Consolidation properties of a dewatered municipal sewage sludge
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Brendan C. O'Kelly
BE, MEngSc, PhD, CEng MICE, PGeo MIGI, FGS

Department of Civil, Structural and Environmental Engineering
Museum Building
University of Dublin, Trinity College
Dublin 2, Ireland

and formerly Scott Wilson Consulting Engineers, UK

Tel. +353 16082387
Fax. +353 16773072
e-mail: bokelly@tcd.ie

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Abstract:

The consolidation properties of a dewatered municipal sewage sludge were studied using the oedometer, hydraulic consolidation cell and triaxial apparatus. Bioactive and stabilised test specimens of dried-compacted material and slurry material at different states of biodegradation (loss on ignition, LOI = 55–70 %) were consolidated under applied stresses of 3–400 kPa. The rate of biogas production and the resulting pore pressure response of the unsaturated material were also studied for different specimen drainage conditions.

The sludge material largely comprised organic clay-sized particles and although highly compressible, the material was practically impermeable ($k = 10^{-9}$–10^{-11} m/s for slurry material). Primary consolidation generally constituted only a small part of the overall deformation response for moderately degraded material (LOI ≅ 70 %). Secondary compression was dominant, and for the bioactive material, included a significant contribution due to ongoing degradation of the organic solids. The contribution of primary consolidation to the overall deformation response increased for higher levels of treatment (LOI ≅ 55 %) and the coefficient of secondary compression (C_{sec}) values were reduced; for example, $C_{sec} = 0.10$–0.24 ($\sigma_a' = 35$–150 kPa) for moderately degraded material and $C_{sec} \cong 0.09$ ($\sigma_a' = 300$ kPa) for strongly degraded material.

Biogas evolved from the material at a steady rate of up to 0.33-m^3 gas/day/tonne moderately degraded slurry, which caused the pore pressure to steadily increase at up to 40 kPa/day when the biogas remained trapped within the specimens.

Key words: sewage sludge, consolidation, biodegrade, biogas.

Notation:

c_v	Coefficient of primary consolidation
C_{sec}	Coefficient of secondary compression
C_c	Compression index
C_c^*	Compression ratio
d	Effective drainage length
G_s	Specific gravity of solids
k	Coefficient of permeability
LOI	Loss in dry mass on ignition
m_v	Coefficient of volume compressibility
OWC	Optimum water content for compaction
t_p	Time period for 100 % primary consolidation
u_b	Specimen back pressure
u_e	Excess pore water pressure
U	Degree of consolidation
w	Water content
w_i	Initial water content
σ_a	Applied stress
σ_3'	Effective confining stress

1. Introduction

Sewage sludge, the slurry residue derived from wastewater treatment processes, comprises solid organic particles typically finer than 0.1 mm, with a significant proportion of the particles in the colloidal range of 0.001–1 μm (Campbell et al. 1978). The sludge is usually degraded in bioreactors by naturally occurring bacteria to produce a more stable homogeneous material that is more amenable to disposal. Water and biogas (methane and carbon dioxide) are by products of the biodegradation process. The sludge material must be adequately dewatered, usually by allowing the slurry to air-dry in shallow beds or by consolidation using a mechanical press, for its efficient disposal off site. However, in practice, it generally proves very difficult to dewater the sludge, including by mechanical means; for example, the water content can be typically reduced to 230–570 % using the belt-filter press and lower water contents of typically 100–400 % can be achieved using the recessed-plate filter press (Droste 1997) after chemical additives have been mixed with the slurry to encourage flocculation. However, further reductions in the water content can usually only be achieved by drying processes.

The current understanding of the consolidation behaviour of the slurry material, pertinent to its mechanical dewatering at the treatment plant, and the dried sludge material, pertinent to its likely behaviour when compacted in a monofill, is limited. Some mechanical properties of a dewatered municipal sewage sludge, pertinent to its disposal in a monofill, were reported by O'Kelly (2004, 2005). The consolidation properties of sewage sludge from different sources can often vary significantly due to differences in the amounts and nature of industrial wastewater inputs and depending on the types and levels of treatment; for example, Imhoff et al. (1971) reported that moderately and fully biodegraded sewage sludge had organic contents of typically 70 and 45 %, respectively.

The index, consolidation and compaction properties of sewage sludge from Tullamore municipal wastewater treatment plant, Ireland, were studied. The plant serves an urban population of about 12,000 and had no significant industrial wastewater input. The sludge residue was degraded in a bioreactor at the treatment plant using the anaerobic, activated sludge digestion method (Metcalf and Eddy 1991). The temperature in the bioreactor was maintained at the optimum temperature for mesophilic digestion of 35 ^{o}C (Kilmartin 1991). Polyelectrolyte additives of Magnafloc®LT22S manufactured by Ciba® were mixed with the degraded slurry prior to dewatering using a belt-filter press.

2. Index tests

The greyish black sludge material from the treatment plant had a water content of about 725 %. Electron photomicrographs (Fig. 1) and a wet sieve analysis indicated that the sludge material comprised small quantities of grit, organic fibres and shredded plastic in a matrix of clay-sized particles with about 90 % by dry mass of the bulk material passing the 425 μm sieve. Colonies of microscopic rod-shaped bacteria, which were responsible for ongoing biodegradation of the sludge, were visible at greater magnification (Fig. 1 (b)). An X-ray diffraction analysis indicated that the inorganic clay minerals comprised kaolinite, calcite and quartz.

The liquid limit value of 315 % was measured using the cone penetrometer method. Slurry material refers to sludge with a water content greater than the liquid limit. The plastic limit value was 55 % and the plasticity index was 260 %. The same liquid and plastic limit values were reported for bentonite by Sivapullaiah and Lakshmikantha (2005). The shrinkage limit value of 10 % was determined from repeated mass and volume measurements of cylindrical specimens, initially 38.0 mm diameter by 76.0 mm high, which were allowed to slowly air-dry from the liquid limit condition.

The specific gravity of solids (G_s) value of 1.55 was measured using the small pyknometer method and using kerosene instead of distilled water as the density fluid in the pyknometers. This value falls within the G_s range of 1.40–2.10 reported for sewage sludge by Campbell et al. (1978). Ignition of dry powdered test specimens at 440 ^{o}C over a period of 18 hours gave a loss on ignition (LOI) value of 70 % by dry mass and is a fairly accurate measure of the organic content (Skempton and Petley 1970). The pH of 8.0 for the leachate was measured using an electrometric method. The linear shrinkage value of 32 % was measured as the percentage reduction in the lengths of bars of the sludge material, semi-circular in cross-section, which were air-dried from the liquid limit condition.

The sludge material is classified as organic clay of high plasticity according to the Unified Soil Classification System. The high LOI value and sieve analysis indicated that the bulk of the clay-sized particles were organic, most likely organic macromolecules and bacteria, and that the sludge had been only moderately biodegraded when removed from the bioreactor at the treatment plant.

A strong odour was produced when the sludge material was mixed or dried. Dried test material was prepared by allowing the slurry to air-dry outdoors at ambient temperatures of 5–15 ^{o}C. The material dried slowly, and when spread in 6-mm thick layers on sheltered trays, required a period of about two weeks to fully dry. The initial water content of the test material was controlled by varying the length of the drying period. A greasy residue sometimes formed on the surfaces of undisturbed pats of the sludge material. Laboratory oven drying of test specimens for water content determinations was carried out at an oven temperature of 60 ^{o}C to minimise the potential for charring of the solid organic particles.

3. Compaction test

A standard Proctor compaction test was conducted on air-dried sludge material and plots of bulk density and dry density versus water content are shown in Fig. 2. The densities achieved were low in comparison with mineral soils but are in line with the low G_s value measured for the sludge material. The values of the bulk density increased from about 0.65 tonne/m^3 for the dry material to 1.10 tonne/m^3 for material of soft consistency. The dry density–water content curve was relatively flat and the maximum dry density of 0.56 tonne/m^3 was achieved at about w = 90

%, the optimum water content (OWC) for compaction. The material was stiff and compacted poorly, remaining as separate lumps, for w < OWC.

4. Consolidation tests

Consolidation tests were conducted on slurry specimens and air-dried compacted sludge material using the oedometer, hydraulic consolidation cell and triaxial apparatus (Table 2). The effect of the level of treatment on the consolidation properties were studied by testing both moderately and strongly degraded material. Biogas continued to evolve from the sludge material taken from the treatment plant due to ongoing biodegradation. The rate of biogas production and the pore pressure response of the unsaturated material were studied for different specimen drainage conditions using the hydraulic consolidation cell. Additional treatments can also be applied in practice that effectively prevent further biodegradation occurring. Hence, the effect of neutralising the bacteria, which were responsible for the biodegradation, were also studied. The results of the different consolidation tests will be analysed and discussed after the different experimental procedures have been presented.

4.1. Oedometer tests

Oedometer tests were conducted on Specimens A and B of moderately degraded sludge material taken from the treatment plant (LOI = 70 %). Specimen A, 76.2 mm diameter by 30.0 mm high, was prepared by pouring the freshly remoulded slurry ($w_i \cong 725$ %) into the oedometer confining ring. Specimen B, 76.2 mm diameter by 19.0 mm high, was prepared from air-dried sludge material ($w_i \cong 130$ %) that had been compacted in a standard Proctor mould using standard Proctor compaction effort. Specimen B had a dry density of 0.50 tonne/m^3 and an air voids content of about 5 %.

Specimens A and B were consolidated under two-way vertical drainage conditions and the applied stress was doubled at the start of each load stage, which generally lasted at least 48 hours. The oedometer test on Specimen A commenced with a load step of $\sigma_a = 3$ kPa. The oedometer loading cap was found to tilt and the slurry extruded through the narrow gap between the oedometer loading cap and the confining ring causing unacceptable frictional restraint when higher stresses were initially applied during trial tests on the slurry. Cumulative strain–time plots are shown in Fig. 3 for Specimen A. Water content tests on thin sections taken across the specimen height at the end of the consolidation test indicated a uniform water content distribution and proved, for practical purposes, that full primary consolidation had been achieved. Cumulative strain–time data, plotted using linear and semi-logarithm timescales, are shown for Specimen B in Figs. 4 (a) and (b), respectively.

Considering that Specimen A consolidated steadily even for $\sigma_a = 3$ kPa (Fig. 3) and that the initial compressive strains for both specimens were small, it was concluded that the biogas was able to escape from the specimens due to favourable drainage lengths. Much larger initial compressions would have been expected had bubbles of biogas remained trapped within the specimens. The small reduction in strain that occurred towards the end of the first load step at 25 kPa for Specimen B was possibly due to the uptake of water by the specimen, which was initially in an unsaturated state (5 % air voids).

4.2. Hydraulic consolidation cell tests

Consolidation tests were conducted using the hydraulic consolidation cell (Fig. 5) on moderately degraded slurry taken from the treatment plant and strongly degraded slurry prepared in the laboratory. The first stage of these tests studied the pore pressure response when biogas remained trapped within the specimens. The second stage measured the rates of biogas production. The third stage neutralised the bacteria that were responsible for ongoing degradation of the solid organic particles. The bioactive and stabilised specimens were one-dimensionally consolidated during the fourth stage.

Specimen C was 254 mm diameter and initially 80 mm high, giving an initial volume of 4.0 L. Specimen D was initially 50 mm high, giving an initial volume of 2.5 L. Both specimens were prepared from moderately degraded slurry ($w_i \cong 725$ %, $G_s = 1.55$, LOI = 70 %) that was poured into the hydraulic consolidation cell in three layers of about equal thickness. A vacuum was applied via the lid of a dessicator container, which formed a seal against the top of the hydraulic consolidation cell, in order to degas each layer of slurry after it had been placed.

The first stage of the tests studied the rate of increase in the pore pressure for moderately degraded material at ambient laboratory temperature of 21 ^{o}C. Volumetric strain of the specimen was prevented by closing the specimen drainage lines and the hydraulic pressure line to the cell diaphragm (Fig. 5). The build up in the pressure exerted on the cell diaphragm and the pore pressure response are shown in Fig. 6 for Specimen D. The swelling pressure exerted on the cell diaphragm steadily increased at about 40 kPa/day, and following from Boyle’s Law for gases, the biogas must have been steadily produced irrespective of the induced confining stress. About 6.9 L of biogas escaped from Specimen D when the valves on the specimen drainage lines were opened to allow the excess pore pressure to fully dissipate. The volume of biogas that escaped from the specimen was measured using the collection system shown in Fig. 7.

The second stage studied the rate at which biogas was being produced when Specimen D was allowed to biodegraded further under optimum laboratory conditions. The hydraulic consolidation cell was placed in a drying oven and the volume of biogas that evolved from the specimen was recorded over a period of 21 days (Fig. 8). The oven chamber temperature was maintained at the optimum temperature for mesophilic digestion of 35 ^{o}C. The valve on the hydraulic pressure line to the cell diaphragm (Fig. 5) was closed and the specimen was allowed to freely drain to the biogas collection system. A total of 23.7 L of biogas was produced and further analysis indicated that the biogas evolved at a steady rate of about 0.33-m^3 gas/day/tonne moderately degraded slurry. Index tests conducted on Specimen D at the end of the consolidation test (fourth stage) indicated that the slurry material had been strongly degraded (LOI = 55 %, G_s = 1.72, pH = 7.7) at the end of the 21 days of heat treatment.

The third stage stabilised the bacteria that were responsible for ongoing degradation using further heat treatment. The hydraulic consolidation cell, which was set up such that the undrained specimen was able to swell freely, was placed in the oven chamber and the oven temperature increased to 80 ^{o}C over a period of five hours. Biogas had stopped evolving after the specimen had been maintained at 80 ^{o}C for two and a half hours. The oven temperature was then gradually reduced to ambient laboratory temperature. Specimen D was stabilised before the consolidation stage whereas Specimen C was stabilised after the consolidation stage to allow comparison of the consolidation behaviours of bioactive and stabilised sludge.

The height of Specimen C reduced from 80 to 66 mm (volumetric strain of 17.5 %) during the intervening period leading up to the start of the fourth stage due to some drainage and biodegradation (LOI reduced from 70 to 65 %) of the slurry at ambient laboratory temperature. The unsaturated specimen had been allowed to freely drain to atmosphere under the action of some build up in the pore pressure that had occurred due to biodegradation. The specimen was consolidated under σ_a = 100 kPa with both ends of the specimen freely draining to atmosphere (back pressure, u_b = 0 kPa) so that the initial effective drainage length was 33 mm. The pore pressure response was not recorded since the material was still bioactive.

The height of Specimen D reduced from 50 to 24 mm (volumetric strain of 52 %) due to the much stronger degradation that occurred during the heat treatment at 35 ^{o}C over 21 days. The reduction in the solid dry mass of 33 % was calculated indirectly assuming that the full dry mass reduction occurred due to degradation of the organic fraction alone. The reduction in the water content from 725 to 510 % was calculated based on the reductions in the specimen height and the LOI from 70 to 55 %, with G_s = 1.72. The specimen, which had been stabilised beforehand, was consolidated under σ_a = 300 kPa with the top end of the specimen draining freely to atmosphere (u_b = 0) so that the initial effective drainage length was 24 mm. The excess pore water pressure (u_e) was measured at the bottom end of the specimen using a pressure transducer. The degree of consolidation (U) was calculated from the pore water pressure readings using eq. [1]. The final water contents of Specimens C and D were 255 and 170 %, respectively.

$$U = \frac{\sigma_a - u_e}{\sigma_a - u_b} \qquad [1]$$

where σ_a is the applied stress.

The strain and degree of primary consolidation versus time data are shown in Fig. 9 for Specimens C and D. The data for Specimen C were adjusted to facilitate more direct comparison of the consolidation behaviours. The consolidation times recorded for Specimen C (t_C) were reduced using eq. [2] such that the initial effective drainage length of Specimen C was equal to that for Specimen D. Eq. [2] assumes that the coefficient of primary consolidation values for the two specimens were equal.

$$t_C = \frac{t_D \, d_C^2}{d_D^2} \qquad \text{(Terzaghi 1943)} \qquad [2]$$

where t_C and t_D are the consolidation times and d_C and d_D are the effective drainage lengths for Specimens C and D, respectively.

4.3. Triaxial consolidation tests

Isotropic triaxial consolidation tests were conducted on moderately and strongly degraded specimens, initially 38 mm diameter by 76 mm high, prepared from the consolidated sludge cakes (Specimens C and D). The pore water pressure responses of the triaxial specimens could be accurately recorded since the sludge had been biologically stabilised. Triaxial Specimens E1–E3 of moderately degraded material (LOI ≅ 65 %, w_i ≅ 255 %) were formed by repeatedly cutting Specimen C with a 38-mm diameter sampling tube to build up continuous specimens slightly greater than 76 mm in height. Triaxial Specimen F of strongly degraded material (LOI ≅ 55 %, w_i ≅ 170 %) was formed in a similar manner from consolidated Specimen D.

The cell confining pressure and the specimen back pressure were sequentially incremented in the triaxial apparatus. The pore water pressure parameter B (Skempton 1954) was found to exceed 0.96 for a specimen back pressure of 200 kPa indicating that the specimens were in a saturated condition. The triaxial specimens were prepared in this manner since trial tests had indicated that it would have taken too long to achieve the same degree of saturation using partially saturated specimens prepared from air-dried compacted sludge material.

The cell confining pressures were increased to E1 = 350, E2 = 280, E3 = 235, F = 500 kPa, and the specimens were allowed to isotropically consolidate. Drainage occurred from the radial boundary and from both ends of the specimens. The pore water pressure responses were measured at different stages during the tests to determine the degree of consolidation that had been achieved (eq. [1]). The valves on the drainage lines from both ends of the specimen were temporarily closed, usually for a period of between two and seven hours, and the excess pore water pressures, which began to equilibrate throughout the specimen (Fig. 10), were recorded using a pressure transducer connected via the specimen base pedestal. The degree of consolidation was calculated based on the equilibrium pore water pressure values that were estimated from the data recorded for the different undrained stages. The volumetric strains and degrees of primary consolidation are shown in Figs. 11 and 12.

5. Analysis of consolidation test results

The consolidation properties of the sludge material were studied following analysis of the strain–time responses of Specimens A–F using Terzaghi (1943) consolidation theory. The compressibility was assessed in terms of the different contributions of initial compression, primary consolidation and secondary compression, bearing in mind that the strain–time responses had been recorded using different apparatus and hence under different applied stress and drainage conditions; for example, Specimens A–D were one-dimensionally consolidated whereas Specimens E1–E3 and F were isotropically consolidated. The time period required to achieve full primary consolidation (t_p), which corresponded to the point of contraflexure in the lower part of the strain–time curves, was interpreted throughout using the Log of Time curve-fitting method (ASTM D2435 2004).

5.1. Bioactive, moderately degraded sludge from treatment plant

The amounts of initial compression recorded at the start of the load steps for slurry Specimens A and C (Figs. 3 and 9) were insignificant indicating that favourable drainage lengths had allowed the biogas to escape and that the specimens had remained in an almost saturated condition. Primary consolidation, associated with the dissipation of the excess pore water pressure, was dominant during the early compression of the slurry; for example, analysis of the first load step at 3 kPa for Specimen A (w = 650–725 %) indicated a coefficient of permeability (k) value of $3\text{x}10^{-9}$ m/s. The k value was calculated using eq. [3] and values of the coefficient of primary consolidation (c_v) of 0.44 m^2/year and the coefficient of volume compressibility (m_v) of 21.5 m^2/MN from curve-fitting analysis.

$$k = m_v \, c_v \, \gamma_w \qquad [3]$$

where γ_w is the unit weight of water.

However, further compression rendered the slurry impermeable for practical purposes and secondary compression, due to both creep deformation and biodegradation of the solid organic particles, became dominant below about 650 % water content. The creep rates recorded for the different load steps were fairly uniform; see for example, the strain–time responses for the dried compacted sludge material (Specimen B, Fig. 4a). The coefficient of secondary compression (C_{sec}) values, defined as the specimen strain that occurs over one log cycle of time after primary consolidation was complete, are listed in Tables 2 and 3 for the different specimens.

In this study, the C_{sec} values were calculated based on the specimen strain that occurred over the time periods of 200–2,000 minutes (Specimens A and B); 2,000–20,000 minutes (Specimen C); and 1,000–10,000 minutes (Specimens D–F). Curve-fitting analysis of the strain–time responses indicated that primary consolidation had occurred during the preceding time periods. The C_{sec} values were very high and were generally stress-level dependant; for example, the multiple-increment load tests on Specimens A and B indicated a general trend of C_{sec} increasing from 0.02 to 0.08 with increasing applied stress from 3 to 400 kPa (Table 2), which is typical of very soft, highly organic soils (Hobbs 1986).

5.2. Effect of biological stabilisation

The effect on the consolidation properties of biologically stabilising the moderately degraded sludge was studied by comparing the strain–time responses of bioactive Specimen C (C_{sec} = 0.32 for σ_a = 100 kPa, Table 2) and stabilised Specimens E1–E3 (C_{sec} = 0.10–0.24 for σ_3' = 35–150 kPa, Table 3). Note that these specimens had been consolidated under slightly different stress and drainage conditions in the different apparatus. Specimen C had been one-dimensionally consolidated whereas Specimens E1–E3 had been isotropically consolidated. However, the experimental results indicated that the values of the consolidation parameters corresponding to similar applied stresses could be compared with reasonable accuracy; for example, stabilised Specimens D and F had similar strain responses for σ_a = 300 kPa with C_{sec} = 0.08 and 0.10, although the respective specimens had been consolidated using the hydraulic consolidation cell and triaxial apparatus.

Interpolation of the C_{sec} values for Specimens C and E1–E3 (Tables 2 and 3) indicated that the rate of compression for the bioactive material ($C_{sec} = 0.32$) was about double that for the stabilised material. Secondary compression occurred due to both creep deformation and biodegradation of the solid organic particles for bioactive material whereas creep deformation alone occurred for the stabilised material. The contribution of biodegradation to the long-term deformation response of bioactive material would have been even larger at lower applied stresses since the creep rate was stress-level dependant. Note that the C_{sec} values calculated from the single-increment load tests (Specimens C–F) were much higher than the values calculated from the multiple-increment load tests (Specimens A and B) since the amount of secondary compression is dependant on the stress increment ratio.

The residual excess pore water pressures recorded at the end of the consolidation tests were significant, with typically final degrees of consolidation of only 92 % (Figs. 9, 11 and 12), which was largely due to the very high rates of secondary compression.

5.3. Effect of state of biodegradation

The strain–time responses of moderately degraded Specimens E1–E3 (Fig. 11) and strongly degraded Specimens D and F (Figs. 9 and 12) were compared to assess the effect of the state of degradation on the consolidation properties. Again, the moderately degraded material was impermeable for practical purposes with secondary compression dominant (C_{sec} = 0.10–0.24, Table 3). However, the strongly degraded material was much more permeable with primary consolidation dominant although the coefficient of permeability value of 6×10^{-11} m/s (w = 170–510 %) was still very low. The k value was calculated using eq. [3] and with $m_v \cong 2.0$ m^2/MN and $c_v \cong 0.09$ m^2/year from curve-fitting analysis of Fig. 9. Curve-fitting indicated that the total axial strain for Specimen D comprised 2.5 % initial compression, 86.5 % primary consolidation and 11.0 % secondary compression and that full primary consolidation had occurred after a period of about 2,000 minutes (Fig. 9a).

5.4. Compressibility

The compressibility of the sludge material was quantified in terms of the compression index (C_c), defined as the gradient of the void ratio–logarithm effective stress curve (Fig. 13). The sludge material was extremely compressible with significant reductions in the void ratio occurring with increasing effective stress and for longer loading durations, largely as a result of secondary compression. The C_c values were extremely high; typically 5.4–7.8 for the slurry and 0.6 for sludge material compacted at w = 130 %. Typical compression ratio (C_c*) values of 0.65 for the slurry and 0.20 for the compacted material were calculated using eq. [4].

$$C_c{}^* = \frac{C_c}{1 + e_o} \qquad [4]$$

where e_o is the initial void ratio.

6. Discussion

The laboratory consolidation behaviour of the moderately degraded slurry is consistent with experience of dewatering the same material at the treatment plant where consolidation to w = 725 % was achievable using a belt-filter press. The coefficient of permeability value was 3×10^{-9} m/s over the water content range of 650–725 %. However, consolidation of the slurry became progressively more difficult below about 650 % water content and much higher consolidation pressures, which would have required using an hydraulic consolidation press at the plant, were necessary. The very low permeability and high rates of secondary compression (C_{sec} = 0.02–0.08, from multiple-increment oedometer tests) were consistent with the size and nature of the constituent particles. The flocculated clay-sized organic particles of which the material was largely composed would tended to trap surface and internal water.

Higher states of degradation can be achieved in practice by extending the retention period for the slurry in the bioreactors at the treatment plant. The benefits include:

- Increases in permeability allowing more efficient dewatering using standard mechanical means and hence greater reductions in the bulk volume of material for disposal off site.
- Reductions in the organic content and hence the sludge dry mass; for example, the LOI reduced from 70 % for moderately degraded material to 55 % for strongly degraded material and the dry mass of the bulk solids reduced by one-third.
- Reductions in excess pore pressures due to reduced rates of biogas production and secondary compression.

Hence, more strongly degraded sludge material can be disposed more efficiently and safely off site and the costs of transporting the bulk material from the treatment plant are also reduced. The potential for instability of the slopes at a sludge monofill can be further reduced by biologically stabilising the material. The amount of settlement at the monofill can be predicted using the void ratio–logarithm effective stress data (Fig.13) or an appropriate compression index value. The rate of settlement can be predicted using an appropriate coefficient of secondary compression value considering the in-situ stress regime, level of bioactivity and state of biodegradation of the placed material.

7. Summary and conclusions

The municipal sewage sludge was moderately degraded (LOI = 70 %, G_s = 1.55) at the treatment plant using the anaerobic activated sludge digestion method and dewatered to about 725 % water content using a belt-filter press. The sludge material, which comprised flocculated organic macromolecules and smaller quantities of kaolinite, calcite and quartz, was classified as organic clay of high plasticity. The bulk density of standard Proctor compacted material increased from 0.65 tonne/m^3 for the dry material to 1.10 tonne/m^3 for material of soft consistency. The maximum dry density of 0.56 tonne/m^3 was achieved at 90 % water content.

Primary consolidation was dominant during the early compression of the slurry (w = 650–725 %) with a coefficient of permeability value of the order of 10^{-9} m/s. Consolidation became progressively more difficult, and below about 650 % water content, the sludge material became impermeable for practical purposes, with secondary compression due to creep deformation and biodegradation of the solid organic particles dominant. However, the material was extremely compressible with C_{sec} = 0.02–0.08 from multiple-increment oedometer tests (σ_a = 3–400 kPa). Air-dried, standard Proctor compacted sludge material had a compression index value of typically 0.6.

Biogas evolved at about 0.33-m^3 gas/day/tonne slurry at 35 °C. Trapped biogas induced swelling pressures that steadily increased at up to 40 kPa/day under undrained conditions at 21 °C. The effect of stabilising the bacteria by heat treatment at 80 °C was generally to halve the rate of secondary compression, which subsequently occurred due to creep deformation alone of the organic particles.

Stronger levels of biological treatment reduced the organic content and hence the dry mass of the bulk solids. The production of strongly degraded sludge (LOI = 55 %, G_s = 1.72) caused the solid dry mass to reduce by one-third and yielded a more permeable material with a coefficient of permeability value of the order of 10^{-11} m/s (w = 170–510 %).

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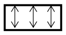
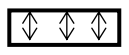
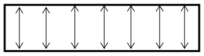
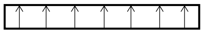
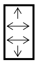
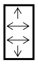
Specimen	Consolidation test	Sludge material			Initial water content (%)	Applied stress (kPa)	Specimen	
		Consistency	Degradation				Dimensions (mm)	Drainage conditions
			Bio-active	State				
A	Oedometer	Slurry	Yes	Moderate	725	MI: σ_a range, 3→100→3	76.2 dia. x 30 H	
B	Oedometer	Dried, compacted	Yes	Moderate	130	MI: σ_a range, 25→400→25	76.2 dia. x 19 H	
C	Hydraulic consolidation cell	Slurry	Yes	Moderate	700	SI, $\sigma_a = 100$ $u_b = 0$	254 dia. x 66 H, two-way drainage	
D	Hydraulic consolidation cell	Slurry	No	Strong	510	SI, $\sigma_a = 300$ $u_b = 0$	254 dia. x 24 H, one-way drainage	
E1 E2 E3	Isotropic triaxial	Very soft	No	Moderate	255	SI: $\sigma_3' = 150$ $\sigma_3' = 80$ $\sigma_3' = 35$	38 dia. x 76 H, all around drainage	
F	Isotropic triaxial	Soft	No	Strong	170	SI, $\sigma_3' = 300$	38 dia. x 76 H, all around drainage	

Table 1. Summary of consolidation tests. (MI = multiple increment. SI = single increment).

	Multiple-increment load tests											Single increment	
	Slurry						Dried compacted					Slurry	
Specimen	A						B					C	
Applied stress (kPa)	3	6	12	25	50	100	25	50	100	200	400	100	
C_{sec}	0.02	0.03	0.07	0.08	0.07	0.05	–	0.02	0.03	0.04	0.05	0.07	0.32
Log time cycle (min)	200–2,000												2,000–20,000

Table 2. C_{sec} values for bioactive moderately degraded sludge.

	State of biodegradation				
	Moderate			Strong	
Specimen	E3	E2	E1	D	F
Effective confining stress (kPa)	35	80	150	300	300
C_{sec}	0.10	0.18	0.24	0.08	0.10
Log time cycle (min)	1,000–10,000				

Table 3. C_{sec} values for stabilised sludge from single-increment consolidation tests.

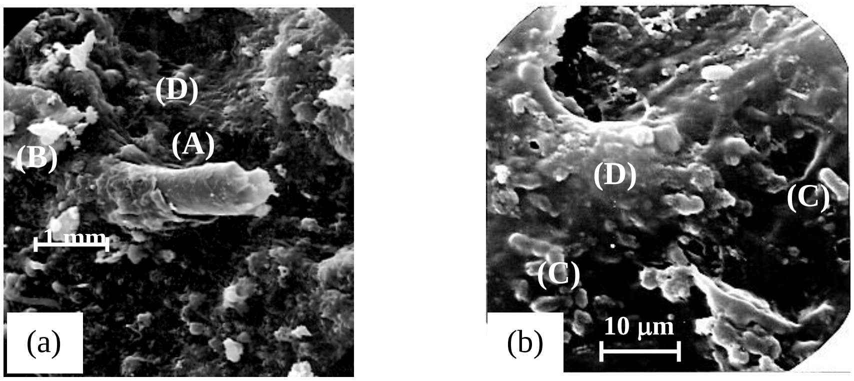


Fig. 1. Photomicrographs of sludge material indicating: (A) organic fibres; (B) grit; (C) colonies of rod-shaped bacteria; (D) matrix of clay-sized particles.

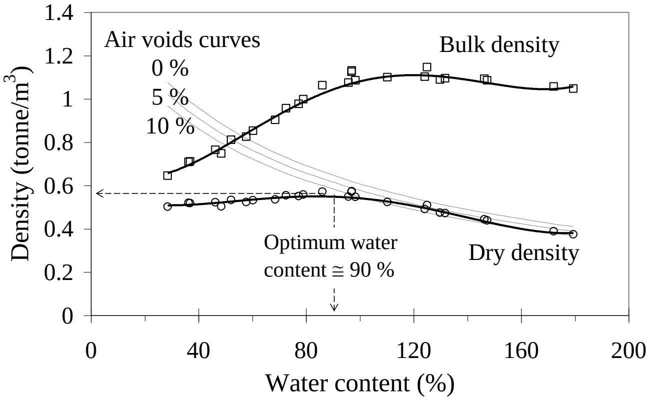


Fig. 2. Compacted density versus water content.

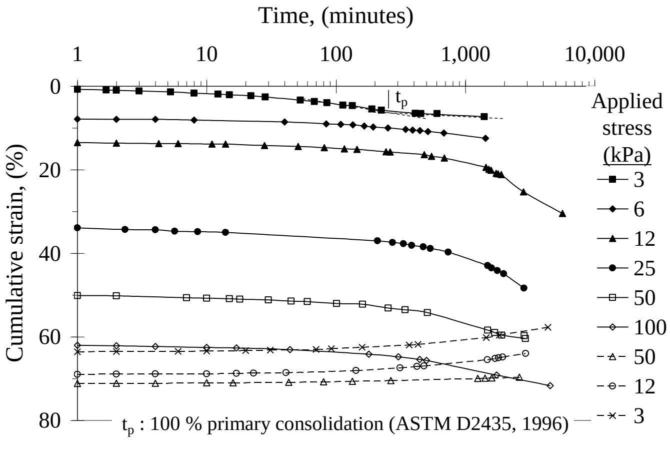
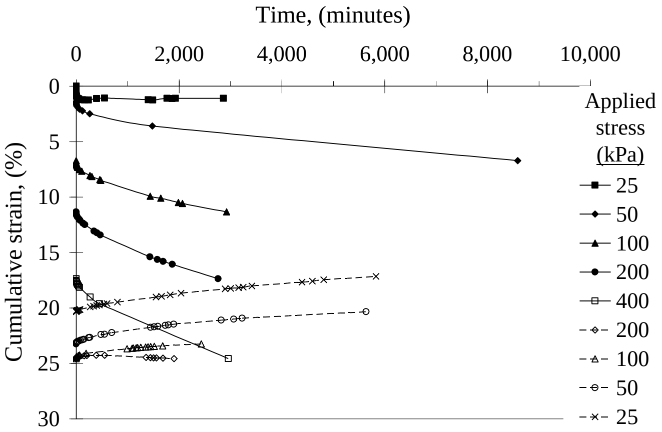
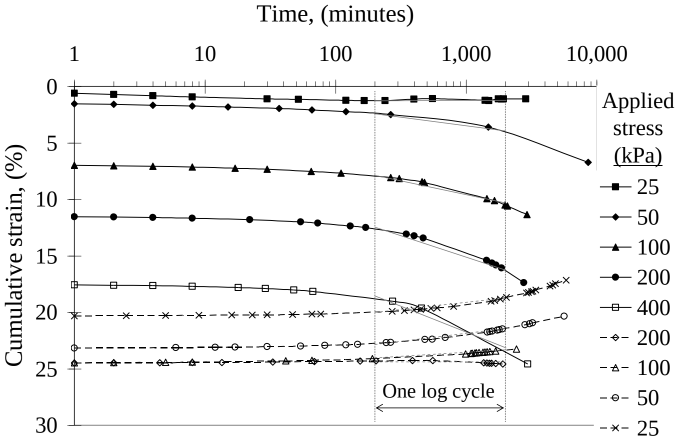


Fig. 3. Oedometer consolidation of moderately degraded slurry (Specimen A).



(a) Cumulative strain versus time.



(b) Cumulative strain versus logarithm time.

Fig. 4. Oedometer consolidation of moderately degraded compacted sludge (Specimen B).

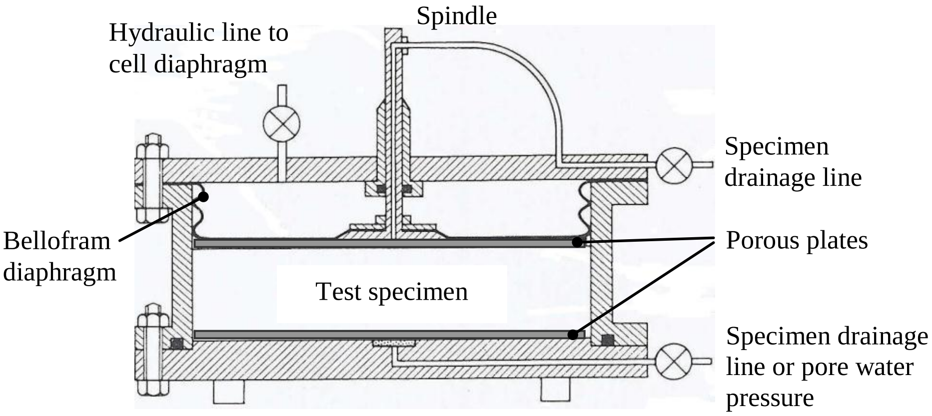


Fig. 5. Hydraulic consolidation cell.

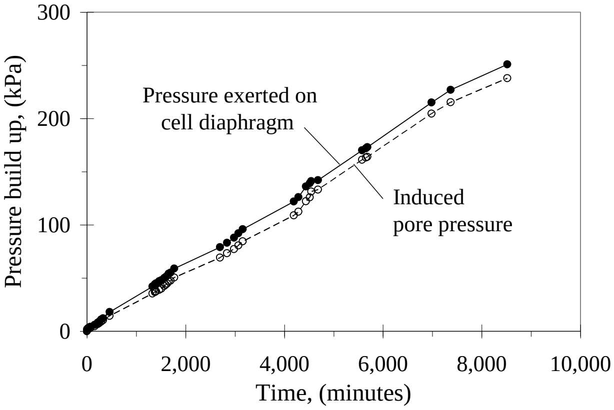


Fig. 6. Pore pressure build up due to ongoing degradation of Specimen D (2.5 L slurry).

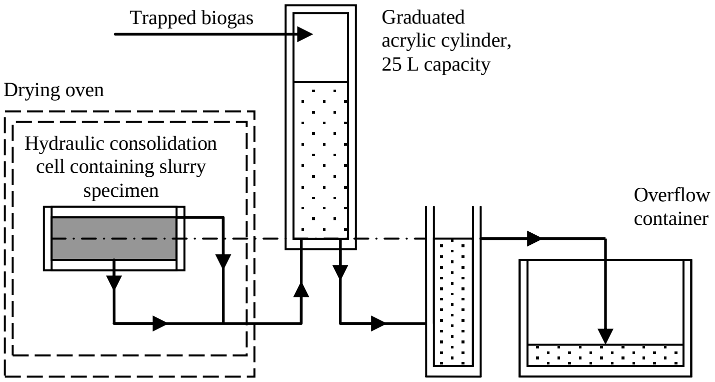


Fig. 7. Set up to measure volume of biogas evolving from slurry specimen.

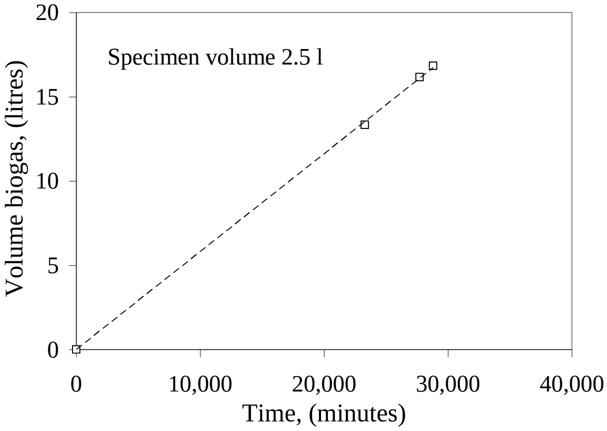
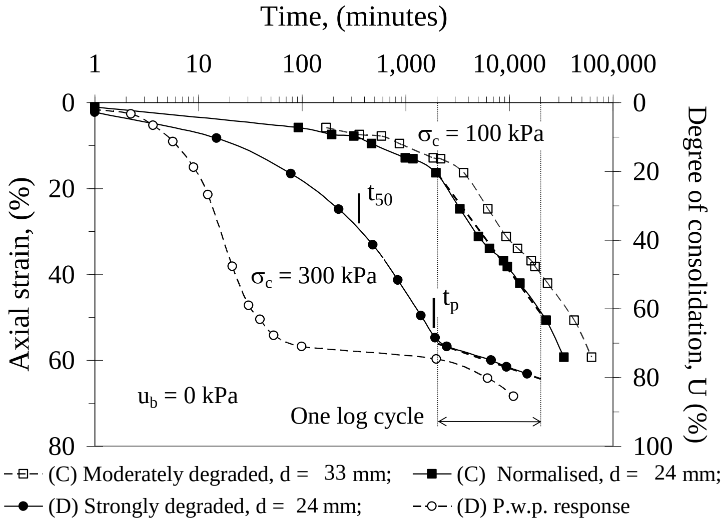
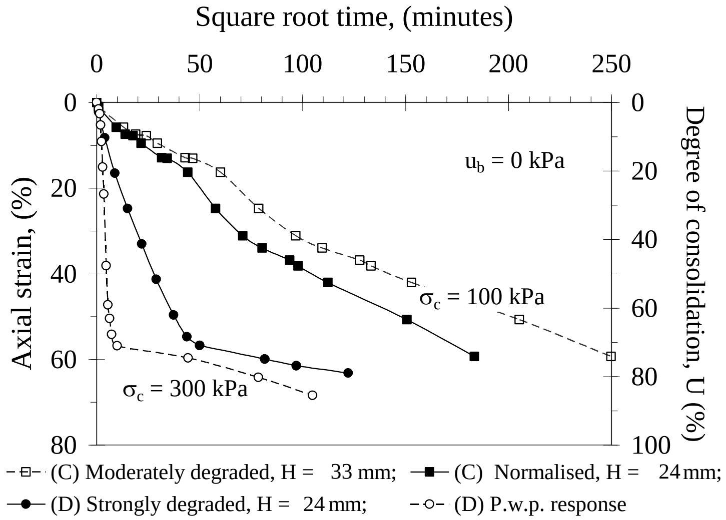


Fig. 8. Biodegradation of moderately degraded slurry at 35°C (Specimen D).



(a) Axial strain versus logarithm time (t_{50} and t_p are time periods for 50 and 100 % primary consolidation).



(b) Axial strain versus square root time.

Fig. 9. Hydraulic consolidation tests on moderately and strongly degraded slurry.

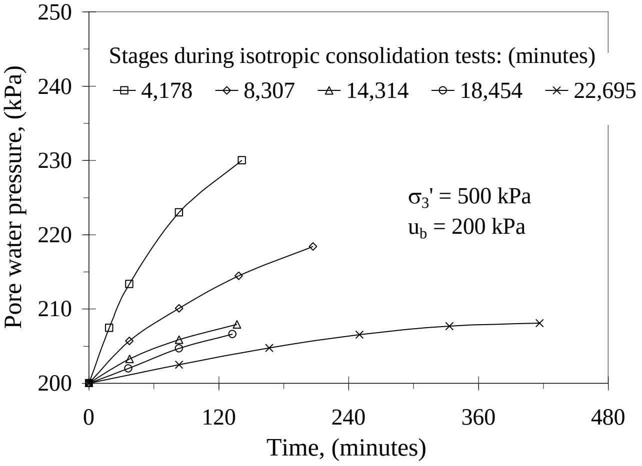


Fig. 10. Equilibration of pore water pressure in Specimen F.

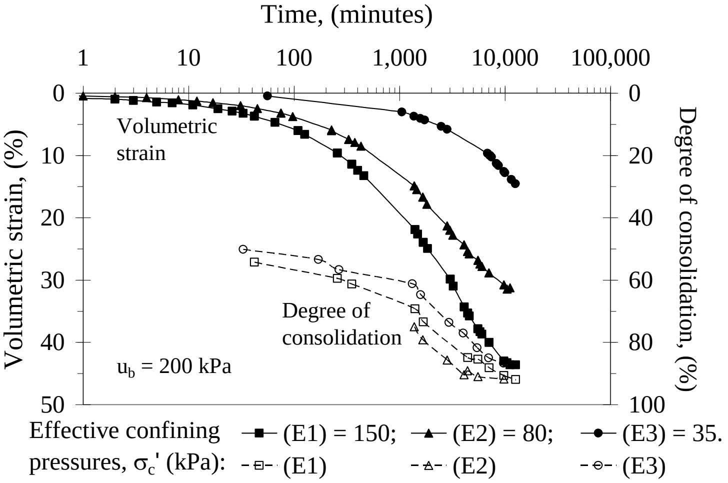


Fig. 11. Triaxial consolidation tests on moderately degraded Specimens E1–E3.

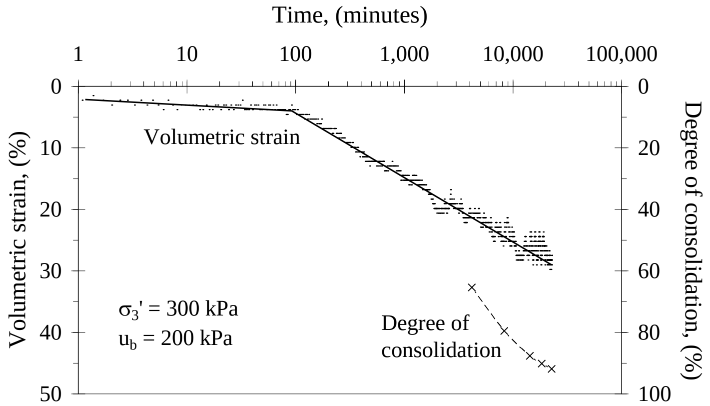


Fig. 12. Triaxial consolidation tests on strongly degraded Specimen F.

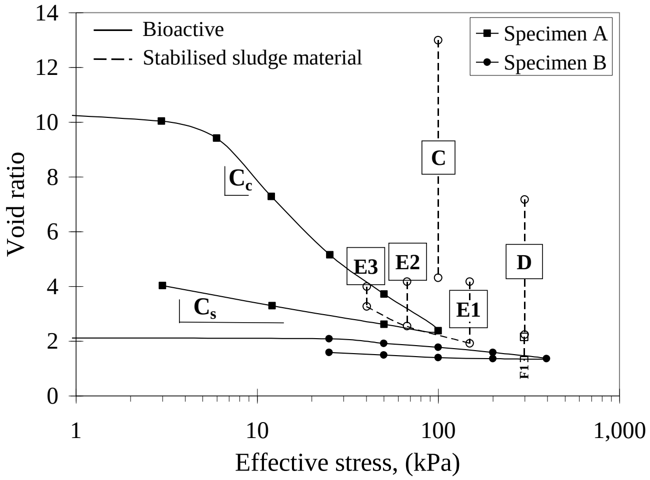


Fig. 13. Void ratio versus effective stress.