Geotechnical Engineering & Environmental Aspects of Clay Liners for Landfill Projects

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ABSTRACT

Waste disposal in Ireland by landfilling remains an integral part of waste management with approximately 2.5 Mt of waste annually placed in landfill. Until the early 1990's little engineering was put into landfilling practices with operations taking the form of uncontrolled infilling of natural depressions and man-made excavations. Landfill philosophy has now moved to containment and isolation of waste, hence the increase in construction of landfill cells using composite lining systems.

In most earthworks, the strength and degree of compaction are the controlling factors but in the construction of clay liners for landfill projects a low permeability requirement presents an additional burden on the selection and emplacement of suitable materials.

This paper presents details on the background and application of clay liners in Irish landfill, source evaluation, engineering and permeability of the clay fill and CQA testing with particular reference to Arthurstown Landfill, Kill, Co. Kildare. The paper also makes reference to the attenuation properties of clay liners and to alternatives in the event that suitable clay is not available.

WHY USE COMPACTED CLAY LINERS

Man has created and disposed of waste materials since the beginning of time. Until recently, disposal was carried out with little regard for the environment. (See Figure 1) Modern living (Post-Industrial Revolution) has led to the characteristics of waste becoming less environmentally tolerable. To some extent, until recent times, the lack of development in Ireland has shielded the environment from the worst affects of uncontrolled waste disposal. The same does not hold true for developed countries such as United States, the U.K. and mainland Europe, where there are many instances of significant environmental deterioration as a result of landfill.

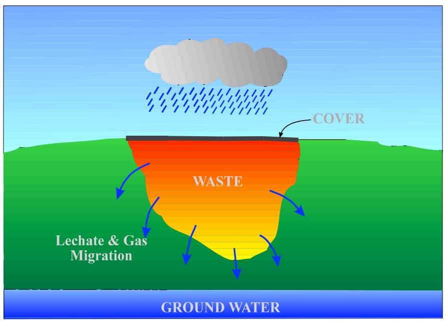


Figure 1

Since the mid-70's, the thinking both in the USA and in Europe has been moving towards containment of waste. In the case of the United States, the Resource Conservation and Recovery Act (RCRA) encompassed what is commonly known as Sub-title B which required (amongst other provisions) that a composite liner system with two feet of compacted soil with a hydraulic conductivity of no more than 1 x 10^{-7}cm/sec and the flexible membrane liner of at least 60/mil (1.5mm) be installed in direct and uniform contact with the compact soil. The USEPA currently requires a three-foot (900mm) soil layer. Similar standards were being developed in mainland Europe. In the late 1980's the European Commission began to draft the Council Directive on the Landfill of Waste. The Directive went through many iterations until it was finally agreed in 1999.

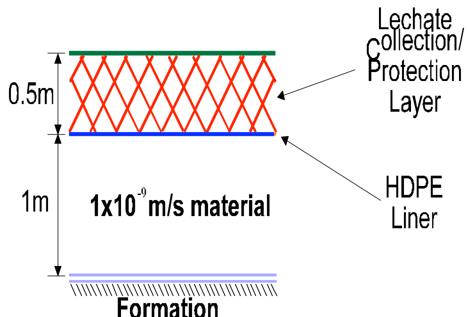
The Directive requires that protection of soil, groundwater and surface water is to be achieved by the combination of a geological barrier and bottom liner. The geological barrier is to be determined by the geological and hydrogeological conditions below and in the vicinity of the landfill such that the underlying soils provide sufficient attenuation capacity to prevent a potential risk to soil and groundwater. The landfill base and sides shall consist of a mineral layer which satisfies permeability and thickness requirements with a combined effect in terms of protection of soil, groundwater and surface water at least equivalent to one resulting from the following requirements:

- Landfill for hazardous waste:
  $k \leq 1 \times 10^{-9}$m/sec; thickness $\geq$ 5m
- Landfill for non-hazardous waste:
  $k \leq 1 \times 10^{-9}$m/sec; thickness $\geq$ 1m
- Landfill for inert waste:
  $k \leq 1 \times 10^{-7}$m/sec; thickness $\geq$ 1m

The Directive permits that, if the naturally occurring soils do not meet the above conditions, then the barrier can be completed artificially and reinforced by other means

giving equivalent protection. In any event, the artificially established geological barrier should not be less than 0.5m thick.

The Directive also requires that both an artificial sealing layer (current practice is high density polyethylene) and a drainage layer be provided and, for the floor of the landfill, the drainage layer must be greater than or equal to 0.5m thick. The Directive permits member states to set their own standards for inert waste landfills.



EU DIRECTIVE REQUIREMENTS (FOR NON-HAZARDOUS WASTE)

It is thus a requirement that the lining systems required for all landfills will comprise a mineral layer of a specific thickness with a specific permeability.

Experience has shown that it is unlikely that a consistent standard of clay will be found in-situ. It is thus common practice to re-engineer a layer of appropriate thickness such that it exhibits the correct maximum permeability. The re-engineered layer is commonly referred to as a compacted clay liner.

GENERAL REQUIREMENTS FOR CLAY LINERS

The permeability of a re-moulded clay is influenced by a number of factors, the key ones being plasticity, density, moisture content during compaction and method of compaction.

Although the detailed requirements for compacted clay liners (CCLs) vary, the following parameters usually apply:

- Coefficient of permeability (hydraulic conductivity) of 1×10^{-9} m/s or less
- Minimum layer thickness of 1m
- Minimum clay content of 10%
- Minimum Fines (clay & silt) content > 30%
- Plasticity index >10% and <65%
- Liquid limit < 90%
- Maximum particle size of 75mm

SOURCE EVALUATION

To evaluate a potential source for clay lining the following suite of tests are recommended and should be carried out in accordance with BS 1377 (1990).

- Natural moisture content
- Atterberg limit (Liquid / Plastic Limits)
- Particle size grading
- Organic content
- Compaction curves (dry density/ optimum moisture content relationship)
- Moisture Condition Value (MCV)
- Permeability

It is highlighted that a potential borrow source may contain variations in fines content, stone content and size, moisture content (e.g. possibly reducing with depth) lenses of fine sands, fluvioglacial gravel horizons etc. Hence the importance of assessing these variations so that accurate quantities can be determined. Ideally, a number of samples from the borrow source should be obtained so that the aforementioned suite of geotechnical parameters can be determined,

Groundwater plays an important role in borrow pit and source evaluation. Where boreholes are sunk, either piezometers or standpipes should be installed to establish equilibrium water levels. This is particularly important where horizons or lenses of sands or gravels are present within boulder clay deposits as they may give rise to sub-artesian conditions.

In the case of Arthurstown (Stages 1 & 2) cable percussion boreholes were sunk to prove the lateral and vertical thickness of the boulder clay deposit and provide samples for laboratory analysis. For Stage 1, trial pits were excavated to depths of approximately 4m, these illustrated the size and structure of the gravel/cobble constituents within the fines matrix.

Sampling & Laboratory Testing

For borrow pit source evaluation, trial pits are recommended in conjunction with boreholes as they will provide a clearer indication of stone content and sizes. They also permit more accurate sampling and provide larger sized samples for compaction tests. A minimum of 20kg of representative soil is required to carry out the classification and performance laboratory tests.

A three week programme should be allowed to complete the suite of laboratory tests, particularly the triaxial cell permeability test which for very low or 'impermeable' clay liner soils typically takes 10 to 12 working days.

The rapid (i.e. results within two to three days of sampling) and cheaper laboratory tests

include moisture content, grading, Atterberg Limit and MCV. The particle size grading provides an excellent initial appraisal of the potential suitability of a soil for the construction of an impermeable liner.

From the grading curve, an approximation of permeability can be made using either the Hazen or Sherard equations. The fines proportion, plasticity and moisture content essentially control the likely permeability of the soil and can be determined from the aforementioned inexpensive laboratory tests.

ENGINEERING PARAMETERS OF CLAY LINERS

Moisture Content & Plasticity

Natural moisture content and plasticity should be carefully established as these are two key parameters in governing the ability of a soil to produce a well engineered and impermeable liner.

A minimum Plasticity Index of 10% is normally required/stipulated as soils with a lower plasticity index are unlikely to achieve a sufficiently low permeability. The authors would generally agree with this viewpoint though some of the low plasticity soils in the northwest (Mayo, Donegal, Sligo) and southwest (Kerry) have produced remoulded permeabilities of 1×10^{-9} m/s or less.

The glacial till / boulder clay soils from these areas often have plasticity index values as low as 4 and plot below the A-Line. An example of an Atterberg Limit plot is given in Figure 2, this illustrates the plasticity of the Arthurstown boulder clay. The boulder clay at Arthurstown is of low to intermediate plasticity (CL) with a Plasticity Index range of 11 to 14%.

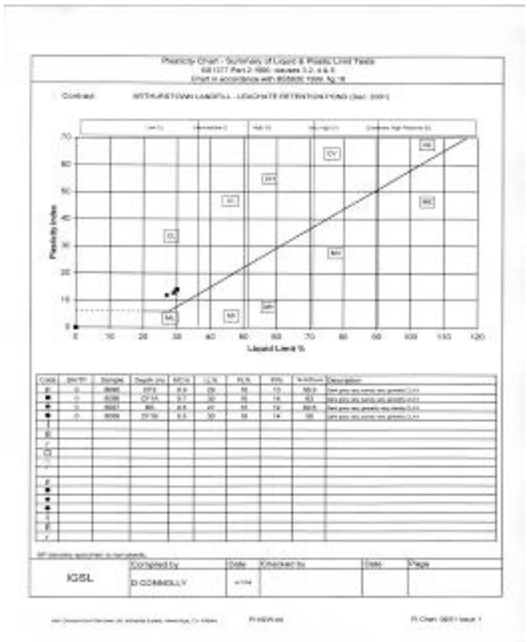


Figure 2: Atterberg Limit Plot

Grading

A typical particle size grading for the Arthurstown boulder clay is presented in Figure 3. The boulder clay source at Arthurstown comprises a very stiff / hard grey black sandy very gravelly CLAY with occasional cobbles. It is characteristic of a heavily over-consolidated lodgement till. Figure 3 shows a clay content of 13.6% and fines content (combined clay / silt) of 43%.

Fines content for the grey black sandy gravelly CLAY is usually within the range 30 to 50%. Inspection of the grading curve shows a very low D_{10} size hence before undertaking triaxial cell tests, indicative permeability would be expected to be very low.

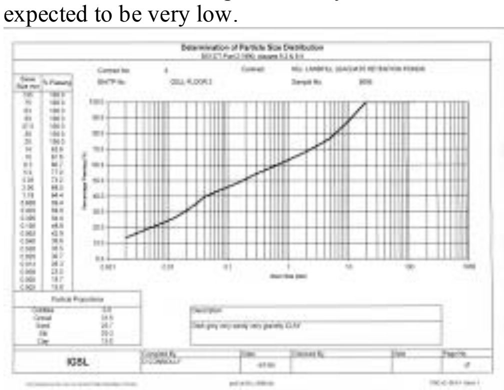


Figure 3: Typical Partial Size Grading

Moisture Condition Value

For a given soil sample there is a unique compactive effort at which the density ceases to increase. The higher the moisture content, the lower the compactive effort beyond which no further increase in density occurs. The compactive effort required to compact the soil to the foregoing density determines the MCV of that sample.

The MCV is a rapid test (field or laboratory) and is principally used to assess suitability of soils for use in earthworks and trafficability characteristics during placing and compaction.

For Irish glacial till/boulder clay soils, the MCV has been found to be very effective in determining soil suitability and is believed to be applicable for clay liners and material acceptability prior to emplacement.

Typically an undrained shear strength (C_u) of 50 kN/m^2 is required in earthworks. For Arthurstown Landfill, the boulder clay used in the construction of the clay liner had a lower bound MCV of 12 and natural moisture content mainly between 9 and 11%.

Compaction

Compaction is a process of reducing the void ratio of a soil by mechanical kneading. The soil is laid out in layers and then subjected to momentary application of load (via rolling, tamping or vibration). The expulsion of air from the voids occurs without significant change in moisture content.

The compaction process creates a denser soil mass and the effect of compaction can be quantitatively described in terms of dry density. Optimum moisture content (OMC) is obtained from compaction testing and this allows comparison with the natural value and provides a maximum dry density (MDD). An example of a compaction test for the Arthurstown boulder clay is shown in Figure 4.

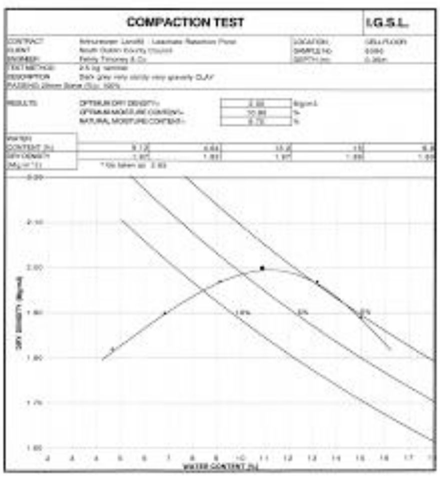


Figure 4: Compaction Test

The laboratory compaction test determines the degree of compaction achievable when using a standard amount of compactive effort

Measurement of in-situ density of the compacted clay fill in the field is used to assess whether the earthworks satisfy the design requirements.

PERMEABILITY MEASUREMENT

Permeability is predominantly measured by taking undisturbed samples (U100's) of the compacted clay liner or re-compacting disturbed samples in the Proctor mould to an equivalent in-situ density. In-situ density is measured (by nuclear method or sand replacement) and this allows the soil to be re-compacted in the mould to a known density.

In-situ permeability measurement is by use of either lysimeter or ring infiltrometer. Both of these methods are of long duration (3 to 6 months) and very expensive. Hence, determination of permeability by laboratory methods is regarded as being the most practical and cost effective.

The triaxial cell test is regarded as the preferred method (to permeameter) in determining laboratory permeability on either undisturbed or remoulded samples.

The advantages of the triaxial cell methods are principally as follows:

- Sample can be saturated under back pressure thus reducing or eliminating obstructions due to air bubbles or entrainment
- Saturation can be achieved more quickly, particularly for compacted soils
- Small rates of flow can be measured easily and the test is carried out under effective stress and at pore pressures which relate to field conditions

For triaxial tests on remoulded material, representative samples of the clay liner soil are compacted in the Proctor mould using either standard (2.5kg) or heavy (4.5kg) compaction methods. The sample is then saturated and consolidated prior to testing.

An example of a saturation stage plot (cell pressure v B value) and consolidation stage (pore pressure dissipation v root time) plot for the Arthurstown clay liner is shown in Figure 5. B values of 0.95 to 0.98 were generally obtained.

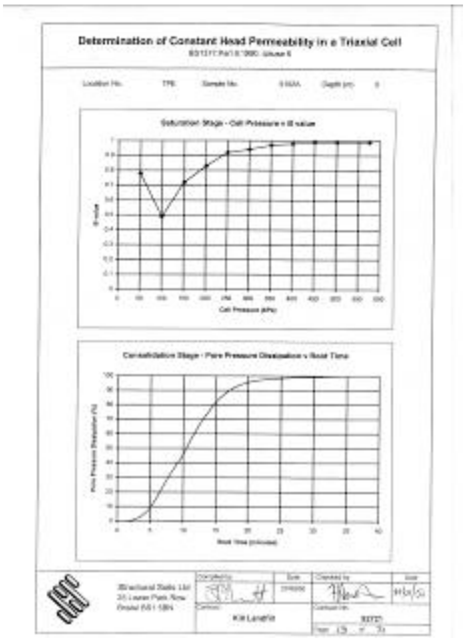


Figure 5: Triaxial Test (saturation / consolidation plots)

The mean effective stress (MES) for the triaxial test is calculated by determining the waste loading imposed on the cell floor (σ_v). For Arthurstown Landfill a characteristic MES value of 150 to 175 kN/m^2 was used. This was calculated as 0.6 $\sigma_{v'}$ where $\sigma_{v'}$ was taken as 300 kN/m^2 for the landfill waste (based on 40m of baled waste).

For the triaxial cell test a plot of cumulative flow against time (i.e. volume in: volume out) is made and the coefficient of permeability is calculated accordingly. An example of this is shown in Figure 6.

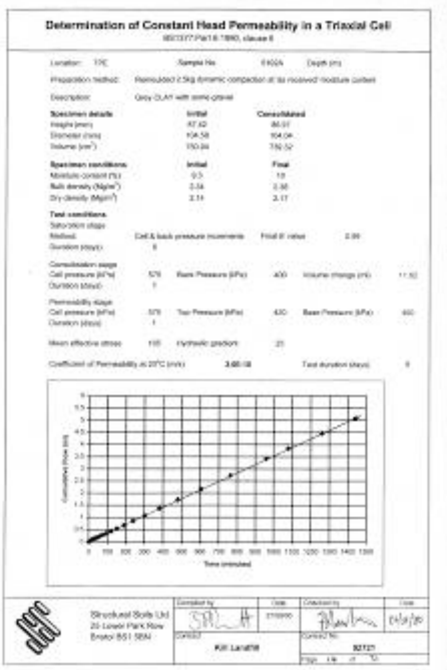


Figure 6: Determination of Permeability

PLACING & COMPACTION OF CLAY LINERS

Prior to placing and compacting clay fill liners, screening is often required to remove over-sized constituents (typically >75mm). This is usually carried out by table shakers or trommels where the as-dug clay fill is fed into a hopper and screened. The screened clay fill is thus referred to as 'processed' and is spread out by dozer to the required thickness.

In most cases of clay liner construction, the soils are placed in 'lifts'. This usually entails four (225mm thickness) or three (300mm thickness) lifts, each compacted with a pad foot or grid roller. A (conservative) rule of thumb is that the compacted layer thickness should be less than the penetrative depth of the feet of the pad or grid roller. The surface of the final lift (100mm) should be smooth and free from cracks as it overlain by a flexible membrane liner.

The use of a pad foot or grid roller is strongly advised as this allows *kneading* of the lumps or clods. The effect on permeability of kneading the clods is very important for clay liners as it produces a reduction in clod sizes. It is important in the field to knead the soil repetitively to reduce the clods and interclod macropores.

With regard to the compacted clay liner at Arthurstown, a small scale compaction trial was carried out prior to Stage 1. This involved placing layers of varying thickness (200 to 400mm) and measuring in-situ density by nuclear gauge. This process ascertained the relationship between layer thickness and number of roller passes and helped optimise the compaction process.

An illustration of the pad foot roller working on the Arthurstown boulder clay during the compaction trial is shown in Figure 7. The pad foot roller used at Arthurstown had a drum width of 2.1m and mass per metre width of roll of 2,166 kN.

Figure 7: Pad Foot Roller Compaction (top) with smooth drum roller for final layer

As a guide for the field operatives, full indentation of a pad foot or grid roller should stipulated to ensure adequate kneading. This field criterion was successfully used at Arthurstown and provided a good 'feel' for the remoulding of the clay liner. At Arthurstown a minimum of six roller passes was required to achieve 95% maximum dry density (i.e. approximately 1.95 Mg/m^3).

Where the dry densities dropped below 1.95Mg/m^3 and moisture contents below 8% scarification and re-working was necessary. As the boulder clay at Arthurstown was close to or at optimum this situation did occur during periods of sustained dry weather (particularly during Stage 1). Scarification was achieved by spraying the clay fill with water from a bowser, re-working and re-compacting until the aforementioned dry density parameter was achieved.

In-Situ Testing & Monitoring

This element of clay liner construction forms part of the Construction Quality Assurance (CQA) and is an integral part of the operations. Given the impracticalities associated with carrying out in-situ permeability tests, the CQA work on the clay liner is based on the following:

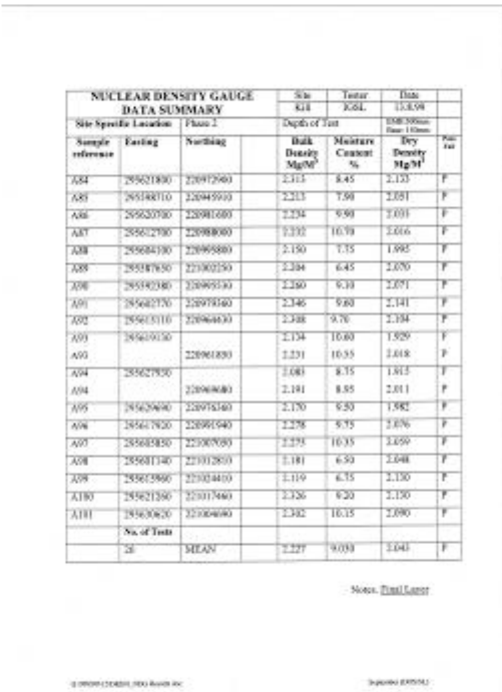
- Determination of placed density & moisture content, preferably using the nuclear gauge probe
- Sampling the compacted clay and carrying out laboratory classification & performance tests
- Sampling the compacted clay liner to undertake laboratory permeability tests

Nuclear Gauge

Measurement of placed density (dry & bulk) and moisture content by nuclear method is strongly recommended as it allows a large number of tests to be rapidly carried out over a completed area.

Prior to undertaking the in-situ density testing, the nuclear gauge unit should be calibrated for the specific soil type. This is undertaken by measuring the known density of compacted clay fill in a calibration box.

The nuclear gauge unit should only be operated by a certified technician / engineer and a RPI badge holder. The gauge is set up over a pre-formed hole (maximum depth of 300mm) and readings taken after approximately three minutes. A typical data sheet with nuclear gauge readings is presented in Figure 8.



NUCLEAR DENSITY GAUGE DATA SUMMARY				Site	Tester	Date	
				Kil	KGL	13.8.98	
Site Specific Location	Phase 2			Depth of Test		[illegible]	
Sample reference	Easting	Northing		Bulk Density Mg/M^3	Moisture Content %	Dry Density Mg/M^3	Pass/Fail
A84	295621800	220972980		2.313	8.45	2.133	F
A85	295148010	220945930		2.213	7.90	2.051	F
A86	295620700	220981600		2.234	9.90	2.031	F
A87	295612700	220988000		2.232	10.70	2.016	F
A88	295684100	220965800		2.150	7.75	1.995	F
A89	295587650	221002150		2.204	6.45	2.070	F
A90	295592380	220995530		2.260	9.10	2.071	F
A91	295602170	220979340		2.346	9.60	2.141	F
A92	295613110	220964630		2.308	9.70	2.104	F
A93	295619130			2.134	10.60	1.929	F
A93		220961830		2.231	10.55	2.018	F
A94	295627930			2.083	8.75	1.915	F
A94		220969680		2.191	8.95	2.011	F
A95	295629690	220976340		2.170	9.50	1.982	F
A96	295617920	220991940		2.278	9.75	2.076	F
A97	295605850	221007080		2.275	10.35	2.059	F
A98	295601140	221012810		2.181	6.50	2.048	F
A99	295615960	221024410		2.119	6.75	2.130	F
A100	295621260	221017460		2.326	9.20	2.130	F
A101	295630620	221004690		2.302	10.15	2.090	F
	No. of Tests						
	20	MEAN		2.227	9.093	2.043	F

Notes. Final Layer

Figure 8: Example of Nuclear Density Log Sheet

The nuclear gauge unit uses the attenuation of gamma radiation due to photoelectric absorption which is directly related to the density of the soil. A column of soil with a diameter of circa 500mm is measured. Results are displayed digitally and can be stored on the data logger or recorded in notebook. An example of the nuclear gauge measurement apparatus used at Arthurstown is shown in Figure 9.

Figure 9: Nuclear Density Testing Equipment & Compacted Clay Liner

Sampling

This takes the form of either core cutter samples (U100 tubes) driven or pushed into the compacted clay fill or bulk disturbed samples placed in sealed polyethene bags. Where possible core cutter samples are recommended as these provide direct samples of the compacted clay liner. Core cutter samples are difficult to obtain where the clay liner contains gravel constituents and the matrix is very stiff in consistency.

In the case of Arthurstown, core cutter samples were attempted on numerous occasions without success. Polymer gel core drilling was also used undertaken to recover undisturbed samples but proved unsuccessful. Hence, representative bulk samples were taken and re-compacted to the in-situ density in the proctor mould for permeability testing. Atterberg Limits, MCVs and compaction curves were also carried out as part of the on-going CQA testing.

It is noted that in order to achieve the equivalent field dry densities for the Arthurstown clay liner, compaction with the heavy rammer (4.5kg) was often necessary. Cumulative plots of in-situ dry densities against moisture content showed that the mean field dry density was midway between the compaction curves using the light (2.5kg) and heavy (4.5kg) rammers.

The authors experience with landfills in Cork and Kerry (where the soils are very silty, firm / stiff in consistency and more amenable to undisturbed core cutter sampling) is that the results of tests performed on the undisturbed samples show lower in-situ permeabilities than those achieved after re-compaction in the laboratory prior to undertaking the triaxial cell tests.

Frequency of Testing

The EPA Landfill Site Design manual (Tables 9.5 & 9.6) sets out testing frequencies for soil liners. The authors view is that these testing frequencies are very onerous, particularly if there is good visual consistency of the clay fill from the borrow source.

Once plasticity and gradings have been fully established during the evaluation stage, then moisture content becomes the key parameter as this governs whether the clay fill is placed above or below optimum.

The number of nuclear density tests set out in Table 9.7 (12/hectare/lift) is deemed low. Given the rapidity of the nuclear gauge density test (typically 5 minutes for a complete test) and its ability to quickly provide a large number of in-situ density results, there is scope for increasing the frequency.

PERMEABILITY BEHAVIOUR

The dry unit weight of a soil varies with moisture content and the maximum dry density is achieved at the optimum moisture content. Figure 10 illustrates the relationship between permeability and moisture content.

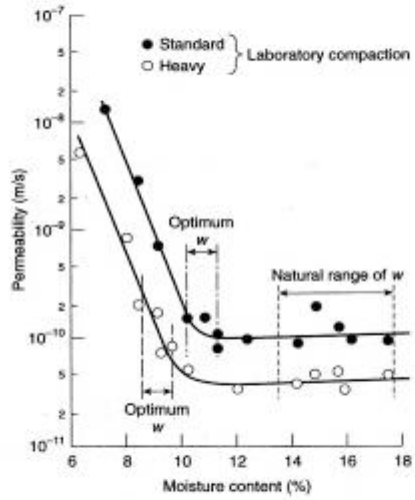


Figure 10: Permeability and Moisture Content relationship

The general trend is that permeability decreases when the soil is compacted at moisture contents below optimum. The corollary of this is that shear strength decreases

as moisture content increases and hence has an adverse impact on trafficability of plant.

A review of the Arthurstown triaxial cell permeability data shows that minimum permeabilities (1×10^{-9} m/s) were in fact obtained when moisture contents dropped as much as 3% below optimum. A plot of permeability against moisture content for the Arthurstown clay liner has been prepared and is shown in Figure 11. There is a wide scatter of data with the majority of the permeability values between 1×10^{-9} and 1×10^{-10} m/s with moisture contents mainly between 8 and 9.5%.

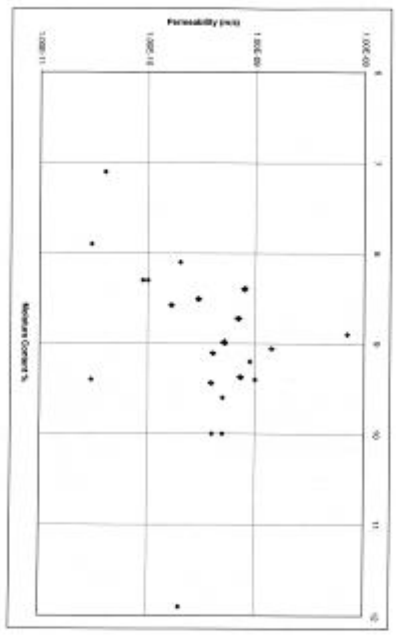


Figure 11: Permeability v Moisture Content - Arthurstown

What is also interesting about the Arthurstown clay fill is that bulk densities did not necessarily drop with a reduction in moisture content. Examination of the permeability and bulk density data shows that below 2.20 Mg/m^3 permeability could be greater than 1×10^{-9} m/s.

LEAKAGE THEORY

There is no such thing as an impermeable barrier. All liners leak. The issue is that we minimise the leakage through good design and construction quality assurance such that its effect on the environment would not be significant. The mechanisms of leakage are:

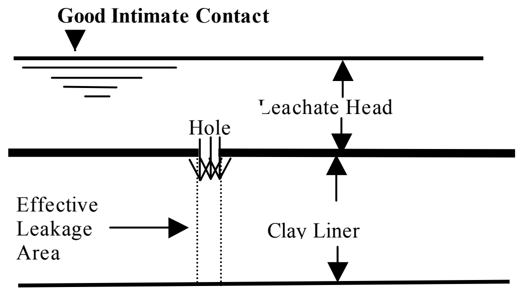
- Flow through holes in the membrane and/or cracks and fissures in the clay; and
- Permeation through both the flexible membrane liner and through the clay itself.

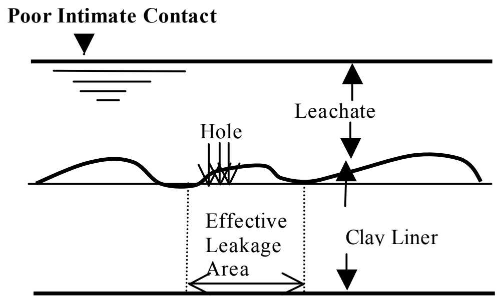
The proper choice of materials will minimise the permeation and good contract quality assurance will minimise leakage through defects both in the liner and in the clay.

Leakage rates through composite liners have been studied by Giroud and Bonaparte, who developed imperical equations that predicted leakage through composite liners for a number of circumstances. Where the hydraulic head above the geomembrane is less than the thickness of the soil component and the hydraulic conductivity of the soil component is less than 10^{-6}m/sec, then the equations are:

- $Q = 0.21\, a^{0.1}\, h^{0.9}\, k^{0.74}$ (for good contact)
- $Q = 1.15\, a^{0.1}\, h^{0.9}\, k^{0.74}$ (for poor contact).

Where a is the area of a hole, h is the head of leachate on the liner and k is the permeability factor





If the leachate head on the membrane is greater than the thickness of the soil, then a further factor is introduced known as I_{avg} and the quantity of leakage derived from the above equations is multiplied by this new factor in each instance.

$Q = 0.21 i_{avg}\, a^{0.1}\, h^{0.9}\, k^{0.74}$ (for good contact)

$Q = 1.15 i_{avg}\, a^{0.1}\, h^{0.9}\, k^{0.74}$ (for poor contact).

A simple sensitivity analysis on the above equations suggest that while hole size (a) has little effect on the leakage rate, both hydraulic head and permeability have a much more significant effect. Hydraulic conductivity of compacted soils can vary considerably (up to

1 order of magnitude) depending on how the soils are treated.

It is concluded that the engineering of the compacted clay liner is the most important factor in minimising leakage.

ATTENUATION

It has been demonstrated above that absolute terms such *as total containment, prevention of leachate* and *landfill gas migration*, or *impermeable* are not achievable. It should not be concluded that failure to achieve the above conditions is a reflection of either poor materials or workmanship. All materials have a finite permeability and thus some finite seepage is inevitable.

The compacted clay element of the composite lining system fulfils a second role in that it facilitates the attenuation of contaminants that may be present in the leachate as it migrates slowly through the soil. If a material possessing good chemical buffering capability as well as low hydraulic conductivity and high sorption capacity can be secured, this would ensure that a competent containment/attenuation barrier system against leachate transport would be obtained.

This subject has been studied in some depth by Yong *et al*. Studies of the chemical buffering by soils are conducted in a similar manner as in solution chemistry, except that soil suspensions are used in place of solutions in the titration procedure. The titration procedure allows one to study the capacity of the soil to absorb or desorb ions. The ability of the soil to act as an acid (or base) and thus resist pH changes during titration with the contaminant solution will demonstrate the attenuation characteristics of the soil for the selected contaminant. Improved assimulation of actual field conditions can be made using soil column leaching tests. Such tests determine the attenuation characteristics of the compacted soil and distribution of contaminants within the soil as a function of the amount of leachate transported through the soil sample.

There is neither a standard method nor EPA/Directive requirement for assessing the attenuation capacity of the soils. Where alternative clays are available, both of which satisfy the permeability requirement, attenuation capacity could be used as a decision making tool. Both physical and chemical characteristics of the soils should be determined to assist in the assessment of the attenuation capacity. The following is a typical list of parameters that might be required:

- Natural water content
- Specific gravity
- Liquid limit
- Plasticity index
- Percentage clay fraction
- Dry density
- Optimum moisture content
- Permeability
- Percentage organics
- Specific surface area
- Cat ion exchange capacity.

In addition, the chemistry of the pore water and leachate should be known to the evaluation team. Parameters such as pore volume can be used to determine the quantity of leachate that might be permeated through a particular sample. Comparison of the break through concentration against the number of pore volumes permeated through the soil will assist in determining the attenuation capacity of the soil.

Yong produced a table giving the sorption selectivity of heavy metals in different soil types and he has also prepared a competency assessment protocol which was used for his studies and might be used for future attenuation studies.

Leachate attenuation by mineral clays might be improved by the addition of organo-clays to the mineral clay. Some work on this has been undertaken by E.A. Voudrias and others. Their work has shown that the breakthrough time for certain contaminants increases from say 10 years to 50 years as a result of the incorporation of organo clays into the lining systems.

Attenuation theory has been taken to a new level by considering the concept of reactive walls. Work has been done by Bradl and Bartel on the concept that as landfills age and the concentration of contaminants arising reduces, leachate can be directed in a controlled fashion through a designed attenuation layer and traditional leachate treatment can be abandoned.

Put simply, a permeable barrier of selected soil can be placed in the leachate stream as it leaves the landfill and intensive monitoring downstream of the barrier can be undertaken until such time as breakthrough is observed. The soil, which will then be saturated with contaminants can be returned to the landfill or disposed of elsewhere. A new reactive barrier can then be installed and the process continued until no significant contamination breaks through. The concept of reactive barriers may be a more sustainable process than traditional leachate collection and treatment.

ALTERNATIVES TO COMPACTED CLAY LINERS

The enhancement of the soil used in compacted clay liners has, from the point of view of attenuation, been discussed above. If the available soil cannot be compacted to achieve the required permeability ($k \leq 1 \times 10^{-9}$m/sec), then it is possible to condition the soil such that it does achieve compliance. There are also synthetic materials available that can be used in lieu of the compacted clay layer, however their use is limited by the requirements of the Directive and by the fact that long term durability of some materials is being questioned.

Bentonite is a naturally occurring clay deposit containing montmorillonite group clay materials. The clay occurs naturally in several parts of the world and each deposit varies in chemical composition. Bentonites have particular properties including the ability to absorb large quantities of water molecules and both cat ions and ions into their crystalline structure. The incorporation of Bentonite fines into a naturally occurring soil, e.g. sand, will significantly alter the physical and chemical properties of the soil.

Although Bentonite enhanced mineral liners have been used extensively in some countries, there has been very little use of them in Ireland. In fact it has not been used in the Republic of Ireland although Limerick County Council is currently preparing to install a Bentonite enhanced soil (BES) liner as the mineral component of a composite lining system at Gortadroma landfill. It is understood that trial mixes and test pads are currently being installed such that the methods can be proven before full scale lining commences.

The basic principle of BES is to add a suitable percentage of natural Bentonite to a soil of a suitable grading. In some instances, the Bentonite has been mixed with clay and, in the case of Gortadroma, Bentonite is being mixed with a pencil shale. The Bentonite infills the voids between soil particles and surface coats the mineral particles. Soil particles are then bonded by both physical and chemical forces.

The nett effect of the addition of Bentonite to a soil is to improve plasticity and workability and to decrease permeability of the mixture. It is likely that the BES will be more consistent than a naturally occurring soil. Adjusting the mix will alter the target permeability. A typical mix will incorporate 3% to 5% of Bentonite, but a final decision can be made only on completion of trial mixes.

Apart from the advantages mentioned above, a Bentonite enhanced clay liner is likely to swell if leachate comes into contact with it. This is a particular advantage where it is used as a secondary liner beneath the FML. The disadvantages are that there is a range of Bentonites available with different properties and leachate attack should be assessed using long-term testing to ensure that the permeability does not increase with time. There is a large-scale testing programme required which includes a very long timescale to be completed adequately. A change in actual leachate from the design/test leachate could affect the long-term protection of the liner.

It has been suggested that BES is more suitable for capping and that it should be used as a basal liner only at low-risk sites where groundwater resources are not at risk. Installations of BES is a specialised task and should be subject to extra strict quality control.

Bentonite can also be incorporated as a tool to enhance containment by encapsulating a thin layer of the clay between two geotextile sheets and simply rolling it out as an underlay to the flexible membrane liner. Although GCL provides an excellent barrier, in recent years its use is being challenged because of its small thickness and its susceptibility to leachate permeation. It has been demonstrated that, under the effect of leachate, ion exchange occurs which transforms sodium bentonite (the preferred product) into calcium bentonite.

Calcium bentonite exhibits desiccation and cracking with consequent breakdown in its barrier performance. Current research into the enhancement of compacted clay liner includes the use of kaolinite clay in lieu of the bentonite clay. Current indications are that the long-term durability of kaolinite enhanced soil is better than that of the BES. There is also work being done with polymer enhanced bentonite and, as with the kaolinite, it seems to be less susceptible to degradation due to ion exchange. Polymer enhanced clay liners are also known as trisoplast which is a mixture of approximately 90% sand, 10% sodium bentonite and .2% polymer. Trisoplast may have a role to play in landfill capping where it is not physically possible to compact a clay because of the yielding nature of the waste underneath.

CONCLUSIONS

Based on the authors experience with design and construction of clay liners the following conclusions are made:

- A thorough evaluation of a borrow source is recommended and a small scale compaction trial is highly advantageous,

- Engineering a soil to produce a CCL with a minimum k of $1x10^{-9}$ is not as difficult as might be envisaged,
- High quality compaction and kneading is a vital component in achieving a competent liner,
- Permeability behaviour is dependent on three key factors namely, moisture content, plasticity and grading,
- CQA forms a vital part of clay liner construction and needs to be carefully planned and executed,
- Good contact between the FML and the CCL is vital if we are to achieve minimal leakage,
- There are alternatives available if the available materials are unsuitable,
- The CCL fulfills a second role in the attenuation of contaminants.
- Total containment is never achieved,

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