Sewage sludge to landfill: Some pertinent engineering properties

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ABSTRACT:

More stringent controls on the quality of wastewater discharges are giving rise to increasing volumes of sewage sludge for disposal, principally to land, using either land-spreading or sludge-to-landfill operations. Current sludge-to-landfill methods generally involve mixing the concentrated sludge with other solid waste in municipal landfills. However, stricter waste disposal legislation and higher landfill taxes are forcing the water industry to look for more efficient disposal strategies. Landfill operators are also increasingly reluctant to accept liquid sludge due to construction difficulties and the potential for instability of the landfill slopes.

The engineering and drying properties of sewage sludge are presented and applied, in particular, to the design, construction and performance of sewage sludge monofills. Sludge handling and landfill construction are most effectively conducted typically within the water content range of 85% water content, the optimum water content for standard proctor compaction, and 95% water content, the sticky limit of the sludge material. Standard proctor compaction of the sludge within this water content range also achieves the maximum dry density of about 0.56 tonne/m^3 which maximizes the storage capacity and hence the operational life of the landfill site. Undrained shear strength-water content data (pertinent to the stability of the landfill body during construction) and effective stress strength parameters, which take into account the landfill age and the effects of ongoing sludge digestion, are presented. Landfill subsidence which occurs principally due to creep and decomposition of the sludge particles is significant and continues indefinitely but at progressively slower rates.

IMPLICATIONS:

Stricter waste disposal legislation, higher landfill taxes and reluctance on behalf of landfill operators to accept liquid sludge are forcing the water industry to look for more efficient disposal strategies for ever increasing volumes of sewage sludge. The paper advocates dedicated sludge-to-landfill operations which involve placing and compacting the dewatered sludge in layers to achieve the maximum dry density, thereby maximizing the operational life of the landfill. Potential environmental hazards, including slope instability and large volumes of leachate associated with current practice in which the liquid sludge is usually mixed with solid waste at municipal landfills, are minimized using the design and construction recommendations presented.

INTRODUCTION

Sewage sludge is the slurry residue derived from wastewater treatment processes. More stringent controls on the quality of wastewater discharges are giving rise to greater volumes of the sludge for disposal. Principal disposal routes include agricultural recycling and land restoration or sludge to landfill operations, either co-disposal at municipal solid waste landfills or mono-disposal at dedicated sites. The sludge must be adequately dried or dewatered to engineer, for example, the efficient handling and trafficability by machine plant, optimum compaction and an adequate factor of safety against slope instability for the sludge to landfill route. The dewatered sludge is a soil-like material, and as such, its performance in the landfill can be modeled using soil mechanics theory and knowledge of the drying, shear strength and consolidation properties of the compacted material. Geotechnical properties are presented which, when applied to the design of a sludge landfill, will help minimize potential environmental hazards by increasing landfill stability and controlling leachate and biogas generation. In the process, these procedures will maximize the storage capacity and hence the operational life of a given sludge disposal site. The landfill design must take account of the effects of digestion on the engineering properties of the sludge material when determining the long-term factor of safety against instability of the landfill slopes.

The current level of knowledge of the engineering and drying properties of sewage sludge is limited.[1] The focus of this investigation was to determine the engineering and drying properties of sewage sludge of various consistencies using standard soil laboratory tests. Soil index tests, which characterize to some extent the engineering behavior of the sludge material; compaction; shear strength and consolidation tests, were conducted. Full descriptions of the laboratory tests are given by Head.[2,3,4] Biologically active and neutralized samples were tested to study the effects of the initial level of treatment at the wastewater plant and ongoing sludge digestion in the landfill body.

Sludge samples were obtained from Tullamore Municipal Wastewater Treatment Plant, Ireland, which serves an urban population of approximately 12,000. Treatment at the plant involves anaerobic, activated digestion of the thickened sludge which has the effect of reducing the sludge dry mass and produces a more stable, homogeneous sludge.[5] Polyelectrolyte dosing of the digested sludge facilitated sludge dewatering to approximately 720% water content using a belt filter press. Water content (WC) is defined as the ratio of the mass of pore water to the mass of solid particles, expressed as a percentage. In water treatment literature, sludge consistency is usually quantified in terms of the solids content (SC), defined as the ratio of the mass of the solid phase to the bulk sludge mass, also expressed as a percentage. Based on these definitions, water content and solids content are related using Eq. 1.

$$SC = \frac{100}{1+\left(\frac{WC}{100}\right)} \qquad [\%] \qquad (1)$$

PHYSICAL PROPERTIES

The plasticity characteristics, particle size distribution, specific gravity of solids and loss on ignition values for sewage sludge direct from the treatment plant are summarized in Table 1. The plasticity characteristics were evaluated based on the results of Atterberg limit tests which yielded a liquid limit of 315% water content and a plastic limit of 55% water content. The plasticity index of 260% is the difference between the liquid limit and plastic limit values. Approximately 90% of the sludge dry mass passed the 425µm sieve size when the sludge material was washed through that sieve. Material retained on the sieve comprised grit and silt particles, organic fibers and shredded plastic. The specific gravity of solids value of 1.55 was measured using the pycnometer method. The loss on ignition (LOI) value, an indirect and reasonably accurate measure of the soil organic content, was 70% dry mass for an ignition temperature of 440^{o}C. The linear shrinkage value, defined as the reduction in the length of a bar of sludge material when dried from the liquid limit condition, expressed as a percentage of the initial bar length, was 32%.

The sieve analysis and LOI value indicate that the sewage sludge largely comprised organic clay-sized particles. Soil classification using the Plasticity Classification Chart [6] indicates organic clay of high plasticity. The LOI value measured for the sludge material from the wastewater treatment plant indicates that it was initially only moderately digested. Strongly digested sewage sludge typically has an LOI value of between 45% and 55%.[7] The specific gravity of solids value is low, although similar to values reported for peats.[8] Most soils typically have a specific gravity value in the range 2.5 to 2.7.

Further tests were conducted on bulk samples of the sludge which were stored outside in drums and allowed to digest naturally at ambient temperature. Ongoing sludge digestion breaks down the remaining volatile organic solids, generating biogas and additional pore water as by-products. Two and a half years after treatment at the wastewater plant, the specific gravity of the sludge had increased from 1.55 to 1.63 while the LOI value had decreased significantly from 70% to 58% (Figure 1). Ongoing digestion causes the proportion of the denser inert particles present in the sludge to increase; hence, the specific gravity of solids value gradually increases over time. The sludge also became slightly more acidic with time with the pH reducing from its initial value of 8.0 to between 7.6 and 7.8 for the different samples tested.

Samples of moderately digested sludge, typically of 2.5 liters volume, were also digested further in the laboratory by heating at 35^{o}C (the optimum temperature for mesophilic digestion) over 21 days. Strongly digested sludge with specific gravity of solids and LOI values of 1.72 and 55%, respectively, (point A, Figure 1) was produced in this manner. Biogas evolved from these samples at a fairly steady rate of approximately 0.3 liters biogas/day/kg sludge. The sample volume was reduced by typically 1.3 liters, a reduction of approximately 50% of the initial dry mass of the sludge material.

DRYING AND COMPACTION

Layers of sewage sludge dried slowly at ambient temperatures of between 5°C and 15°C. The drying periods were varied to control the initial water content of the test material. Figure 2 shows bulk density and dry density versus water content data achieved for drying and compaction processes. Density values are low, but in line with the low specific gravity of solids values measured. A zero air voids curve included in Figure 2 indicates the upper limit for the dry density that can be achieved for the sludge material.

Sludge densities produced by natural evaporation alone were determined from regular mass and volume measurements of cylindrical samples, initially 38mm diameter by 76mm high, which were slowly air-dried from the liquid limit condition over a 30 day period (heavier curves, Figure 2). This density data is pertinent, for example, to the air-drying of liquid sludge in drying beds.

Laboratory compaction tests were conducted on partially dried sludge using standard proctor compactive effort. The dry density-water content curve for compaction alone (lower light curve, Figure 2) is relatively flat. At low values of water content, below 85% water content, the sludge material is stiff and is difficult to compact. As the water content is increased the sludge becomes more workable, facilitating compaction and higher dry densities are achieved. At higher water contents, however, the dry density decreases with increasing water content, with an increasing proportion of the sludge volume being occupied by water. Optimum compaction is achieved at approximately 85% water content and produces a maximum dry density of 0.56 tonne/m^3. Slightly higher dry density values are obtained over the water content range for greater levels of sludge digestion since the specific gravity of solids increases with higher levels of sludge digestion (Figure 1). The test data is used to control, for example, the density of sewage sludge disposed to landfill site. The storage capacity of the landfill is optimized by compacting the sludge material to achieve the maximum insitu dry density which extends the operational life of the landfill. Proctor compactive effort causes some overcompaction of the sludge material which results in swelling and some softening of the compacted material. A lighter compactive effort, also suggested by Loll [9], is recommended for field compaction operations. The sludge compacted poorly.

Further tests were conducted to determine the densities that are achieved by air drying sludge which had been compacted under optimum conditions. This data is pertinent to the natural drying of sludge material compacted in the landfill. Test specimens were prepared from samples that had been compacted at approximately 85% water content using standard proctor compactive effort. These specimens were air dried, with regular measurements of the sample mass and volume. Significantly higher bulk and dry density values (similar to those values achieved by natural evaporation alone) are achieved in this manner.

The volumetric shrinkage, re-hydration and adhesion properties of the sludge material were also measured. The shrinkage ratio, defined as the ratio of the change in volume of the sludge material to the change in water content, is typically 1.34 for digested sludge. The sludge material ceases to contract on drying at 10% water content, usually referred to as the shrinkage limit. Free swell tests [10] indicated that dry sludge material has the potential to approximately double in volume on re-hydration. This is pertinent, for example, to the swelling behavior of thermally dried sludge pellets disposed to landfill. However, re-hydration of the soil generally occurs very slowly. The lowest water content at which the sludge material adheres to metal tools, often referred to as the sticky limit, was determined as 95% water content. Handling operations and landfill construction may prove difficult above approximately 95% water content due to the tendency of the sludge to stick to machine plant.

SHEAR STRENGTH

The shear strength properties of the sludge were measured. Short-term shear strength, usually referred to as the undrained shear strength, is pertinent to engineering efficient handling, trafficability and providing an adequate factor of safety against slope instability during landfill construction. The effective stress strength properties, which consider the effects of sludge digestion and equilibrium pore pressures, are used to determine the long-term factor of safety against instability of the landfill slopes.

Undrained Shear Strength Properties

The undrained shear strength properties were determined using laboratory vane shear tests, with a cruciform vane 12.7mm wide by 12.7mm long, and triaxial compression tests on samples nominally 38mm diameter by 76mm long. The test specimens, which ranged from liquid to very stiff consistencies were sheared quickly. Specimens drier than the optimum water content for compaction (85% water content) were obtained by air drying samples that had been compacted at a water content slightly above the optimum water content value. The undrained shear strength of these specimens is representative of the strength values obtained in practice where the sludge is allowed to dry and consolidate naturally after field compaction near the optimum water content value. The air void content was approximately 5% for all these test specimens.

Figure 3 shows the undrained shear strength-water content data measured. The undrained shear strength increases exponentially with reducing water content. The rapid increase in shear strength is largely due to the high organic content and colloidal activity (defined as the plasticity index to clay fraction ratio) of the sludge material. High colloidal activity indicates that the constituent particles have extremely high surface area relative to their mass. High organic content enhances inter-particle bonding.[11] Hence, large cohesion can be mobilized between the solid particles.

Good agreement was obtained between the shear strength data measured using the different test methods: the undrained shear strength in triaxial compression is only marginally lower than that measured using the vane shear apparatus. Hence, in practice, the vane shear apparatus can provide a quick and accurate measure of the sludge consistency and can be used to determine whether the sludge material is adequately dewatered prior to landfill disposal.

Effective Stress Strength Properties

The effective stress strength properties of the sludge material were determined using triaxial compression tests and with measurement of the pore pressure response. The tests were conducted on specimens, 38mm diameter by 76mm long, of moderately and strongly digested sludge. The specimens were prepared from sludge cakes which had been consolidated from the liquid state using a large hydraulic consolidation cell.[4] The sludge cakes were pasteurized so that the triaxial specimens would remain in a saturated state, thereby facilitating accurate measurement of the pore pressure response during the sample shearing stage. The hydraulic consolidation cell containing the sludge cake was gradually heated to 70^{o}C, maintained at this temperature for three hours before dropping back to room temperature. The sludge cakes were allowed to swell inside the hydraulic consolidation cell but without drainage of leachate during this stage. The triaxial specimens were consolidated isotropically before shearing the samples. The specimens were sheared very slowly, without drainage of the samples, at an axial compression rate of 0.002% strain/minute which was sufficiently slow to allow all pore pressures to equilibrate throughout the sample. The test results for the moderately and strongly digested sludge were analyzed using the Mohr circle of effective stress analysis and the Mohr-Coulomb failure envelope. The analysis for the moderately digested sludge is presented in Figure 4.

Sludge digestion causes the effective angle of internal friction (ϕ') value to increase from 32^{o} for moderate digestion (LOI=70%), to 37^{o} for strong digestion (LOI=55%).

The value of the effective cohesion for the sludge remains zero, irrespective of the level of digestion, and is characteristic of normally consolidated soil. These values, which are similar to values reported for peat[12], are for biologically neutralized sludge.

In practice, slope stability analysis of dedicated sludge landfills should be performed using the effective angle of internal friction value for both moderate and strong levels of sludge digestion. Values of other engineering properties used in the analysis must relate to the appropriate level of sludge digestion. The factor of safety against slope instability for the intermediate and long-term conditions is given by the lower of the factor of safety values calculated in this manner. Such analyses assume that provisions are included in the landfill to allow leachate and biogas to readily escape. Biogas which remains trapped in the landfill body can cause significant build up of pore air and pore water pressure, which if left unchecked, causes swelling and can ultimately lead to slope instability. For example, the landslide which occurred at the sewage sludge monofill near Deighton, England, was largely attributed to the build up of pore pressure caused by ongoing sludge digestion.[13]

DEWATERING AND CONSOLIDATION

Under a sustained load, for example, the overburden of the landfill material, the sludge will undergo a volume reduction due to the extrusion of leachate. As the water content decreases, the solids content of the sludge increases, the landfill subsides, and the shear strength of the sludge increases. Test specimens of moderately and strongly digested sludge of different consistencies, including compacted test specimens, were consolidated one-dimensionally. In practice, additional treatment of the sewage sludge can effectively prevent further digestion from occurring. Sludge digestion can be hindered, for example, by the presence of heavy metals from industrial wastes which may become mixed with the sewage sludge. Hence, pasteurized test specimens, which were prepared in the laboratory, were also consolidated.

The consolidation properties were studied using the consolidometer apparatus and the hydraulic consolidation cell.[3,4] Consolidation stages are usually of 24 hours duration. However, for this test program, consolidation stages greater than 48 hours duration were used to facilitate assessment, for example, of the long-term subsidence of sewage sludge monofills. The rate at which pore pressure can build up due to the evolution of biogas which may become trapped within the landfill body due to inadequate biogas and leachate drainage systems was also studied.

Figure 5 shows the cumulative strain-time plots recorded from maintained load consolidation tests on a moderately digested sludge specimen (75.1mm diameter and initially 19.2mm high). The test specimen was prepared from a sample compacted at 130% water content using standard proctor compactive effort to a dry density of 0.50 tonne/m^3. It is customary to plot the consolidation-time data using a logarithm time scale.

Figure 6 shows strain-time plots recorded for samples of moderately and strongly digested sludge which were consolidated from the liquid state using the hydraulic consolidation cell. The samples were 254mm diameter and were initially approximately 45mm high with a water content of 720%. The degree of consolidation (dissipation of the excess pore water pressure) is also plotted for the strongly digested sludge sample.

The sewage sludge is highly compressible with large compressive strains developing at a fairly steady rate under an applied load. However, in general, the strain contributions due to primary consolidation and secondary compression process cannot be easily distinguished using standard strain-time curve fitting techniques. Primary consolidation refers to the compression phase during which drainage and hence dissipation of the excess pore pressure occurs. Secondary compression occurs due to creep and decomposition of the soil structure after the excess pore pressure has virtually dissipated. Secondary compression continues indefinitely but occurs progressively slower with reducing water content.

The rapid dissipation of excess pore pressure measured during the hydraulic consolidation test (dashed curve, Figure 6) indicates that primary consolidation occurs very quickly. Furthermore, based on the shapes of the early portion of the sample strain versus logarithm time curves recorded during the consolidation tests (see for example, Figure 5), it is concluded that primary consolidation generally constitutes only a minor part of the overall settlement for the partially digested sludge. Hence, secondary compression is by far the dominant mechanism producing settlement. The rates of secondary compression, given by the axial strain of the sample that occurs over one log cycle of time (Figure 5), are very high in comparison with typical values for inorganic soil. The consolidation behavior described is consistent with the high organic content and colloidal activity of the sludge which are responsible for trapping surface and interstitial water within the constituent flocs of clay-sized particles. Similar consolidation behavior was reported by Hobbs[14] for peats.

The permeability of moderately digested sewage sludge in the liquid state is very low, estimated of the order of 10^{-9}m/s using Terzaghi theory of consolidation.[15] In general, the consolidated sludge is practically impermeable. However, it is evident from Figure 6 that consolidation of the sludge occurs more readily with increasing levels of sludge digestion. The shape of the strain-time curve for the strongly digested sludge is characteristic of the more rapid consolidation behavior traditionally associated with inorganic soil. Primary consolidation accounts for a larger proportion of the overall settlement and the coefficient of secondary compression value reduces significantly with increasing levels of sludge digestion.

Applied pressure-strain-time relationships from consolidation tests are traditionally summarized using void ratio-logarithm applied pressure (e-log p) plots (Figure 7). Void ratio is defined as the ratio of the volume of the void space to the volume of the solid particles. Applied consolidation pressures ranged from as little as 3kPa to 400kPa during the tests depending on the consistency of the sludge specimens. The slope of the e-log *p* curve, defined as the compression index (C_c), relates directly to the compressibility of the sludge material and is used to estimate the total consolidation settlement that will occur in the field. Also, the rate of expulsion of leachate from the pore voids equals the rate of reduction in the sludge volume. The compression index is stress level dependent, with typical values of C_c=7.0 for consolidation of the sludge to the liquid limit condition, and approximately C_c=0.7 for consolidation of the compacted sludge material. Significant swelling of the consolidated material is likely to occur if the applied load is removed. The swell index (C_s) is defined as the slope of the rebound portion of the e-log *p* curve (Figure 7).

Another aspect of the consolidation tests was to measure the swell pressures which may develop if biogas and leachate were to remain trapped within the landfill body. Samples of moderately digested sludge, typically of 2.5 liters volume, were confined under undrained sample conditions inside the hydraulic consolidation cell at 21^{o}C. The swell pressure induced due to ongoing sludge digestion was found to increase at approximately 40kPa/day under the conditions described. Furthermore, the rate of biogas production, and hence sludge digestion, was found to be independent of the swell pressure induced.

SUMMARY AND CONCLUSIONS

Stricter controls on the quality of wastewater discharges are giving rise to increasing volumes of sewage sludge which are being principally disposed to land, using either land-spreading or sludge-to-landfill operations. The engineering and drying properties of sewage sludge are presented and applied, in particular, to the design, construction and performance aspects of dedicated sludge monofill operations.

The engineering properties of sewage sludge, a concentrated slurry of organic clay-sized particles, change with the level of sludge digestion. Typical organic contents are 70% and 55% dry mass for moderate and strong levels of sludge digestion, respectively. Corresponding specific gravity of solids values are 1.55 and 1.72, respectively. Handling operations and landfill construction are most effectively conducted over the sludge water content range of 85% to 95% water content, which correspond to the optimum water content for field compaction and the sticky limit of the sludge material, respectively. The maximum dry density of typically 0.56 tonne/m^3 is achieved for standard proctor compaction within this water content range. Natural drying of the compacted sludge material should also be facilitated since significant shrinkage occurs which would extend the operational life of the landfill site even further.

Undrained shear strength-water content data (pertinent to engineering slope stability during landfill construction) and effective stress strength parameters, which take account of the landfill age and the effects of ongoing sludge digestion, are presented. The stability of the landfill slopes for the intermediate and long-term conditions would be analyzed using the effective angle of internal friction value (typically 32^o for moderate sludge digestion and 37^o for strong digestion). The analysis must consider the pore pressure response due to the biogas and leachate produced as a result of ongoing sludge digestion.

Sewage sludge is highly compressible yet practically impermeable. For example, the permeability of moderately digested sludge in the liquid state is only of the order of 10^{-9}m/s. The consolidation properties of the sludge are improved for greater levels of sludge digestion. Landfill subsidence, which principally occurs due to creep settlements and decomposition of the solid particles, continues indefinitely but at progressively slower rates.

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Table 1. Physical properties of moderately digested sewage sludge.

Property	Value
Liquid limit	315%
Plastic limit	55%
Shrinkage limit	10%
Plasticity index	260%
Particle size	90% passing 425µm sieve
Specific gravity	1.55
Loss on ignition	70%
pH	8.0
Linear shrinkage	32%

Figure 1. Specific gravity of solids vs. loss on ignition.

Figure 2. Density vs. water content relationships for compaction and drying processes.

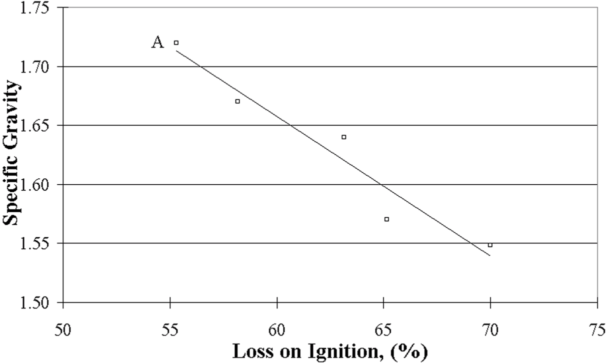
Figure 3. Undrained shear strength vs. water content.

Figure 4. Mohr circle analysis and failure envelope for moderately digested sludge.

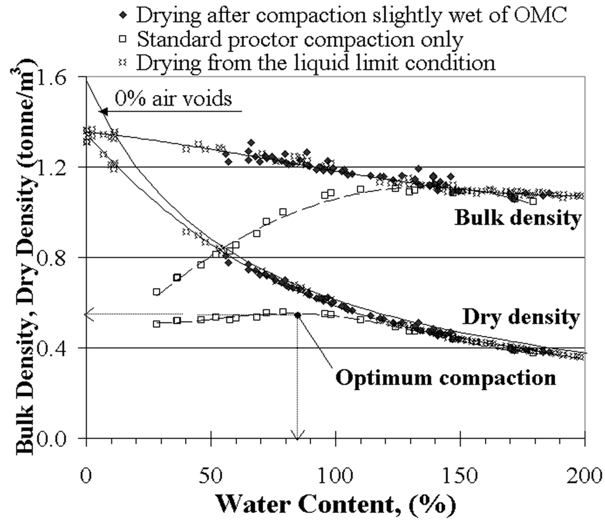
Figure 5. Cumulative strain vs. time plots from consolidation tests on compacted, moderately digested sludge.

Figure 6. Strain vs. time plots from consolidation tests on moderately and strongly digested sewage sludge.

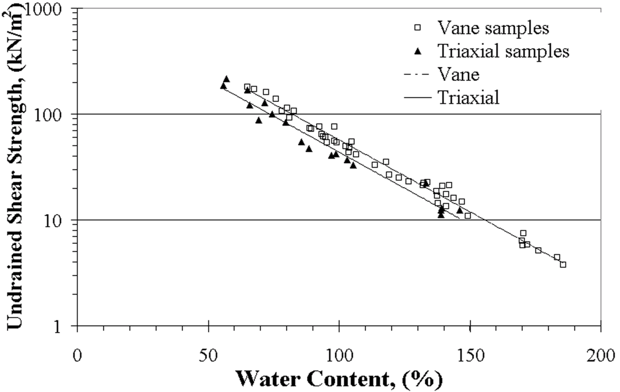
Figure 7. Void ratio vs. logarithm applied pressure.

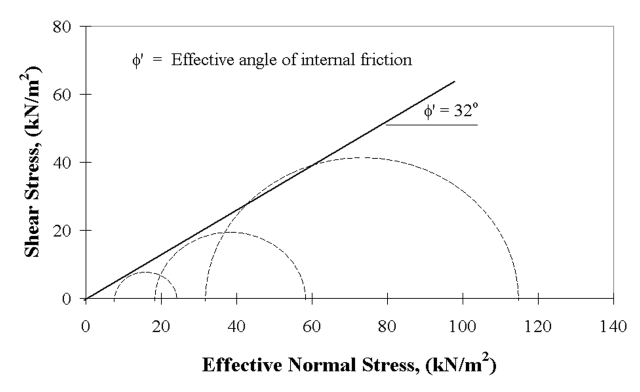


Specific Gravity
1.75
1.70
1.65
1.60
1.55
1.50
A
50
55
60
65
70
75
Loss on Ignition, (%)

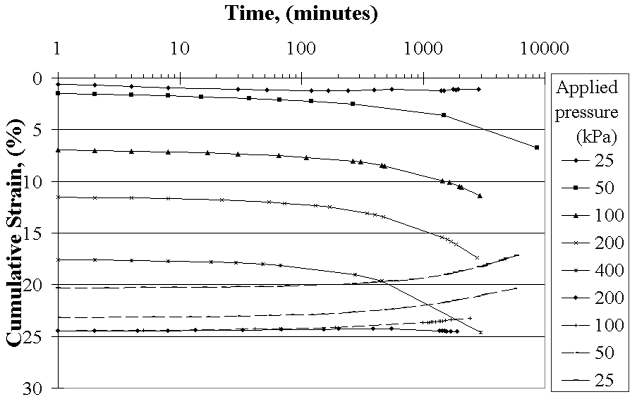


Drying after compaction slightly wet of OMC
Standard proctor compaction only
Drying from the liquid limit condition
0% air voids
Bulk density
Dry density
Optimum compaction
Bulk Density, Dry Density (tonne/m3)
Water Content, (%)
1.6
1.2
0.8
0.4
0.0
0
50
100
150
200

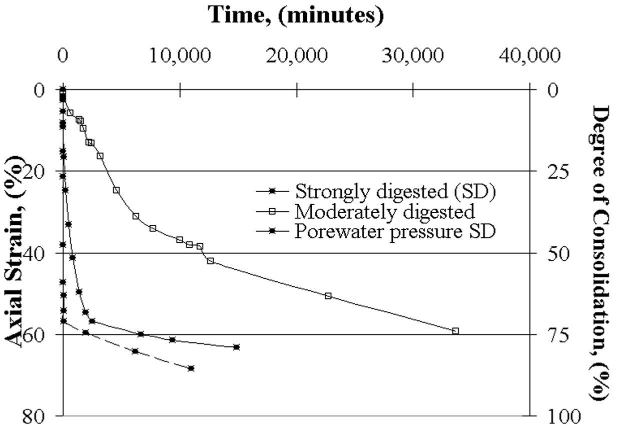

Undrained Shear Strength, (kN/m²)
1000
100
10
1
0
50
100
150
200
Water Content, (%)
Vane samples
Triaxial samples
Vane
Triaxial



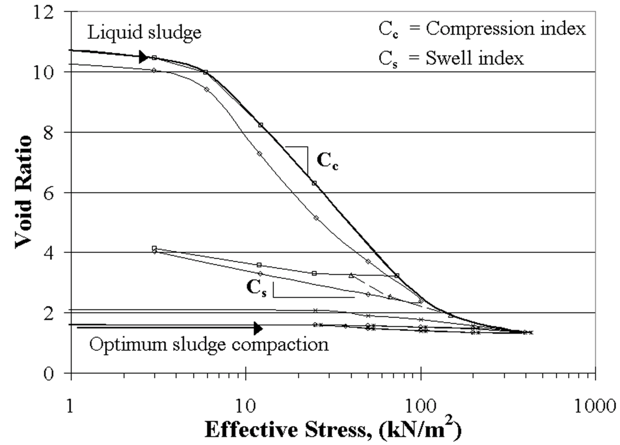
φ' = Effective angle of internal friction
φ' = 32°
Shear Stress, (kN/m²)
Effective Normal Stress, (kN/m²)
0
20
40
60
80
100
120
140



Time, (minutes)
1
10
100
1000
10000
0
5
10
15
20
25
30
Cumulative Strain, (%)
Applied pressure (kPa)
25
50
100
200
400
200
100
50
25



Time, (minutes)
0
10,000
20,000
30,000
40,000
Axial Strain, (%)
0
20
40
60
80
Degree of Consolidation, (%)
0
25
50
75
100
Strongly digested (SD)
Moderately digested
Porewater pressure SD



Liquid sludge
Cc = Compression index
Cs = Swell index
Cc
Cs
Optimum sludge compaction
Void Ratio
Effective Stress, (kN/m2)
0
2
4
6
8
10
12
1
10
100
1000