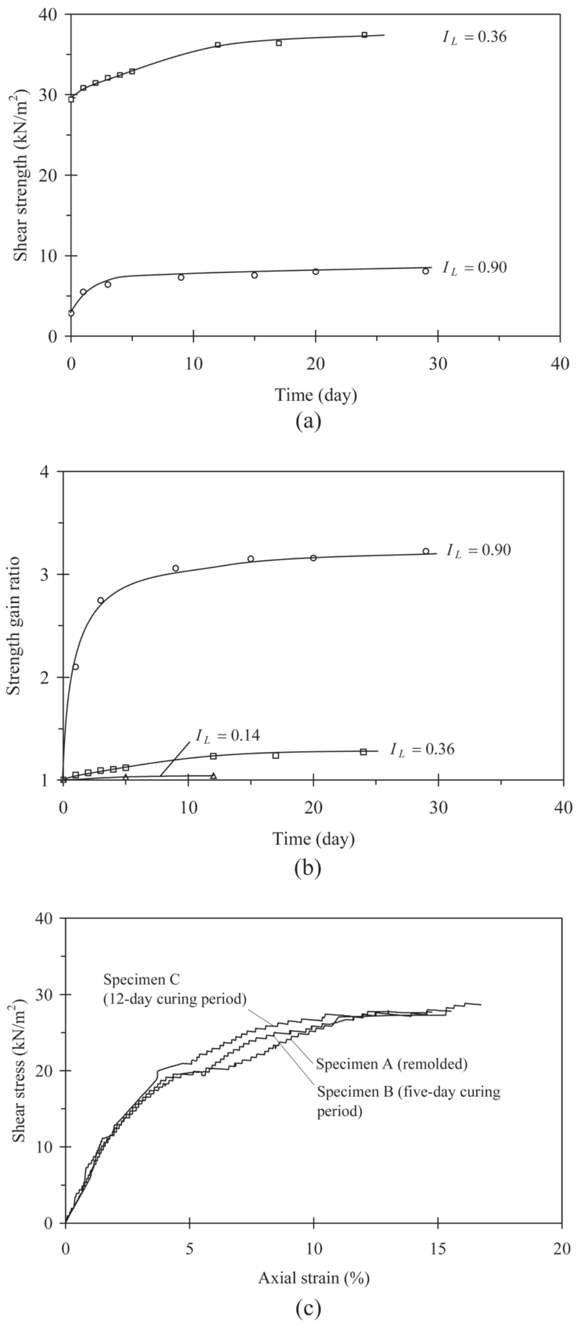


Figure 6. *Thixotropic behavior of alum WTR 2a; (a) Laboratory vane, (b) Strength gain ratio, (c) Triaxial compression ($I_L = 0.14$).*

Effective Stress Shear Strength Properties

A series of isotropic consolidated-undrained triaxial compression tests [29], which included continuous measurement of the pore water pressure response, were carried out in order to study the effective stress shear strength properties. Four physically-identical triaxial specimens (38 mm in diameter and 76 mm high) were prepared for each residue material from saturated cakes that had been pressed from the slurry state in the consolidometer apparatus and allowed to equilibrate under an applied vertical stress of $\sigma_v = 30$ kPa. The sets of residue specimens were isotropically consolidated under effective cell-confining pressures of 30, 60, 120 and 150 kPa in the triaxial apparatus, with the specimens allowed to drain radially to filter-paper side drains, and to porous discs in contact with both specimen ends, against an applied specimen back pressure of 200 kPa over a 24-hour period. An effective confining pressure of at least 30 kPa was applied to these specimens in order that they would be in a normally consolidated condition ($\sigma_c \geq \sigma_v$) during the triaxial shearing stage. The consolidated specimens were sheared slowly in an undrained condition at rates of the order of 10^{-5}% axial strain/min, determined from curve-fitting analysis of the data from the consolidation stage [29], and which were sufficiently slow to allow full equalization of the pore water pressures to occur throughout the specimens at failure. The standard corrections for the restraining effects of the filter-paper side drain and the enclosing rubber membrane on the barreling-type specimen deformation response were applied to the measured data [29].

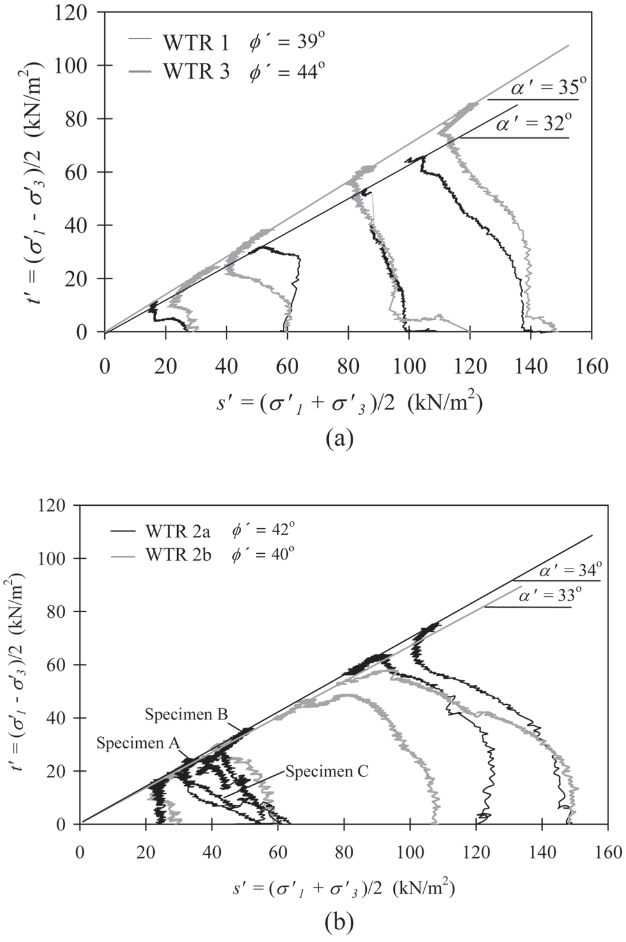


Figure 7. Effective stress path plots; (a) WTR 1 and WTR 3, (b) WTR 2a and WTR 2b.

Figure 7 shows the s′–t′ effective stress path plots; where $s' = (\sigma_1' + \sigma_3')/2$ and $t' = (\sigma_1' + \sigma_3')/2$ are the Massachusetts Institute of Technology stress path parameters; and σ_1 and σ_3 are the major and minor effective principal stresses, respectively. The failure lines of best fit in the s′–t′ plots were drawn passing through the origin (i.e. effective cohesion of zero) and aligned with the stress points corresponding to specimen failure, which typically occurred between 2% and 10% axial strain. Note that the effective stress paths at failure for the triaxial specimens A–C of alum WTR 2a, which had been sheared at similar strain rates but after different curing periods of 0, 5 and 12 days (thixotropy section), were also coincident with the alum WTR 2a failure line in Figure 7(b); further evidence that the effects of thixotropic hardening are not significant at low liquidity index values. Had thixotropy effects been significant, the effective stress paths at failure for specimens A–C would have located above the best-fit failure line for the uncured specimens. The ratio of the mobilized shear strength to the effective cell-confining pressure that had been applied during the triaxial consolidation stage had a mean value of 1.8. The effective angle of shearing resistance (ϕ') values of 39° to 44°, which were calculated from the gradient of the s′–t′ failure lines in Figure 7 using Equation (7), are in line with the ϕ' values of 42° and 44° reported for two alum WTRs by Wang et al. [11].

$$\sin\phi' = \tan\alpha' \tag{7}$$

where

α' = gradient of the s′–t′ failure line to horizontal s′ axis

COMPRESSION PROPERTIES

The compression and consolidation properties were determined as a function of the state of effective stress by testing saturated residue specimens of different size, aspect ratio and consistency under different loading and drainage conditions using the oedometer, consolidometer and triaxial apparatus [33]. Table 4 summarizes the initial dimensions and consistency of the specimens, drainage conditions and the applied stresses of between 3 and 800 kPa which covered the diverse levels of effective stress achieved in mechanically dewatering, storing and landfilling the residue materials: that is, low effective stress levels in lagoons, low to medium effective stress levels in landfills and the medium to very high stresses applied by mechanical dewatering devices at municipal works. The consolidometer and isotropic triaxial consolidation tests have already been outlined in the context of describing the measurement of the effective stress shear strength properties of the residue materials.

Oedometer Tests

Multiple-increment oedometer tests [33] were carried out on saturated materials prepared by thoroughly mixing the dewatered alum residues from the municipal works with distilled water to form uniform slurry pastes, which were allowed to equilibrate in sealed containers over a two-day period. The slurry paste was then pressed into the 76-mm diameter confining ring of the oedometer apparatus, taking care to avoid trapping air voids. The specimen was compressed one-dimensionally, with two-way vertical drainage to atmosphere, under an applied vertical stress that was doubled in moving from one load stage to the next, over the stress range 3–800 kPa. A displacement transducer in contact with the oedometer loading cap continuously measured the specimen deformation response. Each oedometer load stage was two days in duration in order to record sufficient data covering both the specimen consolidation and longer-term creep settlement responses under successive increments of applied stress.

Figure 8 shows the oedometer data, plotted in the conventional form of cumulative volumetric strain against the square root of elapsed time, for alum WTRs 1, 2a and 3. The slurry specimens were highly compressible, deforming at slow but steady rates, and by the end of the final load stage (800 kPa), had undergone very large volumetric strains of up to 62%. The primary consolidation component due to the dissipation of the excess pore water pressure was dominant during the early load stages, with primary compression ratios (defined as the proportion of the total strain due to primary consolidation for a particular load stage) of 0.75 to 0.90. However, secondary compression became increasingly significant at higher stress levels, with the primary compression ratio values for the alum residues reducing to 0.22–0.40 by the final load stage.

Table 4. Summary of the Consolidation Tests.

Test Method	Dimensions[a] mm	Consistency	Water Content Initial %	Final %	Applied Stress kN/m^2	Void Ratio Initial	Final	Duration Load Stage day	Drainage Conditions	Compression Index, C_c
Oedometer										
WTR 1	76 × 29	Slurry	780	280	$\sigma_V = 3$–800 (*MI*)	14.5	6.2	2	Two-way vertical	3.2
WTR 2a	76 × 29	Slurry	700	190	$\sigma_V = 3$–800 (*MI*)	14.1	3.3	2	Two-way vertical	2.5
WTR 3	76 × 29	Slurry	690	310	$\sigma_V = 3$–800 (*MI*)	11.9	5.4	2	Two-way vertical	2.5
Consolidometer										
WTR 1	152 × 139	Slurry	625	475	$\sigma_V = 10$–30 (*MI*)	14.1	8.8	7	Two-way vertical	3.9
WTR 2a	152 × 139	Slurry	580	420	$\sigma_V = 10$–30 (*MI*)	10.9	8.4	7	Two-way vertical	3.1
WTR 2a	167 × 139	Very soft	500	330	$\sigma_V = 7.5$–60 (*MI*)	8.8	6.2	7	Two-way vertical	2.6
WTR 2b	152 × 167	Slurry	760	435	$\sigma_V = 10$–30 (*MI*)	15.4	8.1	7	Two-way vertical	5.5
WTR 3	152 × 93	Slurry	600	410	$\sigma_V = 10$–30 (*MI*)	11.1	7.8	7	Two-way vertical	3.1
Isotropic Triaxial										
WTR 1	38 × 76	Very soft	475	340	$\sigma'_c = 30$–150 (*SI*)	8.8	7.3	1	All around	2.3
WTR 2a	38 × 76	Very soft	420	350	$\sigma'_c = 30$–150 (*SI*)	8.4	7.9	1	All around	0.8
WTR 2b	38 × 76	Very soft	435	340	$\sigma'_c = 30$–150 (*SI*)	8.1	7.2	1	All around	1.1
WTR 3	38 × 76	Very soft	410	300	$\sigma'_c = 30$–150 (*SI*)	7.8	6.7	1	All around	1.4

MI, multiple increment; *SI*, single increment; σ_v, applied vertical stress; σ'_c, effective confining pressure.

[a] Specimen dimensions are given as diameter by height.

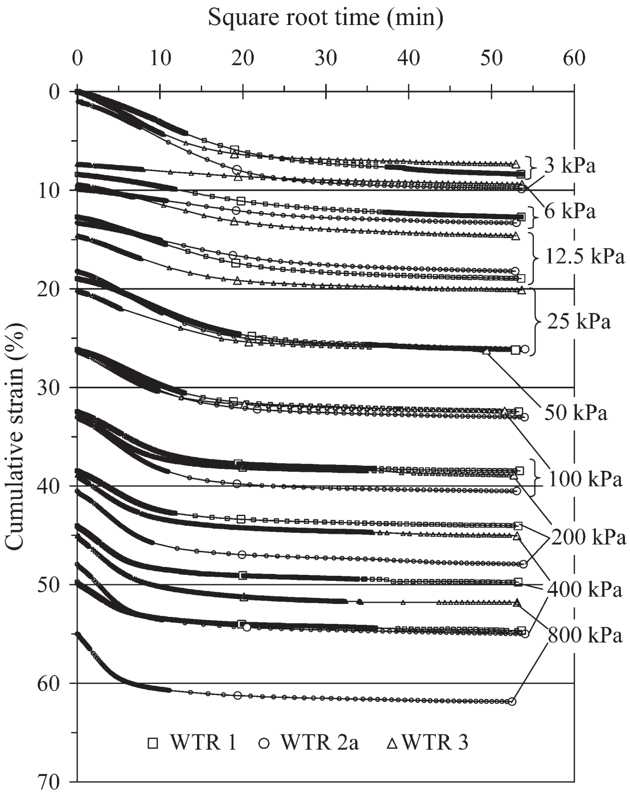


Figure 8. *Oedometer data.*

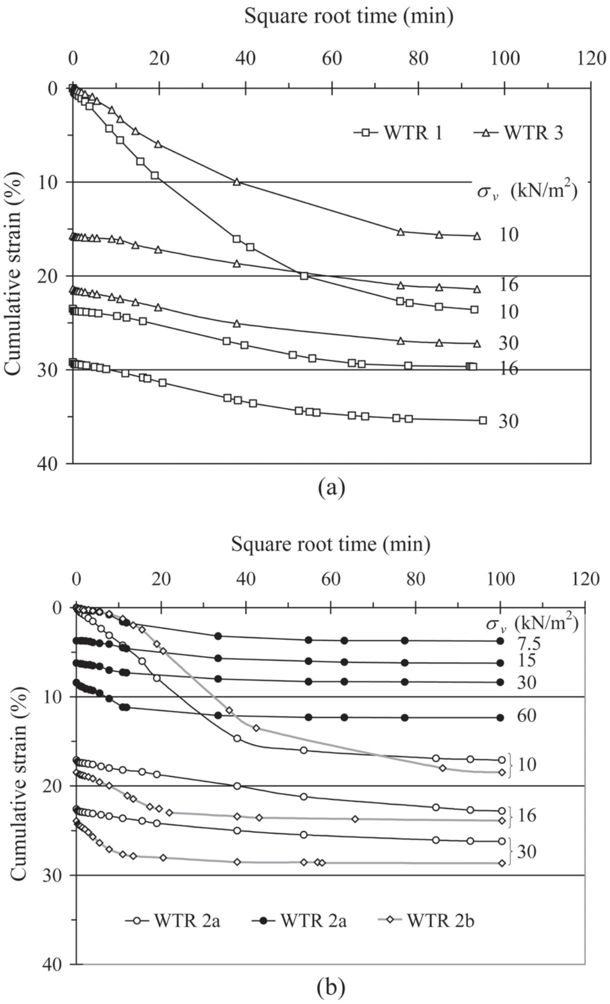


Figure 9. *Consolidometer data; (a) WTR 1 and WTR 3, (b) WTR 2a and WTR 2b.* Note: *hollow symbols, slurry specimens; solid symbols, very soft specimen; σ_v, applied vertical stress.*

Consolidometer Tests

Specimens of very soft and slurry consistencies were compressed one-dimensionally under applied stresses of 10–60 kPa, with two-way vertical drainage to atmosphere, using a 152-mm diameter consolidometer press [30,31]. Each load stage was extended to seven days in duration, compared to the two days that was used as standard for each oedometer load stage, because of the greater specimen drainage length in the consolidometer tests. Periodic measurements of the deformation response were taken using a long-stroke dial gauge in contact with the specimen loading platen (Figure 9). Again, the slurry specimens were highly compressible, and by the end of the final load stage (30 kPa), had undergone large volumetric strains of up to 36%. Water content tests carried out on the pressed residue cakes confirmed that the water content distribution was uniform across the specimen thickness, indicating that full consolidation had been achieved throughout the specimens by the end of the final load stage.

Triaxial Consolidation Tests

Four triaxial specimens (38 mm in diameter and 76 mm high) were prepared for each residue material from the cakes produced at the end of the consolidometer tests. The sets of residue specimens were allowed to drain radially and from both ends under isotropic effective confining pressures of 30, 60, 120 and 150 kPa, with continuous measurement of the volume of pore water that drained from the specimens over a 24 h period, against an applied back pressure of 200 kPa, in the triaxial apparatus [33]. The volumetric strain data are shown against the square root of elapsed time in Figure 10 and against the state of effective stress in Figure 11(a). The drained bulk modulus (*B*, as MN/m^2) response is shown in Figure 11(b), where *B* is defined as the ratio of the effective stress to the volumetric strain (decimal value). The very soft residue specimens were also highly compressible, and by the end of the consolidation stage at 150 kPa, had undergone large volumetric strains of up to 33%.

Compressibility Data

The stress–strain–time data from the oedometer, consolidometer and triaxial consolidation tests are summarized in the conventional form of void ratio against logarithm of effective stress in Figure 12.

The compression response was quantified in terms of the compression index (C_c) values, which are included in Table 4. Note that the level of compression depends on a range of factors, including: initial water content (void ratio); hydraulic conductivity; specimen thickness and drainage length; applied stress; and load-stage duration. The slurry residues were highly compressible, with values of $C_c = 3.2$, 2.5 and 2.5 given by the gradients of the oedometer void ratio against logarithm of effective stress curves [Figure 12(a)] for alum WTRs 1, 2a and 3, respectively. Note that for most inorganic clays, $C_c < 1.0$, and generally less than 0.5. The consolidometer data gave higher values of $C_c = 2.6$–5.5 (Table 4) due to greater amounts of secondary compression settlement achieved by the end of the longer-duration load stages (seven days compared to the two days used as standard for each oedometer stage). Primary compression ratio [C_c^*, Equation (8)] values of 0.19, 0.17 and 0.20, which take into account the initial consistency (void ratio) of the specimens, were determined from the oedometer data for alum WTRs 1, 2a and 3, respectively.

$$C_c^* = \frac{C_c}{1 + e_o} \tag{8}$$

where

e_o = initial void ratio.

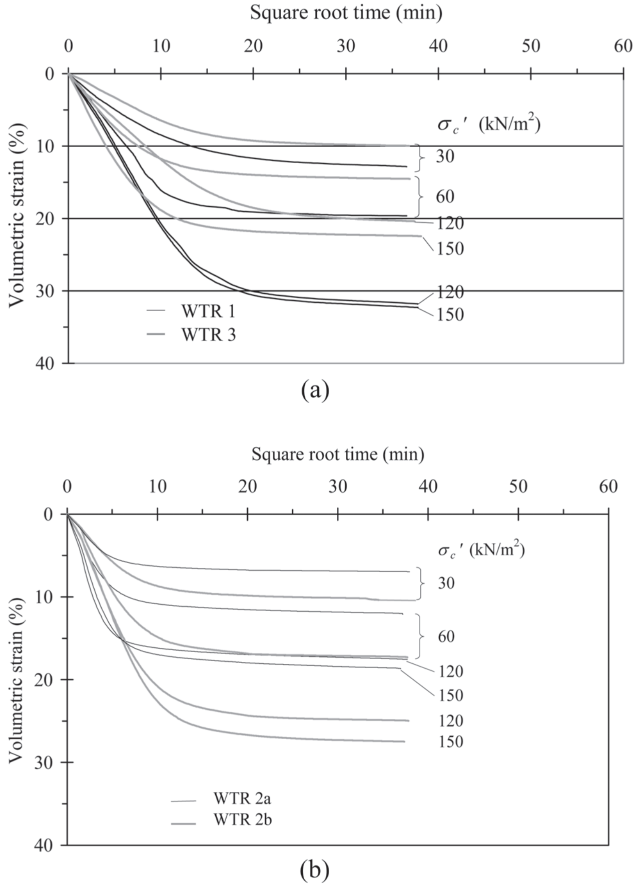


Figure 10. *Triaxial consolidation data; (a) WTR 1 and WTR 3, (b) WTR 2a and WTR 2b.* Note: σ'_χ, *effective confining pressure.*

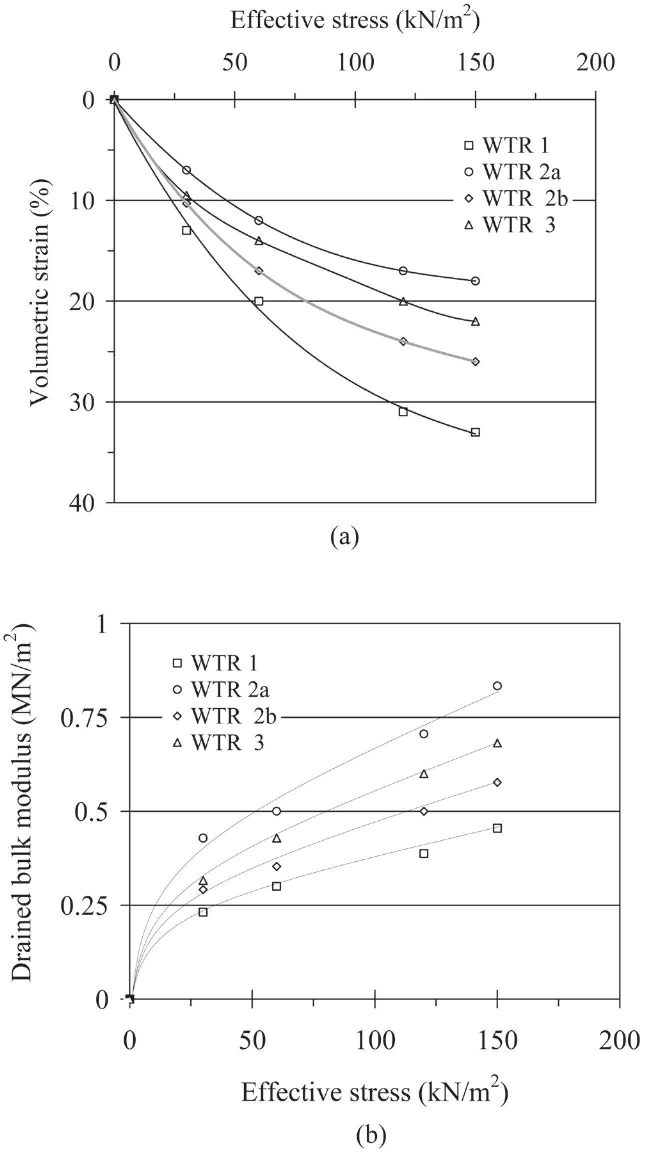
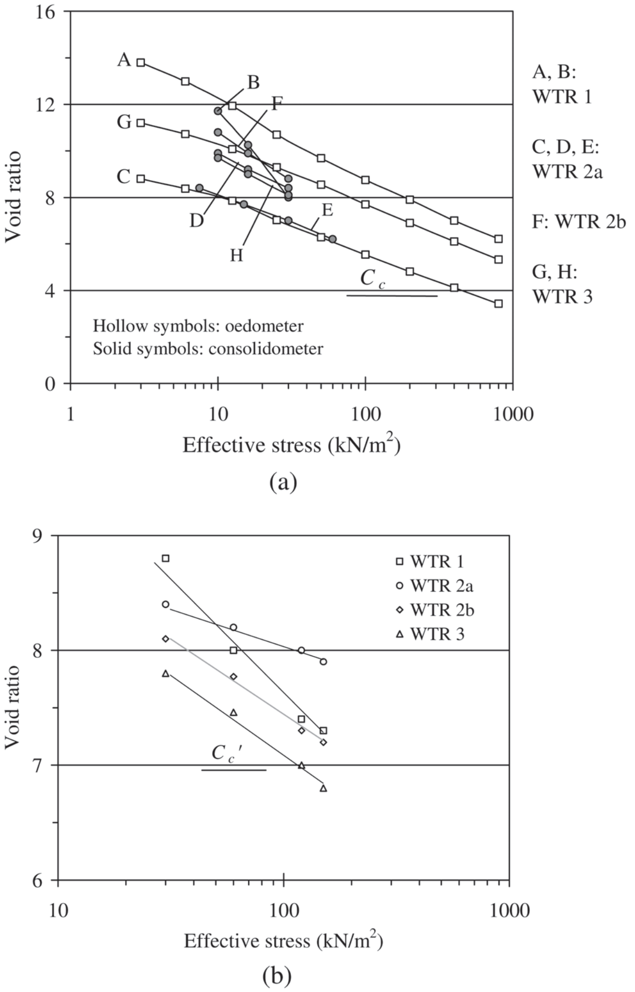


Figure 11. *Dewaterability under isotropic confining pressure; (a) Volumetric strain, (b) Drained bulk modulus.*



(a)

(b)

Figure 12. Void ratio against effective stress (primary consolidation settlement); (a) 1–D compression in oedometer and consolidometer apparatus, (b) Isotropic triaxial consolidation. Note: Cc, *compression index.*

Consolidation Rate

The rate of consolidation of the residue materials was very slow, and typical of high-plasticity clays. Standard curve-fitting techniques [33] were applied to the oedometer and triaxial consolidation data presented in Figures 8 and 10 in order to determine the values of the coefficient of primary consolidation (c_v), which were in good agreement for the residue materials, increasing from 0.1 to 0.8 m^2/year with increasing effective stress from 3 to 800 kPa (Figure 13).

Hydraulic Conductivity

The hydraulic conductivity [k, Equation (9)] was determined indirectly from the oedometer data presented in Figure 8 as

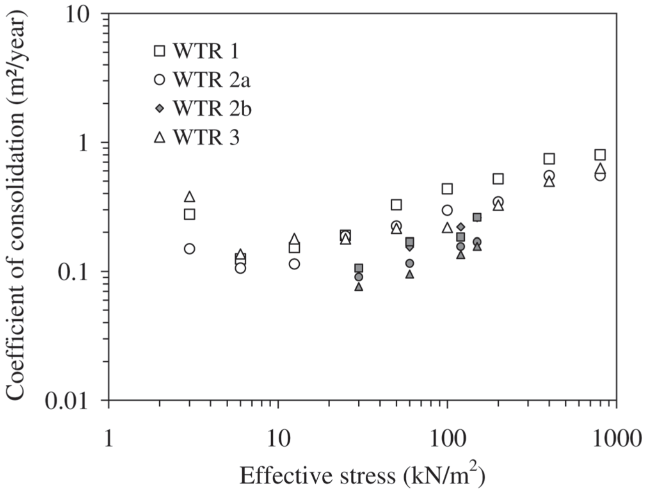


***Figure 13.** Coefficient of primary consolidation against effective stress.* Note: *hollow symbols, oedometer data; solid symbols, triaxial data.*

$$k = m_v c_v \gamma_w \tag{9}$$

where

γ_w = density of the pore water (assumed 0.98 tonnes/m^3)
m_v and c_v = coefficients of volume change and primary consolidation, respectively; with m_v defined as the volumetric strain per unit increase in effective stress

The hydraulic conductivity values were very low and inversely related to the state of effective stress on a logarithm–logarithm plot [Figure 14(a)], with the hydraulic conductivity decreasing significantly from about 2×10^{-4} to 1×10^{-6} m/day with increasing effective stress (reductions in water content and void ratio) from 3 to 800 kPa. This is consistent with the experience of mechanically dewatering the wet alum WTRs at the treatment works. Wang and Tseng [12] also reported that the hydraulic conductivity of alum WTR reduced from 10^{-4} to 10^{-6} m/day over the effective stress range of 2 to 540 kPa. Direct comparisons at the same levels of effective stress indicate that the hydraulic conductivity values of WTR 2a and WTR 3 are broadly similar, and about one order of magnitude greater than that measured for WTR 1 [Figure 14(a)]. It is postulated that this difference is partly due to the higher organic content of WTR 1 (*TVS* = 57%) compared to either WTR 2a or WTR 3 (*TVS* = 45–46%). The hydraulic conductivity data are also shown against the water content w in Figure 14(b) and against the void ratio e in Figure 14(c), since these parameters that can be readily determined in practice using the standard oven-drying method [20] and phase relationships. For example, assuming fully saturated conditions, the void ratio is given by

$$e = wG_s \tag{10}$$

where

G_s = specific gravity of solids

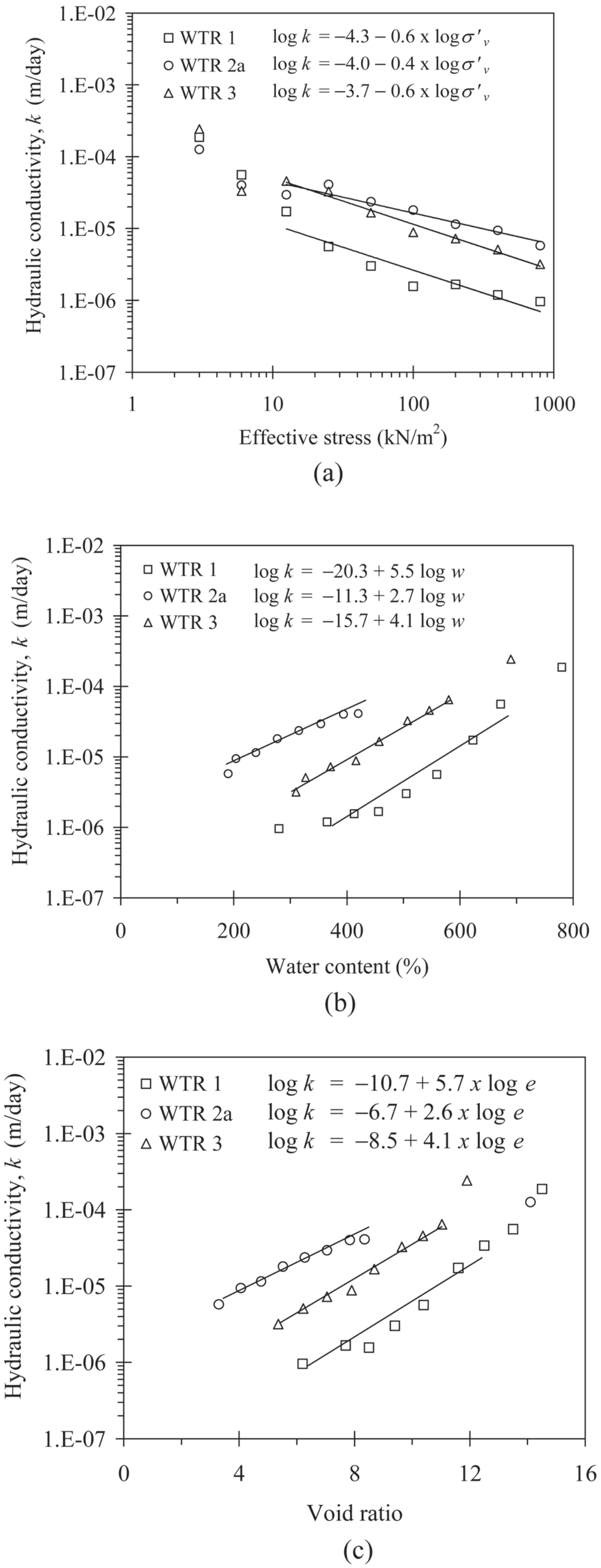
Secondary Compression Rate

The rate of secondary compression (creep) for the alum WTRs was quantified in terms of the coefficient of secondary compression C_{sec}, defined as the 1–D volumetric strain per ten-fold increase in elapsed time after the substantial completion of the primary consolidation phase (i.e. under constant effective stress). High values of C_{sec} = 0.005–0.010 were determined from the oedometer data, with a mean value of $C_{\text{sec}} = 0.006$ over the effective stress range 3–800 kPa (Figure 15). The C_{sec} values, and hence anticipated long-term settlements, were consistently greater for WTR 1 than for either WTR 2a or WTR 3, owing to its higher organic content [23]. Figure 15 also shows the data values of 0.15–0.18 determined for the secondary compression index [$C_{\alpha e}$, Equation (11)] and 0.03–0.05 for the ratio of $C_{\alpha e}/C_c$ [34], which are typical ranges for organic soils.

$$C_{\alpha e} = C_{\text{sec}}(1 + e_o) \tag{11}$$

EFFECTS OF CATCHMENT GEOLOGY AND CHEMICAL ADDITIVES ON THE ENGINEERING BEHAVIOR

Despite significant differences in catchment geology, and allowing for minor differences in the chemical



(a)

(b)

(c)

Figure 14. *Hydraulic conductivity data; (a) Against effective stress, (b) Against water content, w, (c) Against void ratio, e.*

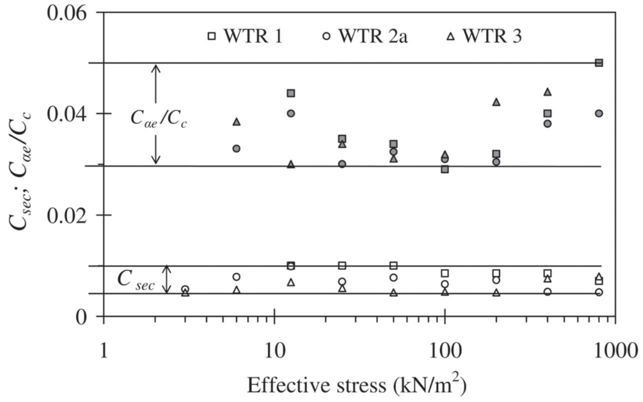
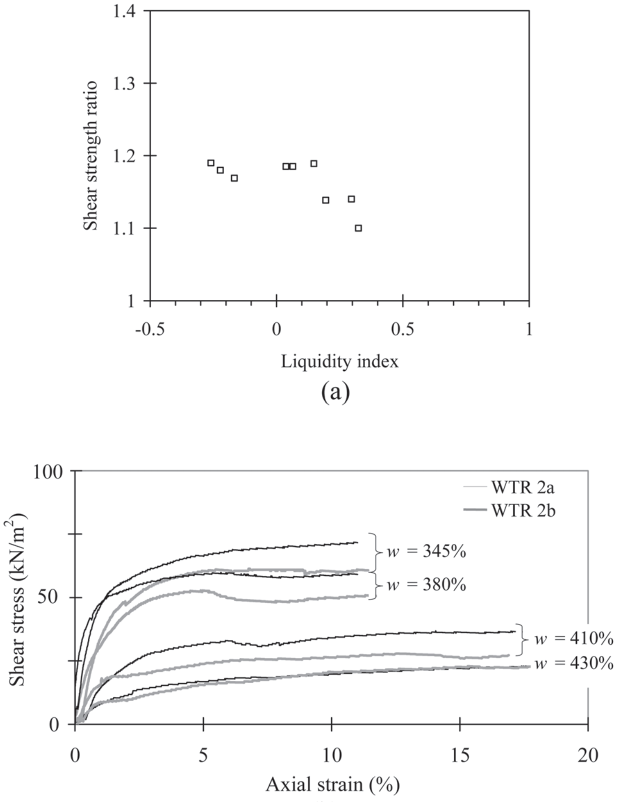


Figure 15. *Secondary compression data. Note:* C_c, *compression index;* C_{sec}, *coefficient of secondary compression;* $C_{\alpha e}$, *secondary compression index.*



(a)

(b)

***Figure 16.** Effect of polyelectrolyte on the triaxial undrained shear strength; (a) Ratio of the undrained shear strength of alum WTR 2a to that of the non-chemically treated residue WTR 2b, (b) Shear stress against strain data for specimen pairs at similar water contents (w).*

dosages and seasonal variations in the source waters (the test materials had been sampled at different times during the year), the three alum WTRs were found to have broadly similar geoengineering properties, most likely due to the fact that the behavior was dominated by the high organic content ($TVS = 41$–57%).

At a given water content, the triaxial undrained shear strength of the alum WTRs was consistently greater than that measured for the non-chemically treated residue WTR 2b [Figure 5(b)], which can be explained by the action of the polyelectrolyte additive in aggregating and binding the constituent flocs to form floc clusters, thereby producing greater inter-particle contact and reducing the size of the pore voids and capillary channels (in combination with the deactivation of some pore water by the alum coagulant [12]). For example, Figure 16a shows the ratio of the triaxial undrained shear strength values measured for alum WTR 2a and the non-chemically treated residue WTR 2b. The shear strength of alum WTR 2a, which comprised 4.8% polyelectrolyte by dry solids mass, was between 1.1 and 1.2 times greater than that measured for residue WTR 2b. Stiffer responses and values of peak shear stress of up to 20% greater were also measured for alum WTR 2a,(compared with residue WTR 2b) from consolidated-undrained triaxial compression tests on specimen pairs at similar water contents [Figure 16(b)]. Hence, the effective angle of shearing resistance of alum WTR 2a was also slightly greater than that measured for residue WTR 2b ($\phi' = 42°$ and 40°, respectively).

Although the chemical additives are necessary for the efficient operation of the treatment processes, they also have a downside in that the thickened alum WTRs are potentially more difficult to consolidate, and hence the larger bulk residue volume will settle to a greater extent, and typically over a longer period, when placed in a lagoon or monofill. For example, Figure 12(b) shows that alum WTR 2a was less compressible than the non-chemically treated residue WTR 2b, with compression index values of $C_c = 3.1$ and 5.5 determined from the slurry consolidometer tests (Table 4). Alum WTR 2a was also found to consolidate at a slightly slower rate, reflected by its lower values shown in Figure 13. Hence, from Equation (9), the hydraulic conductivity of alum WTR 2a is lower than that of the non-chemically treated residue WTR 2b, owing to the effect of the chemical additives, since the mineralogy; organic content; and test conditions are similar. This is consistent with Wang and Tseng [12] and O'Kelly [15] who reported that relatively large amounts of additional pore water are trapped and absorbed by the aluminum hydroxide precipitates and polyelectrolyte molecules within the constituent flocs, which causes a reduction in the hydraulic conductivity.

APPLICATION OF THE TEST DATA

Dewaterability of Slurry Residue at Treatment Works

The alum WTR slurry must be adequately dewatered at the treatment works in order to reduce its bulk volume, thereby lowering transportation and landfill-disposal costs, and to achieve an adequate shear strength for efficient handling, trafficability, and geotechnical stability of the landfill slopes. Dewatering is achieved by mechanical and/or thermal means, or by allowing the slurry to dry naturally in drying beds, depending on the size of the treatment works. The reduction in the residue volume, ΔV, achieved by mechanical dewatering systems can be estimated using Equation (12) and the void ratio–logarithm of effective stress data shown in Figure 12.

$$\Delta V = V_o\left(\frac{\Delta e}{1+e_o}\right) = V_o\left(\frac{\sigma'}{B}\right) \qquad (12)$$

where

V_o = initial volume
e_o = initial void ratio
Δe = reduction in void ratio under the effective stress
σ' = applied by the mechanical dewatering system
B = drained bulk modulus [Figure 11(b)]

Note that it is technically feasible to recover the alum from the slurry residue by chemical means, and proprietary full-scale treatment systems are currently under development in practice. The aluminum hydroxide precipitate that forms during the coagulation process readily dissolves in highly acidic solutions [35] and the liquid alum can then be decanted and crystallized by evaporation. Alum recovery is most successfully carried out using sulfuric acid over the range of pH 2–3, and for retention periods of 10–20 min [36]. However, the effectiveness of these techniques has been varied to date, with the purity of the recovered alum and the overall economy of the recovery process remaining controversial issues. The data for alum WTR 2a and the non-chemically treated residue WTR 2b tested in this study indicated that the chemical additives had the effect of reducing the hydraulic conductivity of the slurry residue. Further studies are necessary in order to determine the extend to which these effects are reversible, since alum recovery may also lead to greater levels of mechanical dewatering of the residue being achieved, and hence reduced landfill-disposal costs.

Acceptability of Residues for Landfilling Based on Shear Strength Criteria

In accordance with current guidelines [4–6], municipal landfill operators will usually not accept sludge or residues with a water content value greater than 300% (*SC* = 25%), which has been set as an indirect measure of the shear strength necessary for efficient handling, trafficability, and geotechnical stability. In municipal landfills, the wet residue material is usually placed in thin layers and mixed and scarified insitu with the solid waste, which has the effect of reducing the water content and increasing the shear strength of the residue fraction. Minimum shear strengths of 20 and 25 kPa have been recommended by Loll [26] and Siedlungsabfall [37] for the co-disposal of sludge and residue materials at municipal landfills. An undrained shear strength of at least 20 kPa was achieved at 340% water content (*SC* = 22%) for the three alum WTRs tested in this study [Figure 5(a)], although Figure 1 shows that for other municipal sludge and residue materials, the undrained shear strength may be significantly less than 20 kPa [8,11,16] at the maximum 300% water content value for municipal landfilling.

No universal relationship exists for soils between the water content and the undrained shear strength, which is also dependent on a range of other factors, including: mineralogy; organic content; chemical dosages; and the type of treatment used to separate the residue by-product. Hence, it would be more prudent for landfill operators to specify a minimum value of shear strength based on sound geotechnical considerations, rather than the current requirement for a maximum water content of 300% alone, in determining the acceptability of sludge and residue materials for landfilling. Note that in the case of residue monofills, higher shear strengths of at least 50 kPa are recommended for geotechnical stability.

Data for undrained shear strength against water content, such as that shown in Figure 5(a) for the alum WTRs tested in this study, can be used to select an appropriate mechanical dewatering system in order to achieve a specified minimum value of shear strength before the residue cake is transported for disposal offsite. For example, the recessed-plate filter press devices used at the Ballymore Eustace and Leixlip treatment works reduced the water content value of the alum slurry residues WTR 1 and WTR 3 to 340% and 300% respectively (Table 3), thereby achieving adequate undrained shear strengths of about 25 and 31 kPa respectively, and satisfying geotechnical stability criteria for municipal landfilling. At the Clareville works, the water content value of alum WTR2a was reduced to about 700% using a belt-press device, and to about 570% by allowing the pressed residue to dry naturally in drying beds, although the remolded material was still of slurry consistency, and therefore unsuitable for municipal landfilling. Belt dryer devices that fully or partially dry the pressed residue cake at low temperatures; thermal treatments or soil-conditioning techniques can be investigated as alternative methods to dewater these residues sufficiently and expeditiously. The miniature vane apparatus [28] has been shown to provide a quick and accurate method of measuring the undrained shear strength (O'Kelly [27]; Loll [26]) in order to assess whether the residue material has been adequately dewatered before leaving the treatment plant, and again by the landfill operator before accepting the residue cake for disposal.

Settlement of Sludge Lagoons and Residue Monofills

The high values of the compression index and the coefficient of secondary compression measured for the alum WTRs indicate that residue lagoons and monofills will consolidate significantly and continue to settle by secondary compression (creep) over a long period. This time-dependent settlement response comprises the sum of the primary consolidation and secondary compression components, ΔH_c and ΔH_{sec} respectively, which can be quantified for 1–D settlement conditions using Equations (13)–(14). The time period to achieve substantial completion of the primary consolidation component, t_1, can be quantified using Equation (15).

$$\Delta H_c = H_o \frac{\Delta e}{1+e_o} \tag{13a}$$

$$\Delta H_c = H_o \frac{C_c}{1+e_o} \log \frac{\sigma'_{vo}\sigma'_v}{\sigma'_{vo}} = H_o C_c^* \log \frac{\sigma'_{vo}\sigma'_v}{\sigma'_{vo}} \tag{13b}$$

$$\Delta H_{\text{sec}} = H_o C_{\text{sec}} \log \frac{t_1}{t_2} \tag{14}$$

$$t_1 = \frac{T_v d^2}{c_v} \tag{15}$$

where

d = effective drainage length of the residue deposit (initially H_o in thickness)
e_o = initial void ratio
T_v = dimensionless time factor related to the average degree of consolidation
t_2 = time period that extends into the secondary compression phase ($t_2 > t_1$)
σ'_{vo} = initial vertical effective stress
Δe = reduction in the void ratio due to the increase in vertical effective stress, σ'_v (i.e. applied stress)

The values of the compression index C_c [from Figure 12(a)]; the coefficient of primary consolidation c_v (from Figure 13); and the coefficient of secondary compression C_{sec} (from Figure 15) that are used in these calculations must be consistent with the *insitu* effective stress; loading and drainage conditions. A full explanation of the background to Equations (13)–(15) and their application in determining the magnitude and rate of settlement can be obtained in undergraduate soil mechanics textbooks, including Craig [19].

SUMMARY AND CONCLUSIONS

Despite significant differences in catchment geology, and allowing for minor differences in the chemical dosages and seasonal variations in the source waters, the three alum water treatment residues tested in this study were found to have similar geoengineering and hydraulic properties, akin to high-plasticity non-fibrous organic clays. These viscous slurry residues were highly compressible, although the consolidation rate was low (hydraulic conductivity of the order of 10^{-4}–10^{-6} m/day), and underwent thixotropic hardening in an undisturbed condition. For mechanically-dewatered residue, the ratio of the triaxial shear strength to the effective confining pressure was about 1.8.

Ordinary Proctor compaction produced low values of bulk density and dry density of 0.96–1.13 and 0.21–0.36 tonne/m^3 respectively, over the water content range 200–400%, although field compaction would be most efficiently carried out over the water content range 200–240% using a compactive energy of about one-third that of ordinary Proctor compactive effort. It is also recommended that landfill operators should specify minimum shear strengths of 20 and 50 kPa for residue disposal at municipal landfills and dedicated monofills respectively, in order to satisfy geotechnical stability criteria. Significant settlements of residue lagoons and monofills can be expected to occur over a long period, owing to the low consolidation and high creep rates.

The triaxial undrained shear strength of the alum WTRs was found to be 10–20% greater than that measured for the non-chemically treated residue of similar mineralogy and organic content, which can be largely explained by the action of the polyelectrolyte additive in aggregating and binding the constituent flocs to form floc clusters. Although the chemical additives are necessary for the efficient operation of the municipal treatment processes, they were also found to have a downside in that the thickened alum residue was potentially more difficult to consolidate; hence the larger bulk volume would settle to a greater extent, and typically over a longer period, when placed in a lagoon or monofill.

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