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LFE4 - Earthworks in landfill engineering

Design, construction and quality assurance of earthworks in landfill engineering

reference number/code

We are the Environment Agency. It's our job to look after your environment and make it **a better place** - for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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INTRODUCTION

Landfill sites and in particular lining systems are complex engineering structures requiring detailed design and construction quality assurance. This document provides guidance on the approach to all the earthworks used in landfill construction including general fill through to clay liners for landfill cells and lagoons. However, it does not consider the use of bentonite enhanced soils (BES) and is not specifically applicable to inert sites, for which there are separate guidance documents (Environment Agency 2000 and 2009), and also excludes the placement of restoration soils.

General earthworks need to be constructed to a standard to avoid slippages, failures or significant settlement. Such works may include excavation, backfilling with fill for the landfill cells or lagoon, ramps and other associated structures. Good practice for excavation and compaction of fill is similar to that for road construction and the Specification for Highway Works (SHW) (Highways Agency) provides excellent general guidance on most matters associated in specifying and constructing fill materials.

The largest differences from highway engineering practice are in the specification and construction of clay liners where low hydraulic conductivity rather than the highest strength is generally the target, and a more rigorous independent verification scheme known as Construction Quality Assurance (CQA) has to be used. The latter is required for aspects of construction for which failure could cause a significant increase in environmental risk.

CQA is typically required for all aspects of containment engineering, lining and associated drainage. Containment engineering may include lining beneath lagoons, tanks and pipework and beneath reinforced concrete slabs for composting, biopiles and other waste management activities where leakage of leachate could cause risk of pollution.

Lining systems must be robust and constructed to the highest engineering standards to provide short, medium and long term environmental protection. One of the main components of almost all lining systems is a clay liner. This is normally constructed from reworked clay materials, either naturally occurring clay materials or weathered and/or processed mudrocks. This guidance is written in accordance with the Environmental Permitting Regulations and the Landfill Directive and therefore the clay liner may constitute the artificially completed Geological Barrier (GB) or the Artificial Sealing Layer (ASL)

This document is intended to serve as a guidance note for designers, specifiers, engineers, contractors, landfill operators, regulators and anyone else with an interest in earthworks on landfill sites. **We do not aim for it to be prescriptive but inevitably, in some parts of the text, reference is made to absolute standards or minimum requirements and these are highlighted by enclosing them in a "box".** This document is intended to represent good practice for the majority of landfill-related earthworks projects and as such both the approach taken and the content should be considered seriously. This document is subject to review and amendment as methods improve and are shown to be acceptable.
This document is adapted from and supersedes the earthworks elements of:

- *Earthworks on Landfill Sites* ,Environment Agency (all versions),
- *Waste Management Paper 26B,* Department of the Environment 1995,
- *Waste Management Paper 26*, Department of the Environment 1986,
- *Good Practice in Landfill Engineering*, Department of the Environment 1995,
- *Guidelines on the Use of Landfill Liners*, NWWRO 1988.

Chapter 1 - Background and scope

1.1 Background

It is the responsibility of the site permit holder to ensure that the site design, construction and operation provide the required levels of environmental protection. The granting of an environmental permit and our acceptance of your site management system and CQA plan does not relieve you of this fundamental responsibility. Accordingly, any design or construction proposals you make should ensure you carefully adhere to the relevant pollution control objectives in the site management system. Annex 1 of the EC Landfill Directive (1999) provides the main focus of design. Additional guidance can be found in Landfill (EPR 5.02) (2009) which contains further discussion of these objectives. Table 1 (in Section 2) summarises the main stages in obtaining agreements with us for the design, construction and validation of a clay liner.

1.2 Scope of Document

This document deals only with the detailed design and construction of individual cells and associated infrastructure and does not deal with all aspects covered by the environmental permit. It is assumed that the environmental permit and the site management system are in place.

The scope of this document does not include earthworks in connection with Inert Landfill sites: the Environment Agency has produced separate guidance for these.

This document deals with the issues relating to the design, construction and validation of earthworks for landfill sites, i.e. not just clay liners but also the cut and fill slopes required in the formation of the landfill cells, lagoons, ramps and bunds. Non-liner earthworks construction may involve granular materials. When considering liners, this document considers only the clay element of the liner i.e. that part which is constructed from compacted clay or weathered mudstone. These are natural clay-rich materials, mainly glacial tills and weathered mudstones (reflecting the predominance of these materials in landfill liners) but also include other naturally occurring clay deposits such as the major geological strata comprising clays and marls and colliery discards.

This document also emphasises the need to consider the interfaces of such earthworks with geosynthetic layers and liners commonly specified as part of a landfill lining system.

The document is of a technical nature and it is essential that you seek geotechnical expertise in implementing the guidance. Typically, a qualified civil engineer, geotechnical engineer or engineering geologist would have the appropriate expertise providing they have adequate experience of landfill design and construction. Your designer should have experience comparable to that of your CQA Engineer as detailed in Table 6 in Section 6.

1.3 Definitions

Earthworks: can be constructed from clays, sands, gravels and crushed rock whilst clay liners are generally constructed from clays or weathered mudrocks. For general earthworks you should generally follow the advice in SHW (Highways Agency) on acceptability, testing, layer thickness, compaction and testing for general fill. Where clay liners are to be constructed there are various considerations not necessarily given adequate priority in highway engineering. Section 2.5 gives further information on acceptability of material properties for clay liners.

Sustainability: demands that on-site or local materials are used where feasible. The Environment Agency actively encourages the use of low grade materials, processed to make them acceptable, in appropriate situations within landfills.

Hydraulic conductivity: is the term that is more accurately used in preference to “permeability” as the former infers that the permeant is water. In this guidance we use both terms as appropriate and generally consider permeability to mean hydraulic conductivity as this is the term which is widely used in the industry.

The conductivity of landfill gases is also important but is difficult to routinely determine and has been proven to be related to hydraulic conductivity.

Clay: is a naturally occurring material composed primarily of fine grained crystalline minerals below 2 microns which is plastic within an appropriate moisture content range. Its main minerals are known as “clay minerals” and are primarily hydrated aluminium silicates.

Flexible Membrane Liner (FML) is synonymous with Geomembrane: These terms describe the geosynthetic membranes used to line and cap landfill sites. Whilst this guidance is concerned with earthworks these materials are commonly used as part of the design and reference is made within this document to them in terms of their often close proximity to the clay liner.

Geosynthetic Clay Liner (GCL): this is a composite geosynthetic made by sandwiching powdered/granular bentonite clay between two geotextiles to form a composite sandwich which swells on hydration but is restrained by needle-punching or stitching: others have bentonite stuck to one side of an FML. This geocomposite is commonly used as part of waste management lining and capping systems.

Construction Quality Assurance Plan (CQA Plan): This is the overall document required by the Environment Agency which comprises:

- CQA method statement – outlining the CQA methodology:
- Specification:
- Design drawings:
- CQA pro-forma:
- CQA testing tables.

Chapter 2 - Design

This chapter deals with both the design of all earthworks at a landfill i.e. excavations, subgrades, bunds, embankments, and the specific landfill items such as liners, foundations for leachate chimneys/manholes and access ramps

2.1 General

It is essential that you use the services of a suitably experienced civil or geotechnical engineer or an engineering geologist to carry out all the elements of the earthworks and liner design including consideration of the factors which could impact on the liner's integrity.

The minimum level of qualification/experience for the Design Engineer is the same as for the CQA Engineer Route A (see Section 6, Table 6). However, this does not preclude less experienced designers working under close supervision by appropriately experienced team leaders.

Under the Construction (Design and Management) Regulations 2007 (CDM 2007) you, the developer, have responsibility to appoint a CDM Co-ordinator as all landfill projects are, by their size, notifiable projects.

It is good practice that any engineering design is checked internally, so designs must be produced under a quality system to ensure that the assumptions and design calculations are robust. All internal checking should be signed off by the assessor.

Each individual element of the landfill, e.g. subgrade, liner etc., must be technically justified to produce a satisfactory design. This concept extends both to the design elements within a cell or phase and to the linkage of phases and cells to form the overall containment structure. Consideration should be given to how the site can be constructed and filled with waste, for instance consider stability of the waste during infilling and the loadings on the liner on the slopes by construction plant. Design, constructability and health & safety considerations are part of the responsibility of the designated Designer (CDM 2007).

You must take into account external environmental costs when designing a landfill, for example transporting clays and other materials long distances has an environmental cost in terms of pollution caused by traffic movements and may be unsustainable. You must carefully consider these costs when selecting the earthworks and liner materials. For example, an on-site mudstone which may marginally fail the necessary criteria could well be improved by mechanical processing, thus removing the need to transport replacement materials. Justification is required for <u>not</u> using site derived materials.

Lining a site should also assist in controlling landfill gas.

2.2 Risk assessment

The design and engineering of a landfill site must be supported by a comprehensive assessment of the risk of adverse environmental impacts, harm to human health and damage to property resulting from the proposed development. Any risk assessment must be based on a detailed geological and hydrogeological site investigation and an understanding of the nature and quantities of wastes proposed for the site. Therefore it is important that people who are experienced in the principles involved and in the application of those principles to landfill engineering sites may carry out a landfill site risk assessment.

The formal risk assessments required with an Environmental Permit application are the Hydrogeological Risk Assessment (HRA), the Stability Risk Assessment (SRA) and the Landfill Gas Risk Assessment (GRA). All these require input of the performance of the subgrade and lining system. The HRA is generally carried out first because it has the most impact on the overall liner design but the SRA will determine the allowable slope angles. The design and risk assessments may be an iterative process between the respective teams.

Your site investigation may indicate that an in-situ, non-engineered, naturally occurring clayey material exists below the site and your risk assessment may indicate it provides adequate containment for certain types of waste. You must provide us with conclusive proof of the geotechnical characteristics (particularly in-situ hydraulic conductivity) of the clayey material beneath the site and the consistency of those characteristics throughout its mass. Our experience has shown that it is often difficult, and expensive, to prove that a naturally occurring stratum possesses uniformly low hydraulic conductivity. For this reason, we generally don't recommend non-engineered clayey barriers as the sole means for protecting groundwater. Additionally, such barriers are unlikely to limit landfill gas migration sufficiently for them to be acceptable as a sole means of gas control at sites receiving biodegradable wastes.

If your risk assessment indicates the need for a liner, you must consider which liner type will be most suitable (single, double or composite). Once you've selected a liner type, you can undertake a detailed design. If a clay liner is part of a composite lining system, the design must take into consideration the interaction between the various layers of that lining system, which may include geosynthetics. The interlayer stability is critical and many failures in liners have occurred because inappropriate design values have been used in stability analyses included in the SRA.

There are several computer software packages available which can assist in designing and risk assessing different landfill designs. To be of any value they require site-specific data and whilst these software packages may assist the experienced designer/engineer, they may, if used by inexperienced staff, prove an unacceptably simplistic approach to the subject.

2.3 Typical sequence for the design, construction, validation of a landfill

Table 1 provides a typical sequence for the design, construction and validation of a landfill cell using compacted clays. There are often slight variations on this, e.g. the Field Trial Liner may be incorporated as the initial stage of the Construction Stage particularly where the materials are proven in earlier cells.

Some of the reports listed in Stage B (Table 1) are often combined into one report: it is not a requirement to submit them to us as separate reports.

Table 1: Typical Stages in the design, construction and validation of a compacted clay liner

Stage A: Liner design and method statements	
A1	**Stage:** Hydrogeological Risk Assessment, Stability Risk Assessment, Gas Risk Assessment together with a preliminary design and specification are submitted to and agreed in writing with the Environment Agency as part of the Environmental Permit application.
	Details: Suitably qualified, competent and experienced staff should undertake this. Liaison with the Environment Agency is essential at all stages. When the clay layer forms part of a lining system the performance specifications must be stated for this lining system. Any hydrogeological model produced must model the performance specification of the clay element of the lining system.
Stage B: Cell/Development Phase Specific Design (Pre-Construction)	
B1	**Stage:** Detailed liner design submitted to and agreed in writing with the Environment Agency including a specific Stability Risk Assessment.
	Details: The whole lining system should be technically justified, with care taken to ensure that the clay component of the composite liner is complementary to other elements of the landfill design. This will include the suggested support media and an outline of proposed mixing and installation method.
B2	**Stage:** CQA Method Statement (generally a single document) submitted to and agreed in writing with the Environment Agency
	Details: The CQA Method Statement must include a detailed and systematic programme for checking all fundamental elements of the design and construction; the specification and properties of the materials to be used, the mixing method, the methods of installation where these could affect the environmental performance of the liner and the form of reporting and validation.
B3	**Stage:** Source evaluation of clays to be used as a clay liner and laboratory-based testing must be submitted to the Environment Agency.
	Details: The operator should carry out a geotechnical assessment of the intended source material or any proposed conditioning This may take the form of a site investigation or representative production samples from an existing extraction source and adequate laboratory testing to demonstrate it can meet the specified properties.
B4	**Stage:** Field Trial liner carried out before construction of the liner commences and the Field Trial report submitted to the Environment Agency.
	Details: The Environment Agency should be invited to attend the field trials (and any proposed mixing) and placement methods. The trial liner report must provide evidence that the proposed mixing and installation method is capable of achieving the required performance specifications in the field environment.
Stage C: Cell Specific Construction	
C1	**Stage:** Construction and CQA
	Details: The Contractor shall provide to the CQA Engineer those Construction Method Statements (based on the detail in the CQA Plan) as are required under the Contract. It is essential that the responsibilities of the various parties involved in the works are clear, and that the independent CQA Engineer/Inspector and our Inspector maintain liaison throughout the construction period.
Stage D: Cell Specific Validation	
D1	**Stage:** Validation report submitted to and agreed with the Environment Agency
	Details: The validation report should include a comprehensive record of the actual construction of the liner, providing a long term record of the works.
D2	**Stage:** Written acknowledgement from the Environment Agency
	Details: Once the validation report has been reviewed by the Environment Agency as being acceptable, the permit holder will be informed in writing and subject to other permit conditions being met, landfilling may commence.

2.4 Design Methods

Design should be based on either Eurocodes or conventional British Standards but BS EN 1997-1: 2004 (Eurocode EC7) is our preferred design approach. (Note: modified British Standards will be available for use/reference after April 2010 to aid designers used to those documents).

Most aspects of design can follow the Eurocode EC7 approach but, at the time of writing, partial factors for the analysis of interfaces between geosynthetics and clay liners or between geosynthetic and geosynthetic are not available therefore limit equilibrium methods are still justified. The design could therefore be carried out using EC7 for the soil design and British Standards for the geosynthetics. Alternatively, as geosynthetic interfaces are inherently less variable than soil, it will be acceptable to apply the same partial factors to the interface strengths as those for the soil parameters: the design could then be carried out totally using the EC7 approach.

Whichever method is used the possible occurrence of large strains in the geosynthetic components should be considered and the lack of excessive strains confirmed. Hence, although these materials may not reach their failure stress, strains and deflections can become excessive if the design has not considered strain compatibility.

Design to Eurocodes

Eurocode 7 (EC7) is one of the set of ten Structural Eurocodes and deals with geotechnical design. It is published in 2 parts:

- Part 1: General rules and
- Part 2: Design assisted by field and laboratory testing.

EC7 requires that "For each geotechnical design situation it shall be verified that no relevant limit state ….is exceeded." There are two major divisions of limit states:

1. Ultimate limit states,
2. Serviceability limit states.

Ultimate Limit States

EC7 distinguishes between five different types of Ultimate Limit State (ULS) and uses abbreviations as follows:

EQU loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of the structural materials and the ground are insignificant in providing resistance, e.g. tilting of a foundation on rock.

STR internal failure or excessive deformation of the structure or structural elements, including footings, piles, retaining walls etc in which the strength of structural materials is significant in providing resistance.

GEO failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance, e.g. slope stability, bearing resistance of spread footing or pile foundations.

UPL loss of equilibrium of the structure or the ground caused by uplift due to water pressure (buoyancy) or other vertical actions.

HYD hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients

Formulae for checking these ultimate limit states are given in EC7. The avoidance of ultimate limit states mainly applies to persistent and transient situations. The partial factors that are given in the National Annex to EC7 are only valid for these situations and are applied to the various parameters, actions and resistances. In accidental situations, all values of partial factors should normally be taken as equal to 1.

The EC7 approach is to apply partial factors in the design to modify each of the parameters, soil properties, loads and resistances and then verify that no relevant limit state is exceeded.

The EC7 approach may be summarised as follows:

- Obtain field and laboratory test values from representative samples that define the relevant material properties.
- Compare these values with published values and/or the designer's experience.
- Either use the results in a statistical manner (provided sufficient data are available from the same source) or use experience to decide on a cautious mean value. This is defined as the characteristic property of the material (see Appendix B for guidance on selection of characteristic values)
- Calculate the design parameters by applying the appropriate partial factor to the characteristic values. It should be noted that different factors apply to undrained and drained strength parameters and also upon the design combination (see below).
- The design values of loads (Actions) and resistances are derived by applying the appropriate partial factors to the representative value of the action or resistance. The factors have different values depending upon whether they are permanent or variable, favourable or unfavourable and also upon the design combination (see below).

The choice of which partial factor to use for each parameter, property, action or resistance combination is governed by the ULS being considered and which **design approach** is being used. In the UK **Design Approach 1** is mandatory and it has two different **combinations** of partial factors.

Simply:

Combination 1 has factors which increase the loads (Actions) but keep the design material properties the same as the characteristic values

Combination 2 has factors which decrease the design material properties but keep the permanent design loads (Actions) the same as the characteristic values.

The value of each partial factor is prescribed in EC7. See Appendix B for an example.

Stability is achieved in ULS GEO when:

E_d (design effect of the loads i.e. actions) $\leq$ R_d (design resistance)

or

$R_d / E_d = \Gamma \geq 1$ = the overdesign factor (ODF) for stability which is not a safety factor.

The partial factors are applied to the material parameters and/or actions and/or resistances to derive design values from the characteristic values. Any uncertainty regarding sufficiency or quality of data should be allowed for by the engineer in his choice of the characteristic parameters. As the partial factors are prescribed by EC7 it is possible to seek a value of Γ (ODF) > 1 to allow for consequences of failure, however this is not recommended and the greater the consequence of failure then the more conservative should be the characteristic values selected i.e. lower characteristic strengths coupled with higher characteristic loads. This will keep the required value of Γ closer to (but not less than) 1 for stability.

The UK National Annex to Eurocode 7, Part 1: General Rules lists the partial and correlation factors for ultimate limit states

Note: At the time of writing the National Annex does not give guidance on the factors to be applied to the interface shear strength between soil and geosynthetics and between geosynthetic and geosynthetic. Until such time as national guidance is provided it is proposed that the values given in the UK National Annex to EC 7 for soil strength partial factors be applied in a similar fashion to interface shear strength parameters.

Serviceability Limit States

Serviceability limit states are defined as:

"States that correspond to conditions beyond which specified service requirements of a structure or structural member are no longer met"

For example:

- Excessive settlement of a leachate monitoring foundation causing tensile strains in the underlying basal liner leading to rupture of the basal liner.
- Excessive differential settlement of a basal liner, caused by a soft subgrade area, leading to increased leachate flow through the basal liner.
- Excessive deflection of a retaining wall.
- Insufficient pumping from an excavation leading to inundation.
- Excessive leachate flow through liners leading to pollution of groundwater.

Limit state design requires that the occurrence of serviceability limit states is sufficiently improbable.

Verification that a serviceability limit state has not been exceeded is expressed in EC7 by

$$E_d \leq C_d$$

E_d = design effect of actions (eg displacement, distortion, flow volumes)
C_d = limiting design value of the effect of actions

Design values of actions and of material properties for checking the avoidance of serviceability limit states will normally be equal to their characteristic values i.e. partial factors should normally be taken as 1.0. In cases where differential settlements are calculated, a combination of upper and lower characteristic values of deformation moduli should be considered, to account for any local variations in the ground properties.

The limiting values of deformations should be specified as design requirements for each supported structure. In landfill design, the most critical serviceability requirements are the limiting values of strain for the elements in the liner and the capping. The allowable tensile strains have been the subject of much discussion over the years. The accepted values (Table 2) are set so as to limit the formation of stress cracks which obviously are detrimental to the permeability of the liner.

Table 2: Limiting values of local tensile strain* for the elements in the liner and the capping are:

Sealing material	ε_{max} %	Reference
Compacted clay liner	3	Scherbeck and Jessberger 1992
HDPE up to 3mm thick	3**	Müller 2001, Seeger and Müller 2003 and Müller 2007
Geosynthetic clay liner	6	Koerner and Daniel 1994

* Tensile strain may be caused by bending or elongation due to subsidence or indentations.

** This value allows for local strains due to indentation.

2.5 General Earthworks

General earthworks on landfill projects include the re-grading, excavation and compaction of fill to provide the sub-grade on which to construct the containment facilities and the associated infrastructure. These should be designed and specified to comply with good practice and ensure adequate foundations in terms of bearing capacity and settlement, stability of slopes, retaining walls etc. Much experience and standard design practice for general earthworks has been accumulated by the civil engineering industry which should be utilised wherever possible.

For general earthworks good practice in the design and specification should generally follow the advice in the regularly updated Specification for Highway Works (Highways Agency 2007) (SHW) on acceptability of materials, testing, layer thickness, compaction and testing for general fill. Experience shows many specifiers use only Part 1 Series 600 whereas the other sections and volumes and proper use of Numbered Appendices are necessary to fully specify earthworks.

Where clay liners are to be constructed there are various considerations not necessarily given adequate priority in highway engineering. Section 2.6 of this document gives further information on acceptability of material properties for clay liners. Any material you propose is likely to be a mixture of grain sizes and clay types, therefore your designer, in consultation with us, must determine the materials acceptability for a lining system or for use as a subgrade.

There may be site specific requirements, for example the required shear strength for stability of a slope or material requirements to provide erosion protection, however, the specification and conformance testing of these may well be significantly less onerous than for a clay liner designed as part of a containment structure. Differing approaches are often suitable for the general earthworks and the lining/containment earthworks. The designer should consider whether the earthworks are to be constructed using:

- Method Specification – used for most general earthworks;
- End-Product Specification – **always used for liners** but also for specific earthworks requiring tight control.

These specification types are discussed in detail in Appendix C. Whichever type is used it is imperative that the soil is comprehensively characterised (hydraulic conductivity/moisture content/air voids content relationships and/or shear strength/settlement/moisture content and density relationships) before site works commence and not left to the last minute.

2.6 Clay Liners and Caps

Clay liners can be used to construct the Geological Barrier if none exists or to augment a natural Geological Barrier (i.e. in these situations they form an artificially constructed Geological Barrier). Alternatively they can form the Artificial Sealing Layer where geosynthetics are not being used.

The typical applications and limitations of natural clay liners and composite liners are summarised in Table 3. These are specified using an End-Product Specification as this is a requirement of the Landfill Directive and the Environmental Permitting Regulations.

Table 3: Clay liner systems: Applications, advantages and limitations

Liner type	Applications	Advantages	Limitations
Clay liner as the Artificial Sealing Layer	**a)** Low risk sites **b)** Side slopes flatter than 1 in 2.0 **c)** Used in composite and multiple liner systems	a) Robust and relatively thick (with regard to penetration by sharp waste) b) Absorbs cations and anions from leachate c) Relatively simple structure d) Proven record	a) Potential variable consistency of source material b) Susceptible to shrinkage and swelling c) Can be susceptible to leachate attack d) Protective covering required to avoid dehydration e) Weather conditions influence workability, compactability and stability
Clay liner as an artificially constructed Geological Barrier (i.e. where a composite liner is being specified (clay + FML)	a) Medium risk sites b) Improved containment of landfill gas if FML continued up sidewalls	a) Reduced leakage rates of a composite b) Different material properties of clay and FML bring added resistance against leakage c) Relatively simple structure	a) Clay element susceptible to shrinkage and swelling b) Low friction between FML and clay c) Protective covering required for FML d) Side slope constrained by stability considerations e) FML may be subject to attack from aggressive leachates. f) Complex construction with multi layers of geosynthetics.

Note: 1. FML = flexible membrane liner (geomembrane)
2. Side slopes can be steeper with special design and construction methods.

2.7 Material Properties for Liners and Caps

If you plan on using natural clays in a landfill liner, they must meet the following criteria.

a) Low hydraulic conductivity,
b) Adequate shear strength,
c) Minimal shrinkage upon reduction of moisture content (this is met by application of the plasticity index limits),

The above properties dominate the choice, but the following properties are also very important and must be considered:

d) Plasticity.
e) Workability.
f) Low frost susceptibility.
g) Adequate chemical resistance.
h) Low dispersivity.
i) Adequate attenuation/retardation capacity.

To select acceptable materials initially they should comply generally with the parameters in Table 4:

Table 4: Typical clay liner or cap properties

Property	"Minimum" Requirement	Test
Permeability/ Hydraulic conductivity	See your environmental Permit	BS1377 : 1990 , Part 6 : Method 6
Remoulded undrained shear strength	Typically ≥ 50 kN/m^2 or other site specifically defined value	BS1377 : 1990, Part 7 : Method 8
Plasticity index (I_p)	10% ≤ I_P ≤ 65%	BS1377:1990:Part 2: Methods 4.3 and 5.3
Liquid Limit	≤ 90%	
Percentage fines <0.063 mm (63 µm)	≥ 20 % but with a minimum clay content (particles < 2 µm) of 8 %.	BS1377 : 1990, Part 2 : Method 9.2, 9.5)
Percentage gravel > 5 mm	≤ 30%	
Maximum particle (stone) size	2/3rd compacted layer thickness Typically 125 mm but must not prejudice the liner, for instance by larger particles sticking together to form larger lumps.	

Processing of the material will be necessary where the as-dug material is not acceptable, or if you're doubtful as to the acceptability of the material, for example because of any of the following:

a. Stone content too high.
b. Clay content too low .
c. Clod size too large – destructive trial required to determine size reduction possible.
d. Mudrock - breaking down required.
e. Clay is too dry therefore significant water addition required.
f. Clay is too wet therefore reduction in moisture content is required.
g. Two or more materials are to be mixed and blended.

You should detail your proposed processing specification and methodology in your method statement and QA/QC procedures. Your quality testing must extend to include any material processing you carry out.

2.8 Minimum Design Requirements

For Liners and Caps

Except for inert sites, for which there is separate guidance, we require:

1. That the proposed material is physically and chemically acceptable for its proposed use.
2. The hydraulic conductivity of a clay liner must comply with the specification in Annex 1 of the Landfill Directive.
3. Thicknesses should be in accordance with the class of landfill being designed (generally this should not be less than 0.5 m).
4. The minimum gradient of the base of each cell should be between 1% and 2% (1 vertical to 50/100 horizontal) towards the sump
5. Bunds and slopes must be designed to remain stable with sufficient freeboard over the permitted leachate level.

If your designer deems it appropriate to deviate from any of the above requirements, you/he must justify the deviation to us both geotechnically and in terms of environmental protection, in particular to demonstrate “equivalence”.

A well constructed clay liner will facilitate leachate management and effective control of the leachate head within the site is essential to minimise leakage through a clay liner. For this reason, you will usually require full granular drainage blankets (500 mm thick with proven durability and drainage properties) or equivalent in accordance with the Agency Guidance.

Capping typically uses geosynthetics but clay capping can be used. Whatever sealing layer is used there may be associated mineral layers for gas and/or surface water drainage, cover and landscaping and these must be designed to similar standards as a liner system in terms of specification and stability.

For General Earthworks

You must demonstrate that the materials:

- are “acceptable materials” in terms of SHW,
- can be classified in general accordance with SHW,
- can be compacted to a specification, either by method or end product specification,
- can be laid in accordance with good practice, layering, keying into existing surfaces etc.

Note: The above does not apply to waste regulation layers.

However, it is appreciated that waste or contaminated material may be used inside a landfill cell, eg for ramp construction and bunds, and the deployment of these materials should follow the same principles as the SHW even though they would not be “acceptable materials” in terms of SHW.

It is essential that the design, risk assessment and any CQA Plan for any earthworks (including those of a temporary nature eg access ramps) are appropriate and proportionate to the risks and are submitted to us to demonstrate that they will have no impact on the performance of any element of the existing design.

Temporary works are often perceived as unimportant and have often been built with no design or control but if they fail by sliding they can cause extremely costly damage, may breach the protection provided by the lining and allow pollution from which prosecution could ensue.

2.9 Hydraulic Conductivity for Liners

Our basic requirement for a natural clay liner is that it maintains a low hydraulic conductivity over a long period of time. In this document 'hydraulic conductivity' is synonymous with 'permeability coefficient' and is strictly limited to the test results of saturated samples in accordance with BS1377 (1990) Part 6 Method 6 (triaxial cell test). Samples tested should replicate field conditions and should use appropriate hydraulic gradient and stress conditions.

The hydraulic conductivity of any soil, whilst not a fundamental property of the material, depends on a number of variables including the following:

- Particle size distribution.
- Particle shape and fabric of the soil.
- Soil density (degree of compaction).
- Moisture content.
- Nature of the permeating fluid.
- Mineralogy.
- Variations in test type and procedure.

A potential source of clay may appear capable of achieving the required low hydraulic conductivity. However, inadequate compaction and/or excessively dry material can introduce discontinuities such as fissures and cracks, resulting in higher hydraulic conductivities. Similarly, high natural moisture content or wetting and associated softening during handling can make the material unworkable and/or the structure unstable. Furthermore, subsequent drying of wet clays after installation can result in shrinkage and cracking of a liner, again compromising the integrity of the seal.

Work by Benson, Daniels and others has shown that the hydraulic conductivity of clay liners is significantly influenced by clod size. Soil that is compacted too dry can contain clods which are too strong to break down. To achieve low hydraulic conductivity it is necessary to destroy the clods and eliminate large inter-clod voids, either by wetting and/or by using a higher compactive effort. It is accepted that to achieve low hydraulic conductivity it is necessary to compact clay until it has low air voids content (see Appendices C & D)

2.10 Chemical compatibility for liners

The weight of experience in the UK and the majority of the published data lead to the conclusion that the chemical compatibility of clay liners for sites handling inert and non-hazardous wastes is not a significant problem. For hazardous waste disposal sites the increased thickness of clay liner required by the Regulations (5 metres) provides confidence that the clay liner will not be affected throughout its life by the constituents of the waste/leachate.

If compatibility is to be formally addressed in a site specific situation then this should be carried out at the feasibility/trial liner stage and not as part of routine CQA testing.

2.11 Mudrocks

Using mudrocks for landfill liners is generally acceptable, but these materials may, if not adequately weathered, require processing before they are acceptable for incorporating into a liner. Such processing is typically mechanical, requiring the breaking down of the larger particle sizes by crushing, grinding or grading. Often the moisture content requires adjustment.

Control at the source of the material is also required to ensure that any variations in the material are identified and remedial action taken.

If there are concerns about the chemical nature of shales e.g. if they are black pyritic shales etc then you must carry out chemical testing on representative samples for total sulphur, acid soluble sulphate, calcium oxide content and pH to indicate the likelihood for potential engineering problems such as expansion. You should forward these results to us for consideration. You should include a discussion of expected problems and your proposed solutions in this submission. Care is required when sourcing such materials to ensure they possess the necessary geotechnical properties and chemical stability.

2.12 Bunds, Support Slopes and Ramps

Both permanent and temporary bunds or support slopes and ramps must be designed to be adequate for their proposed use. Temporary bunds are normally used to control leachate and surface waters and the design should ensure adequate liquid control and should demonstrate stability for their required lifespan. It is important to demonstrate the unconfined stability of the waste mass to ensure that sliding does not occur down the sideslope and along the basal liner to the bund i.e. the bund should be a sufficient distance away from the toe of the slope to provide adequate resistance to sliding. Water and leachate retaining bunds must have horizontal (longitudinal) crests. The cores of bunds may be constructed of different material from the liner as long as there is continuity of the liner.

You must maintain an adequate standoff between the waste and the edge of the lining system to provide adequate storage to prevent surface runoff or falling wastes escaping the containment area.

If you wish to deviate from this standard, you must demonstrate to us the technical justification.

The locations of proposed access ramps should be shown and, where in close proximity to the liner and elsewhere where there is specific risk, their stability shall be demonstrated by calculation whether they are made from soil or wastes. The two main aspects of these designs are:

- they are stable for their intended use in geotechnical terms
- they do not overstress/strain or puncture the underlying liner system

The maximum side slope gradients, minimum base width of the ramp and the interface stability on the side slope of the cell must be determined with the crest loaded by the maximum anticipated loads such as waste delivery vehicles and compaction plant. Often the highest loadings are loads of heavy plant braking whilst moving downslope.

It is essential that any earthworks proposal includes a risk assessment by a competent person which demonstrates that no damage will be caused to the permanent works by any temporary structure.

2.13 Capping

The Landfill Directive Annex 1 describes the layers normally required for the various types of landfill.

Landfill caps must be designed for example to:
- prevent intrusion into the wastes
- control water infiltration
- control the emission of landfill gas
- be stable to erosion
- be resistant to attack by roots

These objectives can be achieved by placing 1.0 m of compacted clay to the same standard as specified for a basal liner. However, it is difficult to achieve the required compaction and thickness control with waste as a subgrade and also avoid the long term effects of substantial settlements caused by the consolidation/degradation of a municipal waste sub-grade. Other materials such as geomembranes, geotextiles, and geosynthetic clay liners may be used economically and effectively either in isolation or in a composite capping system.

Other items which must be considered are:
- Thickness and nature of the regulation layer beneath the cap
- Drainage for gas and condensates below the cap
- Surface water run-off above the cap
- Stability of cover soils during construction and in the long term.
- Seasonal timing of the works to enable establishment of grass to aid stabilisation.
- Dangerous Substances and Explosive Atmospheres Regulations (HSE 2002) commonly called DSEAR Regulations.

2.14 Top Surface of Clay Liner

You may intend to place a geomembrane or geosynthetic liner on the upper surface of the clay. Where this is the case, you must ensure that the upper surface of the clay is such that damage to the geosynthetics will not occur in terms of ripples or undulations, protruding sharp objects such as stones, and soft materials. Such issues are controlled by inspections required by the CQA Plan.

There are technical guidance documents on geomembranes (Environment Agency 1999).

2.15 Foundations for Leachate Extraction Structures and Monitoring Points

The foundations to these structures are required to provide a stable base as they may be subjected to substantial down drag due to the settlement and degradation of the waste.

The designer must demonstrate stability with adequate margins of safety in accordance with accepted practice/standards and must show that any settlements of the subgrade do not cause excessive tensile strains in the overlying lining system (see Table 2).

2.16 Drainage

Provision of drainage is very important and an integral aspect of earthworks design. Both the temporary and permanent works drainage should be addressed in any design. This may include design of under drainage to relieve groundwater pressures during construction, cut-off drainage around an excavation, collection of run-off to avoid erosion damage to a side slope or other site specific features. Dewatering wells and trenches are common in landfill development to avoid uplift pressures on a liner during construction and during the early operational life before there is adequate overburden pressure from the waste to counter-balance the uplift pressure.

Collection of run-off during construction and during operation and adequate capacity settlement ponds are essential to ensure no environmental hazard to adjacent watercourses or sewers caused by flooding or suspended solids. The capacity of attenuation and settlement measures required during construction phases is often greater than during the operation of the landfill. It is good practice to construct any permanent settlement ponds at the start of the construction contract and to have extra settlement capacity available (the volume decided by design) to remove silt throughout the construction period. It should be remembered that any pollution of a watercourse by suspended solids (silt) is a criminal offence. Discharge licenses may be included as part of the Environmental Permit of a waste site or may be required separately but both are administered by the Environment Agency.

Design is commonly carried out using standard software packages but adequate training is essential to develop good design from these excellent tools. Good practice and detailing can be found in many publications including Highways Agency/Halcrow (2008-Ref 56) and CIRIA (1986-Ref 15).

2.17 Minimum Information Requirements for Earthworks

Every design whether a general one for the whole site, a specific one for individual cells or phases, or changes to parts of the original design or specification must be accompanied by a report (in EC7 it is called a Geotechnical Design Report) containing the information listed in Appendix A although much may have been submitted in advance as part of the Permit Application.

Please note that this list may not be exhaustive for your particular site, the requirements for which will be stated in the Permit.

Chapter 3 - Source Evaluation

This chapter deals with our requirement for a source evaluation (material characterisation) report which must detail the proposed materials' capability to meet the design criteria.

3.1 Source Sampling

You must:

- Visually inspect the proposed material by means of trial pits or boreholes (described in accordance with BS5930: 1999: Amendment 1, Dec 2007 which incorporates and improves upon the requirements of BS EN ISO 14688-1 and 2 and BS EN ISO 14689-1) in order to assess any horizontal and vertical variation of the source material.
- Take samples in the approved manner, as detailed in BS EN ISO 22475-1: 2006.
- Prepare a plan showing each sample location and include this plan in the Source Report that you submit to us (Section 3.4).

Where the material is to be reworked, it is not necessary for the samples to be undisturbed and samples can be 'as-dug' material but must be representative. Where the clay material is to form a cut face/in situ subgrade then the samples taken should be undisturbed and BS EN ISO 22475-1: 2006 should be consulted as to the type of sample required to give the requisite quality.

It is important to ensure the samples are truly representative and include the full range of the material from the best to the worst of each material considered for use. Sample mixing is generally not acceptable as mixing in the field is difficult and is not common practice.

The number of sample points depends upon its natural variation, consistency and method of deposition. If it is from a new source it needs more testing than a previously proven source. A natural un-excavated source of clay may need less testing than a stockpile of excavated and selected/mixed material or recycled materials. Some natural clays show much more variation than others because of the geological conditions of their deposition and this will affect the sampling and testing strategies. In general the amount of testing relates to the level of variability (see Section 3.3 and Tables 5 to 8 for further details).

3.2 Source Testing Strategy and Significance

Ideally, you should carry out a high frequency of classification tests (moisture content, plasticity, grading and particle density) before the more expensive and time consuming tests (compaction, strength, hydraulic conductivity, interface shear strength). This will provide a better understanding of the type and variability of the material, and give an indication of how many of the other tests are required. For instance, the initial classification test results could indicate more than one statistical population is presenti.e.more than one type of material (eg one clay may have more sand and gravel content than the other) and each population would need separate assessment or an acceptable efficient mixing strategy – but see 3.1 above.

Once you have decided on the number of populations (and their classifications under SHW) that are possible for use on your site then the materials should be subjected to the more expensive and time consuming tests to determine, amongst other properties, compaction characteristics, hydraulic conductivity (permeability) of recompacted samples (and undisturbed if this material represents the subgrade), shear strength of undisturbed and recompacted samples and interface shear strength of undisturbed and recompacted samples against the geosynthetic materials likely to be used on the site.

Whilst the number of tests should be based on the judgment of an experienced geotechnical engineer or engineering geologist some examples are given below of typical situations for liner material whilst fewer numbers could be appropriate for general earthworks (also see Appendices C and D):

3.3 Source Acceptability Testing

The range of tests you perform at this stage must be sufficient to ensure that enough of the clay source has the desired properties to achieve your design criteria. The testing regime we've outlined below is limited to those tests we consider to be essential. If you consider other physical properties are important for a particular installation then you should include tests for these parameters in your testing programme. Your testing programme must be drawn up by an appropriately qualified engineer with adequate experience of landfill design (see also Section 6.3) and take into consideration all related available information including data from previous construction using the source, published data and the likely variability of the soils.

Table 5: Minimum source evaluation testing (for design/specification) rates for clay liners

Tests	***Test frequency***
Classification tests: • Moisture content and Plasticity Index • PSD –wet sieve & sedimentation	1/1500 m^3 (min. 5)
Organic Content (only if likely to be present)	1/1000 m^3
Compaction tests (generally 2.5kg rammer but some soils may additionally require 4.5kg rammer tests)	1/5000 m^3 (min. 3)
Particle Density	1/5000 m^3 (min. 3)
Shear Strength by quick undrained triaxial test on recompacted samples over a range of moisture content and less than 5 % air voids. One recommended test means a set of three individual specimens tested at different cell pressures **Plus** vane shear strengths at each increment of the compaction test	3/5000 m^3 (min 3)
Shear Strength by consolidated undrained triaxial test with pore pressure measurement on recompacted samples over a range of moisture content and less than 5 % air voids. One recommended test means a set of three individual specimens tested at different cell pressures	1/5000 m^3 (min 1)
Hydraulic conductivity measured in the triaxial cell	6/5000 m^3 (min 6)
Shear Strength per soil/geosynthetic or geosynthetic/ geosynthetic interface One recommended test means a set of three individual specimens tested at different normal stresses within the contract specific moisture range. **Interface Shear Strength testing can be delayed until the construction phase but, as there is insufficient published data, it is required that site specific testing is carried out and reported.**	4/10,000 m^2 **of each interface** (min 4)

The testing frequency i.e. number of tests you perform will depend on the homogeneity of the source material as discussed above The Environment Agency R&D Report "Stability of Landfill Lining Systems: Report No. 1 Literature Review. R&D Technical report P1-385/TR1" states "*A single test is not acceptable practice for obtaining characteristic values".* The minimum number of tests required depends upon the variability of the soil, existing data available and comparable experience with the clay/soil (See Tables 5, 6, 7 and 8). There is guidance on developing characteristic values and design values from shear box interface testing in Appendix B).

The range of placement moisture contents and minimum dry densities or maximum air voids content allowed in the specification for the earthworks should be considered when specifying any of the tests. It is important that material properties are measured under the same conditions of moisture content etc as will be appropriate and achievable on site namely:

Shear strength: and interface shear strength changes with time and strain levels. It is important to consider peak tests and large strain ("residual") tests in both undrained as well as effective stress modes for a comprehensive design to be carried out.

It is important to specify the pressures range at which to conduct shear tests. The possibility of curvature of the failure envelope should also be considered and tests should be undertaken to define the failure envelope over the full range of pressures expected (not just three mid range pressures). Sidewall and basal liners are often subject to loading from up to 40 m of waste (pressure ≈400 kPa at the base) whilst for cap liners pressure ≈15 kPa is quite possible: this may require more than three individual pressure ranging from as low as 15 kPa up to possibly 500 kPa, depending upon site specific conditions, to fully define the parameters.

Maximum moisture content: As moisture content increases the shear strength will decrease. The maximum moisture content for construction works is defined by minimum shear strength. For compaction plant and site vehicles, the minimum undrained shear strength will be in the region of 50 kPa to allow effective compaction and trafficking. The maximum moisture content may require to be further reduced by considering the effect on interface shear strength and veneer stability and also settlement.

Minimum moisture content: as moisture content decreases the shear strength will increase. This will make it more difficult to achieve adequate compaction and low hydraulic conductivity at low moisture contents as high shear strength may prevent disintegration and remoulding of clods under compaction. The ability of a compacted clay liner to deflect and shear without cracking and increasing hydraulic conductivity is also affected by moisture content (higher moisture content is better provided that this is sustained during service). Generally, the Plastic Limit is considered to be an approximate guide to the minimum moisture content but trials are being conducted for the Environment Agency to develop a test which will help define the minimum moisture content with a greater degree of confidence. The method requires several samples of soil to be prepared from the proposed moisture content range and these are compacted to dry densities which would plot along the 5% air voids line (see Figure C3). These samples are then strained to the maximum anticipated in a landfill design of 6% before being subjected to a triaxial hydraulic conductivity test in the usual manner. If the tests demonstrate conformance with the hydraulic conductivity specification then the lower moisture content is acceptable.

Plasticity Indices: If the moisture content of the liner material is at or above its plastic limit, the soil is by definition plastic. The plastic limit is difficult to measure accurately and can vary by +/- 4%. Occasionally a soil needs to be laid with moisture content a few percent below the mean value because of reducing shear strength with increasing moisture content. To demonstrate this does not prejudice plasticity with the onset of semi-brittle behaviour further testing is required on strained samples in the triaxial apparatus.

Organic Content: carried out by loss on ignition to determine humus content and/or coal content. This test should be carried out in high risk soils only such as colliery spoil, lacustrine clays and any clays where topsoil has been observed to have been mixed in. Also problems are reported from some secondary (recycled) clay sources. Large or variable amounts of humus or coal can affect the dry density of compacted soils and pose a risk of degradation over time. Whilst large percentages of coal could theoretically cause a spontaneous ignition risk this is unlikely at the high densities of compacted mineral liners. Problems with high organic contents can arise from the inability to achieve good compaction and low permeability. As a general rule clay with an organic content greater than say 5% and a corresponding particle density less than 2.50 Mg/m^3 will require closer scrutiny. The absolute site specific maximum organic content will require definition by compaction and permeability tests. Acceptance rates are source specific.

Dry Density /Moisture Content Relationship: maximum air voids or minimum dry densities need to be defined.

- It is recommended that at this stage 2.5 kg compaction tests are carried out. Experience suggests that most modern compaction plant typically compacts with above the 2.5kg test energy level but below the 4.5 kg test level.
- For liners and high quality earthworks there is ample evidence that compaction which achieves a maximum air voids content of ≤ 5% will produce a liner with a hydraulic conductivity < 1×10^{-9} m/s. (see Daniel (Refs 25 and 26), Daniel & Benson (Ref 27), Benson & Daniel (Ref 19), Benson et al (Ref 20). Thus tests on recompacted samples for liner specification should be between the maximum and minimum moisture contents and at air voids contents ≤ 5%. This will mean a varying dry density. See Appendix C (Figure C3).
- For other earthworks where hydraulic conductivity is not the major consideration, shear strength and/or perhaps settlement may be the governing criteria. In such cases it may be appropriate to consider a minimum dry density in the specification and to use this value in conjunction with the maximum and minimum moisture contents for compaction of samples for testing (Figure C6).
- The behaviour of the soil/rock can be defined by the moisture condition value (MCV) which is a test adopted by the Highways Agency to overcome the problems connected with the plastic limit. The MCV test (BS 1377: Part 4) has been used by HA for many years and recognised limits have developed for maximum and minimum MCV values related to strength and settlement. An advantage of the MCV test is that it can be used as a quick test on site to determine rapidly whether the material at the current moisture content is capable of being compacted to specification. Control on site requires that an MCV correlation curve is developed to define the maximum and minimum MCV values relative to strength, settlement and permeability. However, at the present time MCV testing is not used in landfill engineering because there is a great amount of data available based on standard compaction testing both from the UK and abroad.

Hydraulic conductivity/permeability - the hydraulic conductivity/permeability testing needs to be carried out around the limits of the proposed acceptability envelope. If these all pass the required value by a suitable margin there is confidence that any compacted clay with dry density/moisture content plots falling within this envelope will meet the hydraulic conductivity specification (Figure C3).

At the conclusion of the source acceptability testing there should be adequate data to define the variability of the materials, the compaction characteristics and the hydraulic conductivity and shear strength at the critical edges of the likely density/moisture content envelope. There may be difficulty in compacting soil to achieve states at the critical edges of the density/moisture content envelope using a 2.5 kg rammer, in which case a heavier rammer or compaction into the mould in layers using a hydraulic press and steel formers may be required.

For earthworks that are not liners the same approach should be made but there will be other priorities and it is possible that the testing will be different, e.g. settlement may be more important than hydraulic conductivity or the likely method of specification may be method-related rather than end product specification which is always used for liners.

3.4 Source Evaluation Report

You must send a report of the source testing results.

Your report must include the following:

- The location of the source (address, national grid reference and location plan).
- If the source is from a stockpile, the original location of the material and the period over which the material has been stockpiled.
- The anticipated quantity of material available compared to the volume required for the works.
- The results of any site investigations, including location plans for trial pits and/or boreholes, trial pit and borehole logs to BS5930, types and depths of samples. If a report has been written relating to the acceptability of the clay for its proposed end use, it too should be included.
- The laboratory test sheets for all tests, including failures,
- The results of any field tests, including failures.
- Plots of dry density versus moisture content showing the anticipated envelope of acceptable compaction including moisture content range.
- Expert geotechnical opinion on the acceptability of the material for the proposed use including comments on the risks in selection, placement and compaction.
- A method statement for the field trial, see Chapter 4.

Chapter 4 - Field Trials

This chapter deals with our requirement for a field trial using your proposed material to show that the results obtained during the laboratory based source evaluation stage can be achieved in the field for construction of a landfill liner or cap. Such a trial is mandatory for the construction of a liner or cap. For other earthworks construction in the landfill, if the soil or rock is described well by the standard HA classification then the HA standard method (Series 600) may be used without a site trial with the moisture content range determined by the laboratory based source evaluation exercise. The HA standard method was designed to give the necessary level of compaction having been based on extensive field compaction trials.

4.1 Field Trial Outline Design

The purpose of the trial is to construct a small liner or earthworks using the material and plant anticipated to be used on the main contract and to ensure that the proposed methodology will produce a material that will meet the required specification.

You must supply us with a method statement detailing how you will carry out the field trial.

Your field trial must be designed to provide information on the following:

1. The acceptability of the materials under site conditions.
2. The ability of the material to achieve the geotechnical design criteria.
3. The suitability of the placement, compaction and testing methods to achieve the geotechnical design criteria.
4. The information needed to prepare the detailed construction method statement for the earthworks.

If you propose multiple sources for use in the earthworks, or if you anticipate significant variation in the source material, it may be necessary to carry out field trials for each separate source or material variant.

You should commence the trial with layer thicknesses and number of compacting passes in general accordance with the SHW Tables 6/1 and 6/4 in terms of material classification, compacted layer thickness, method of compaction, roller weight etc., subject to any variations necessary to take account of site specific conditions.

The moisture content of the soil used in the trial will be that operational on the test date but it should be within the range already decided by your source evaluation testing. If it is not then it must be adjusted to fall within the acceptable range.

4.2 Field Trial Procedures

Ideally the trial should be carried out in advance of the main liner/earthworks construction but is often the carried out at the commencement of the contract. In this latter case communicating the results to the Environment Agency has to be very swift in order to ensure they are aware of the methodology to be used and the acceptance envelope to which the works must adhere.

The dimensions of your trial must relate to the design of the liner and/or earthworks, the earthworks equipment and the requirements of the proposed field tests, samples, measurements and observations.

The area, ignoring perimeter zones, must be at least three construction machine widths wide and three to five construction machine lengths long plus acceleration and deceleration zones appropriate for the plant.

You must carry out the trial on the same subgrade on which the actual liner and/or earthworks will be constructed. Where significantly different gradients are incorporated in the design, you must undertake a number of field trials at gradients that reflect the different field conditions. We recommend that for each trial, you place and compact in lifts. Each lift (layer) ought to be typically between 200mm and 250mm in thickness after compaction and a minimum of two test layers should be constructed over a sacrificial base layer.

On completion of a trial the top two layers shall be destructively tested by careful excavation to investigate the adequacy of inter-lift bonding and the presence of discontinuities (e.g. inadequately disintegrated clods).

The field trial must be supervised by a suitably qualified and experienced engineer (see Section 6.3), preferably the CQA Engineer who will be responsible for the quality assurance programme for the construction of the main liner and/or earthworks. You must invite the Environment Agency inspector to observe the construction and testing stages.

The Field Trial results must be formally submitted as part of the CQA Report.

4.3 Field Trial Sampling and Testing

Four undisturbed samples (cores) plus a large disturbed sample must be taken from each layer after the completion of each lift. You should then determine the following properties as required by the specification:

1. density, (by core cutter or sand replacement or nuclear density meter methods)
2. moisture content (by drying and by nuclear density meter if proposed to be used)
3. classification – plasticity indices, particle size distribution, particle density
4. hydraulic conductivity – constant head triaxial cell method (if for a liner)
5. shear strength (as appropriate for other earthworks)

Where you use a nuclear density meter you must calibrate its results against field dry density and laboratory moisture content (BS 1377 1990 Pt 9 Test 2.5). Where only core cutter densities or sand replacement densities are determined it is appropriate to sample both the top and bottom of a layer as the compactive effort may vary and the core cutter is relatively shallow.

4.4 Field Trial Measurements and Records

As a minimum, you must take and record the following measurements.

1. Records must be made of the type and condition of the material.
2. Details must be recorded of the method of transportation, treatment and the placement of the material.
3. The type, dimensions, weight and operating speed of compaction plant must be recorded, together with the specification sheet for the roller/s
4. The number of passes of the roller, or of each type of roller if more than one is used, must be documented. The number of passes is defined as the number of times that each point on the surface of the layer being compacted is traversed by the compaction roller in its operating mode.
5. The method of measuring the moisture content and density of each sample point must be recorded.
6. Records must be kept of all field tests and samples, including failures with a diagram showing sample positions.
7. Photographs of the trial (particularly the destructive testing).
8. If the field trial liner is to be incorporated into the works the subgrade needs to be surveyed and tested in accordance with the CQA Plan.

4.5 Field Trial Report

The trial report should be used to confirm and/or refine the proposed method statement for the actual construction. The trial permits changes to the initially proposed methodology and allows all parties to be assured that the earlier assumptions are correct or that they have been corrected.

The Report should provide all the detailed records of the trial including changes and reach conclusions about any revision to the construction methodology with a statement as to the suitability of the method to provide a material which complies with the specification.

On completion of the field trials, you must forward the report to us.

Required amendments to your proposed construction method statement following the trials or during subsequent construction must be agreed with the CQA Engineer and obtain approval from the Agency.

Provided that the CQA Engineer recommends that the methods proposed give a material in compliance with the specification then the compaction works may proceed at your risk until written agreement is received from us.

Chapter 5 – Construction

This chapter deals with our requirement for a specification, which is part of the CQA Plan and aspects of control of the materials and works. The specification must provide an engineering description of the works including the required acceptance criteria and details of the installation methods. It should also detail any limits to operational activities that may impinge on the lining and earthworks but which are not dealt with elsewhere.

5.1 Specification

The specification forms part of the CQA Plan for your development works which may be a cell basal and side wall liner, cell cap or dividing bund etc.

Construction of the base and side slopes and subsequent capping of the landfill is usually carried out sequentially under a number of separate contracts for each cell over many years.

As such you must submit your CQA Plan to us for written approval before proceeding with the construction of each cell and also before construction of the capping of each cell.

Remember the works will be judged against the quoted specification. Do not specify property values which are impossible to achieve in the field. Severe delay can ensue.

5.2 Pre-placement Considerations for Liner Construction

The hydraulic conductivity of reworked clay is dependent upon a number of factors: these include the structure and fissuring possible around clods of clay and possible foreign bodies such as larger stones.

Therefore, prior to placement and compaction, all significant foreign matter and oversized stones must be removed.

Clod size may also be restricted, as large clods can be difficult to spread and compact. This will have been addressed in the source assessment and field trial and you must address these matters, which may require special processing techniques, in your construction method statement.

5.3 Construction Moisture Control

Controlling moisture content in earthworks construction using clayey materials is often difficult, particularly in areas of high rainfall or where the construction works occur during the winter months. The moisture content may increase during wet periods above the maximum moisture content allowed in the specification. Similarly, if left exposed to drying conditions, clay may suffer reduced moisture content to below the minimum moisture content allowed in the specification and a corresponding loss of plasticity and workability which may result in formation of fissures. Therefore, the clay must not be worked during a prolonged wet or dry period without carefully considering the possible problems and implementing previously-agreed methodologies to alleviate the effects.

A method statement is required for moisture conditioning and extra monitoring carried out to confirm its success: this may result in changes to the method statement as experience with the material grows. During dry periods, you can maintain the moisture content by cross ripping and light multiple spraying (not one heavy dousing) with clean, uncontaminated water. Conversely, you may need to pump away any water which collects on the clay surface during placement or employ means to reduce the moisture content. If you add water to the material, you must thoroughly mix it to ensure uniform moisture content throughout the thickness of the layer and it will be necessary to leave it for sufficient time for the moisture content to equalize. Please note that the wetting or drying of clays is difficult because of their low hydraulic conductivity and should be avoided if possible.

You should also consider whether clay will be excavated and placed immediately or kept in an engineered stockpile prior to use. Stockpiled clays may be subject to various influences such as wetting and drying which will affect their geotechnical properties. Methods of protection of clay, and other materials on slopes, should be considered. Care must be exercised in using materials which have been stockpiled for prolonged periods. Further testing may be required in such cases before the material can be used in the works.

5.4 Material Placement

During construction, you must follow your method statement. You must agree in writing any proposed changes with us that are likely to have an impact on the performance of the liner. Any significant changes will require further trials to demonstrate the suitability of the proposed changes.

Any testing you require must take place when the construction works dictate, rather than when it is convenient for your testing laboratory. Where results indicate non-compliant construction, you must clearly mark the affected area, record a non-compliance before carrying out the appropriate remedial measures. As noted in chapter 7, the locations of such testing, and the details of the remediation you carry out must be documented and forwarded to us in the validation report.

Further information regarding requirements for survey are given in Section 7.

You must accurately determine the initial and final levels of the liner and/or earthworks using the surveying techniques detailed in your construction method statement.

You must avoid measuring basal liner thickness by excavation or augering, as even the most careful resealing will never be able to reproduce the quality of the original layer.

The minimum liner thickness shall be the stated thickness plus twice the tolerance of the surveying kit used.

Consideration should be given to the use of padfoot and smooth vibrating rollers for compacting clay liners; there may be geotechnical or operational reasons for using only smooth rollers. If this is the case, you should scarify the surface of previous lifts prior to placing the subsequent lift. The scarifying should be sufficiently disruptive so as to ensure adequate bonding and remove any planes of discontinuity and potential weakness at the lift interface. The surface of the lift must be roughened to a depth of 20 – 30 mm with the use of a ripper or other suitable device.

Compaction of clayey caps can be difficult over significant thicknesses of landfill and consideration should be given to the method of compaction and the method of thickness measurement.

5.5 Earthworks Protection

Once the liner, cap or earthwork is constructed it is essential that you protect it from degradation by frost, desiccation or rain damage. Our experience is that in warm dry periods of weather desiccation cracking can penetrate up to 300mm into the upper surface of the clay liner. To prevent this type of damage a suitable sacrificial weather protection layer will be required.

A sacrificial layer may be represented by an additional thickness to the clay liner which may be trimmed prior to placement of the artificial sealing layer, or a geosynthetic protection layer. A technical justification should be provided to support the proposed method of protection however this may change as experience with the material/site conditions grows.

After periods of heavy rain it is often necessary to remove softened clay from the upper surface of a clay liner in order to allow the artificial sealing layer to be placed: this can happen a number of times.

Therefore, where the clay weather protection layer is to be trimmed it is essential that the thickness of the clay liner is surveyed immediately prior to the placement of the artificial sealing layer to ensure the layer thickness is adequate.

We should be informed as to the start date for the installation of materials overlying the clay liner so that we are able to inspect the surface receiving the materials.

Consider also erosion protection on side slopes and take into consideration interface stability issues.

5.6 Liaison with the Environment Agency

Good liaison with our Officers should ensure they will have more confidence in the quality of the works and should help gain quicker acceptance of the validation report. Your CQA Inspector should liaise regularly (preferably weekly) with your nominated contact at the Environment Agency with a progress update covering ideally.

a. Progress in the last week and the proposed work programme for the following week.

b. Weather conditions.

c. In the case of multiple clay sources, the source(s) currently in use.

d. Any testing undertaken with results recorded on the pro-formas listed in the CQA Plan.

e. Any problems encountered with solutions proposed/agreed.

Chapter 6 - Construction Quality Assurance (CQA)

6.1 Background

Whilst this chapter is primarily concerned with quality assurance during construction, assuring quality during the planning and design stages is of fundamental importance if it is to achieve modern high standards. You should not only apply construction quality assurance (CQA) to ensuring the design is implemented as planned, but also quality assurance (QA) to the design process itself and to the subsequent operation and maintenance of the site. Your design QA procedures must be documented and forwarded to us as part of your design submission.

6.2 Definitions

The following definitions are from BS4778 Quality Vocabulary, Parts 1 and 2.

Quality - The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.

Quality Control (QC) - The operational techniques and activities that are used to fulfill requirements for quality.

Quality Assurance (QA) - All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality. QA embraces all activities and functions concerned with the attainment of quality, rather than in the narrower sense only of the provision of proof associated with the word "assurance". Thus quality assurance includes the determination and assessment of quality.

Construction Quality Assurance (CQA) - Construction quality assurance (CQA) is applicable specifically to construction activities and is an essential tool for the assurance of quality and ensures the constructed structure complies with the agreed design and specification. CQA should be certified by an independent (third party) quality engineer. CQA is required to ensure that the objective of producing a high quality, practically flaw free liner is achieved, as even small variations in material and physical characteristics could prejudice the integrity of the liner and hence the design specification may not be met.

6.3 Independent Third Party Quality Assurance

We require independent third party CQA to ensure that the materials and workmanship in any earthworks and/or liner meet the standards specified in your permit and CQA Plan. We recognise that, in order to obtain the highest levels of quality, the experience of the people monitoring the works on the site and those providing office backup must be appropriate to the type and technical complexity of the works. The people responsible for monitoring quality on site are designated as:

1. the Construction Quality Assurance Engineer (CQA Engineer) and
2. the Construction Quality Assurance Inspector (CQA Inspector)

We require that you forward the curriculum vitae of the people to be involved in the CQA procedures to us for approval because it is essential that we have confidence in the capabilities of the staff you are proposing for monitoring quality on site and those providing office backup. It is not our intention to dictate the precise career profile of the type of persons to fit the roles, however, the general guidelines are:

Table 6: Required qualifications and experience for CQA Personnel

CQA Engineer Route A 1. A Chartered Engineer or Chartered Geologist **PLUS** 2. Minimum of four years design and/or supervision of landfill construction which must include earthworks and clay liner construction. **PLUS** 3. Experience in design and/or supervision/construction with geosynthetics where construction includes these materials.
CQA Engineer Route B 1. A formal qualification in science or engineering eg OND/ONC or higher in civil engineering, mining engineering, engineering geology, building, quantity surveying or science with training in soil mechanics. **PLUS** 2. Minimum of eight years design and/or supervision of landfill construction which must include earthworks and clay liner construction. **PLUS** 3. Experience in design and/or supervision/construction with geosynthetics where construction includes these materials.
CQA Inspector Route A The experience profile for the CQA Inspector can be more varied than for the CQA Engineer but for earthworks CQA we require: 1. Minimum of two years continuous supervision of earthworks construction, or similar experience, **PLUS** 2. Minimum one month, one-to-one close proximity training as an assistant to an experienced CQA Inspector on a contract. Followed by mentoring and close supervision by the CQA Engineer during the earthworks and clay liner construction period.
CQA Inspector Route B 1 A formal qualification in science or engineering eg OND/ONC or higher in civil engineering, mining engineering, engineering geology, building, quantity surveying or science with training in soil mechanics. **PLUS** 2 Minimum one month, one-to-one close proximity training as an assistant to an experienced CQA Inspector on a contract. Followed by mentoring and close supervision by the CQA Engineer during the earthworks and clay liner construction period.
Geosynthetics Inspection Where construction includes geosynthetic elements a CQA Inspector must, in addition to the above be able to understand the principles and to demonstrate experience in supervision and/or construction with the relevant geosynthetics **OR** Minimum two days, one-to-one close proximity training as an assistant to an experienced CQA Inspector on a contract with the relevant geosynthetic. Followed by mentoring and close supervision when those materials are being deployed.

Any personnel involved in the CQA procedures must be independent of the permit holder and financially independent of the construction contractor. We have accepted both large companies and sole traders as CQA engineers and inspectors.

The supervision of the earthworks and liner construction by the various parties (CQA Engineer, CQA Inspector, contractor and operator) must be integrated, each having a clear definition of their roles and responsibilities.

Any on-site modifications to either the design or specification must:

a) be referred to and accepted by the design engineer as having no impact on the performance of any element of the design,

AND

b) have formal written acceptance of such changes from the Environment Agency before proceeding with the works and/or implementing any changes except in emergencies

6.4 CQA Plan

The CQA Plan is drafted by the CQA Engineer with reference to the Specification and, ideally, with input from the design engineer.

You must forward the CQA Plan and receive our formal agreement of your plan in writing before you commence work on site.

Useful texts on the CQA process are German Geotechnical Society (1993) and USEPA (1993). Some of these requirements are incorporated in Table 7, which gives typical rates of testing normally required during the construction of a clay liner. You should decide the actual methods and frequencies on a site and material-specific basis including variability of the material, amount and consistency of characterisation testing carried out, consideration of the different types and relative importance of the various earthworks and structures.

Your CQA Plan should specify the testing laboratories you plan to use if known.

These laboratories must be accredited (by UKAS or equivalent) to carry out the tests required.

Note that UKAS accredits a laboratory for specific tests and does not provide accreditation for all the tests that a laboratory is able to do. UKAS have a web site where you can check the accredited tests of all laboratories (http://www.ukas.com/). The contractor shall not be responsible for paying for the CQA function: this is the responsibility of the operator.

6.5 Pass/Fail Criteria for Liners

The methodology to determine pass or fail for the liner is presented in Appendix D.

It is required that control of liner compaction is to be by moisture content and density.

The results are plotted on the graph (see Figure D1) and they are appraised as having passed or failed.

For compliance purposes it is required that at least A % of all results within the acceptable moisture content range (including retests) plot less than 5 % air voids. Provided that anomalous readings above the Zero Air Voids Line (Diamond grey results) have been resolved/rejected or repeated as necessary then this requires that the combined number of “Diamond black” and “Diamond grey” results are ≥ A % of the total number of results within the acceptable moisture content range (“Diamond black” plus “Diamond grey” plus "Diamond white" results).

The minimum value of A varies according to the location of the landfill site:

Site location	**Minimum value of A**
Non sensitive, non-aquifer sites (Secondary Aquifer B)	80
Sites over a sensitive (minor) aquifer (Secondary Aquifer A)	90
Sites over a very sensitive (major) aquifer (Principal Aquifer)	95

“Diamond white” results i.e. those within the moisture content range but with air voids > 5% can be accepted provided that A % of the total number of acceptable tests has resulted from “Diamond black” and “Diamond grey” results.

Table 7: Typical CQA testing during the construction phase of a liner

Test type	Test standard	Default test frequency	Typical no of tests per 5,000m^3	Typical no of tests per 10,000m^3
Moisture content	BS1377 1990, Part 2 Method 3.2	1/250 m^3	20	40
Liquid limit	BS1377 1990, Part 2 Method 4.3	1/250 m^3	20	40
Plastic limit and plasticity index	BS1377 1990, Part 2 Method 5.3 and 5.4	1/250 m^3	20	40
Particle density	BS1377 1990, Part 2 Method 8	1/500 m^3	10	20
Particle size distribution	BS1377 1990, Part 2 Method 9	1/500 m^3	10	20
Vane Shear Strength	BS1377 1990, Part 9 Method 4.4	1/250 m^3	20	40
Hydraulic conductivity (Permeability)	BS1377 1990, Part 6 Method 6	1/500 m^3	10 Note 8	20 Note 8
Density (In-situ)	BS1377 1990, Part 9 Methods 2.1, 2.2, 2.4,	1/250 m^3	20	40
Visual homogeneity	Note regularly	--		
Passes with roller	Note number carried out regularly	--		
Maximum clod size	Note size regularly	--		
Interlift scarifying depth	Note regularly	--		
Lift thickness	Designer specified after Field Trial	As in Spec.		
Surface evenness	Note regularly	--		
Interface testing per interface per 10,000 m^2	ASTM D5321, D6243	4 sets at 3 moisture contents (when clay involved) and 3 normal pressure		

Notes

1) The above default frequencies are for a clay liner to be constructed to a thickness of 1 metre. Where the thickness of the liner is to be less the frequency needs to be increased.
2) Testing/sampling shall be spread evenly over the entire area to be tested.
3) The above default frequency is for consistent clays and variable material will require higher frequency.
4) Test frequencies may be varied with the prior written agreement of the Environment Agency. An agreed frequency of testing shall be source specific, change the source and a new frequency requires to be agreed with the Environment Agency.
5) The omission from this table of any test does not preclude its use. The designer shall discuss appropriate test specifications and frequencies with the Environment Agency.
6) Where use of the nuclear density meter is proposed it should be calibrated as required by the manufacturer, by and as in the laboratories accreditation and be calibrated against laboratory moisture content and density at a ratio of 5 NDG tests to 1 laboratory test.
7) If a reduction in the testing rate is proposed this should be justified in terms of recent past testing results etc.
8) The majority of these tests could be carried out as part of a full and exhaustive characterisation testing programme so that the relationships between permeability/shear strength and moisture content/dry density/air voids shall be established before the earthworks commence. Then earthworks control is by density and moisture content testing as discussed in Appendix D.

Chapter 7 – Surveying Requirements

7.1 Purpose

The purpose of topographical survey work is to ensure that the elements of the landfill construction and infrastructure are built in accordance with the agreed design and also provide a record of the locations, levels, shapes and gradients of relevant features. It is essential that the 'as-built' drawings accurately and precisely portray the layout, locations and levels of the landfill construction.

As the performance of the mineral liner is a function of both its properties and its thickness, in the same way as the mineral liner is sampled and tested to confirm its material properties, a similar quality-based approach should be adopted to control and confirm the thickness and gradients of the mineral liner.

Although this section refers to surveying of elements related to earthworks, similar principles can be reasonably applied to other elements such as geosynthetic elements or drainage layers.

7.2 Survey Techniques and Equipment

A wide variety of techniques and equipment are available; currently landfill engineering works tend to utilise either Total Station (theodolite with an electronic distance measurement device) or Global Positioning System (GPS) methods. It is not our intention to specify, recommend or exclude a particular method; different methods have their own strengths and weaknesses and the most appropriate will depend on the considerations for the project, including practicality, accuracy, speed, and cost.

- Total station methods are considered to be more accurate, which may permit closer control of material thicknesses and but are more time intensive and expensive to operate.
- GPS methods tend to be quicker and cheaper, but their lower accuracy may require a thicker mineral liner to be placed, resulting in higher construction costs. GPS surveying may not be possible where the signal path to satellites is obstructed, such as close to quarry walls and steep slopes.

For the geological barrier (as for the main survey) check surveys should be carried out on the base of the mineral liner (subgrade / formation surface) and on the upper surface when the final thickness has been placed.

Where a mineral cap is to be constructed, the method of thickness measurement also needs to take account of any settlements within the underlying materials. It may be more appropriate to confirm the final thickness via a series of trial excavations or hand augering (with appropriate reinstatement of resulting holes). Note: this is not permitted for the basal liner.

7.3 Main Survey

The majority of topographical setting out and survey work may be carried out by the landfill operator's 'in-house' staff, or by the main contractor or a subcontractor. It is expected that this is the primary control and should be sufficiently intensive and comprehensive to enable the landfill to be constructed in accordance with the design.

The frequency/density of survey points should be sufficient to give confidence that the thickness and level requirements have been met; special attention should be paid to curved surfaces and changes of gradient or direction ; typically a 1 metre thick basal liner with a smooth planar surface profile might be surveyed on a 10 metre grid; at and around changes of gradient and profile (break-lines) the grid density would be increased to a 5 metre grid (for liners designed to be less than 1 metre thick, the frequency of survey points should increased).

As the minimum thickness requirements required by the Landfill Directive are absolute, the target thickness should take account of the accuracy and precision of the survey method. The target thickness of the mineral liner should equate to the design thickness plus twice the limit of precision/tolerance of the survey method being used.

7.4 Check Survey

As part of the CQA Process it is a requirement of The Environment Agency that Check Surveys are carried out to verify the accuracy of the main survey. It is not intended that this survey amounts to duplication of the main survey but to check a proportion of the individual main survey points on the sub-grade surface and the top of clay surface for gross errors. Typically 10% of the main survey points of each of these two surfaces shall be checked over at least two visits and should include the locations and levels of the leachate collection sumps and monitoring points and target pads.

We require that these check surveys be independent of the main contractor and may be carried out by appropriately competent staff from the landfill operator (as long as they are not also responsible for the main survey), the CQA Engineer or an independent surveying contractor.

7.5 Agreement between the Parties

To prevent problems arising, it is imperative that all parties involved agree in advance of the works the equipment and the control stations to be used, their locations and levels and the tolerances specified in the CQA Plan are to be implemented. The minimum tolerance (or maximum difference/variability) that will be considered to be acceptable in comparing the main and check surveys shall also be agreed and specified in the CQA Plan.

If ‘point-on-point’ surveys are to be used for the Main Survey, then the specification for the grid of points shall be agreed.

As part of the validation process it will be necessary for the person(s) undertaking the check survey to confirm in writing the accuracy of the main survey and provide details of their suitability to undertake the work.

Table 8: Checklist of items to be included in Survey Drawings

Title of Project, contract, element of works, etc.	
Drawing version number, with details of revision history.	
Scale (Scale at size to be printed, eg 1:500 at A1)	
Details of the Survey Grid (eg. OSGB36, or local grid).	
Locations of control stations/levels, benchmarks, etc. (permanent and temporary).	
North arrow	
Grid intersections	
Distinguish between surveys done on different times and dates	
Extent or boundary of the survey	
If more than one clay source is used, identify and differentiate between the areas where the materials have been placed	
Sample locations and test locations, including locations of thickness measurements if trial excavations or hand augering are used.	
Spot levels and contour lines at appropriate intervals	
Isopach plans showing mineral liner thickness	
Cross-sections of mineral liner thickness at sideslopes, changes of gradient	

Chapter 8 – Validation report

The validation report presents the final "as-built" construction and engineering details of the works including all test results and non-conformances. The as-built drawings form an important part of the permanent record we and you hold. It must provide a comprehensive record of the construction and be easily understood, particularly in terms of the technical detail. You must specify what form of documentation and presentation you plan to use in your quality assurance method statement.

The final validation report shall include the following information as a minimum:

1. The results of all tests (field and laboratory test reports) shall be summarised by the CQA Engineer. This summary shall include field and laboratory tests and the records of any failed tests with details of the remedial action taken referenced to the appropriate secondary testing.

2. Copies of all manufacturers' test certificates (where geosynthetics have been used).

3. Plans showing the location of all tests.

4. As-built plans and sections of the works including formation and top of clay layer as described in Section 7.

5. Copies of the CQA Inspector's daily records (including, for example plant in use, work done, problems experienced, weather conditions, condition of clay, volumes of water added).

6. Where multiple clay sources are used in the works, plans must be submitted showing the location of each clay source in the works.

7. Records of any problems or non-compliance and the solution applied.

8. Any other site specific information considered relevant to proving the integrity of the liner or earthworks by the Quality Assurance Engineer or the Environment Agency.

9. Validation by the CQA Engineer that all of the works subject to QA and CQA procedures have been carried out in accordance with the method statements, designs, specifications and pass/fail criteria previously agreed in writing with the Environment Agency.

10. If the results of all testing are presented for a particular stage of the works eg:
    - subgrade,
    - compacted clay liner,
    - geosynthetics (e.g. geomembranes and geotextiles)
    - drainage layer
    - pipework

    then each stage can be given our approval in advance of the full validation report being sent to us. The approval of the full report is then a much simpler process.

Appendix A

Information to accompany a Design and/or a Specification Submission
(Requires cross reference with the information on the Permit Application/ Permit)

Your submission would typically be expected to cover the points listed below although many items will have been included in your permit submission and need only reference to the permit application or permit documentation.
Please note that this list may not be exhaustive for a particular site:

Item	Description
Design	
1	The design engineer's name and qualifications
2	The QA procedures applied to the design process
3	SRA, HRA and GRA including: • The concepts underpinning each design element • Information on the geology, hydrogeology and hydrology of the site and the site history, including areas of old waste, mining, quarrying and previous industrial uses • Leachate attenuation including the depth and attenuation/retardation properties of any unsaturated zone • Predicted groundwater upwelling and breakthrough during excavation and construction • Assumptions of leachate and gas migration and control • Derivations of design parameters • Factors of safety/overdesign factors derived in the design analyses • The base of excavation, subgrade type, depths, strength and compressibility • Basal and side slope stability calculations and factors of safety/ overdesign factors (this should include stability calculations/overdesign factors for vertical sidewall liners) • The location and stability of permanent and temporary bunds • The location and stability of access ramps • The location and stability of leachate extraction/monitoring wells • The SRA must show that the earthworks and liner will be stable over their predicted lifespan for the specific works being undertaken, i.e. not a generic analysis for the full site. An assessment must consider both during construction, after construction and during filling and completion of filling/capping of the cell as appropriate.
4	Basal and side slope gradients for leachate management
5	Surface water management within and around the cells during construction, during operation and after capping (see item 7)
6	Construction details of the joints between phases of working
7	The environmental protection requirements of the design and calculations to show how these will be met amongst, in particular, in connection with prevention of pollution of water courses by suspended solids ie silt.
8	The interaction of individual elements of the liner system, especially in the case of FML/mineral composites.
	continued

Item	Description
9	The volumes of individual cells and the volumes of materials required for the engineering works.
Specification	
10	The method of subgrade preparation, and acceptance criteria
11	The method of sub-liner groundwater control
12	The method of any sub-liner leak detection system installation (if appropriate)
13	The allowable working range of classification indices, moisture content, density, shear strength and maximum particle size.
14	The method of providing scaled and coordinated as-built plans to us, including the survey methodology.
15	The methods of determining constructed liner/lift thickness and for ensuring compliance with design tolerances for line, level and gradient.
16	Any differences in construction and testing techniques between base and side slopes.
17	The construction methods for other structures, such as leachate/surface-water drains, leachate chimneys, sidewall risers, retrofit pads, bunds, ramps, sumps and anchor trenches.
18	Remedial action to repair damage to the liner resulting from CQA sampling.
19	Remedial action to be taken in the event of non-compliance with any part of the specified criteria.
20	Procedures for dealing with inclement weather, including frost damage, drying and desiccation, ponding and wetting and softening during construction, and the method of protecting the completed liner, including any temporary and/or long term protection.
21	The specification of the top surface of the liner if a composite is to be employed
22	The measures for pollution prevention in terms of fines run-off, drainage and discharge to surface water or sewer during all stages of construction, filling and capping.
Method Statement/Trial Liner Report	
23	The method of liner and/or earthworks construction; including the plant to be used, compacted lift thickness, minimum number of passes of compaction plant, moisture content range and the method of keying individual lifts. This will be the method approved in the Trial Report. The source materials or compaction methodology must not be significantly changed without a further trial to demonstrate the suitability of the material and/or the revised method
24	The method to be used to wet and/or dry the clay if necessary.
25	Criteria for excluding unsuitable material, for example foreign bodies, and the maximum permissible clod and particle size.
26	The method of material processing (if necessary), including clod size reduction, removal of large particles and foreign bodies, water addition

Appendix B - Derivation of Characteristic Values

1. The characteristic value of a soil property, in simple terms, is a cautious value of that property derived from test results and previous knowledge of the material and behaviour of the proposed site structures.

2. The design parameters used in the analysis of the various limit states are calculated by applying the appropriate partial factor to the characteristic values. It should be noted that different partial factors apply to undrained cohesion, effective cohesion, effective angle of friction and also to peak strengths and residual values. Permeability is used in serviceability limit states and as such its partial factor is 1 i.e. unity. The derivation of the characteristic value of each soil property/parameter is therefore fundamental in the analysis/design process.

3. The characteristic value of a soil property, e.g. strength or permeability, is defined as "a cautious estimate of the value affecting the occurrence of the limit state". [Note: a limit state is defined as "a state beyond which the structure no longer satisfies the design performance requirements". In colloquial terms this indicates failures i.e. collapse in an Ultimate Limit State (ULS) or undue settlement or cracking or water flow in a Serviceability Limit State (SLS)].

4. EC7 Clause 2.4.1 (2) states:

   It should be considered that knowledge of the ground conditions depends on the extent and quality of the geotechnical investigations. Such knowledge and the control of workmanship are more significant to fulfilling the fundamental requirements than is precision in the calculation models and partial factors.

5. EC7 Clause 2.4.3 (1) requires that ground properties shall be obtained from test results and from other relevant data eg back analysis of slope failure or ground settlements. Clause 2.4.5.2 states:

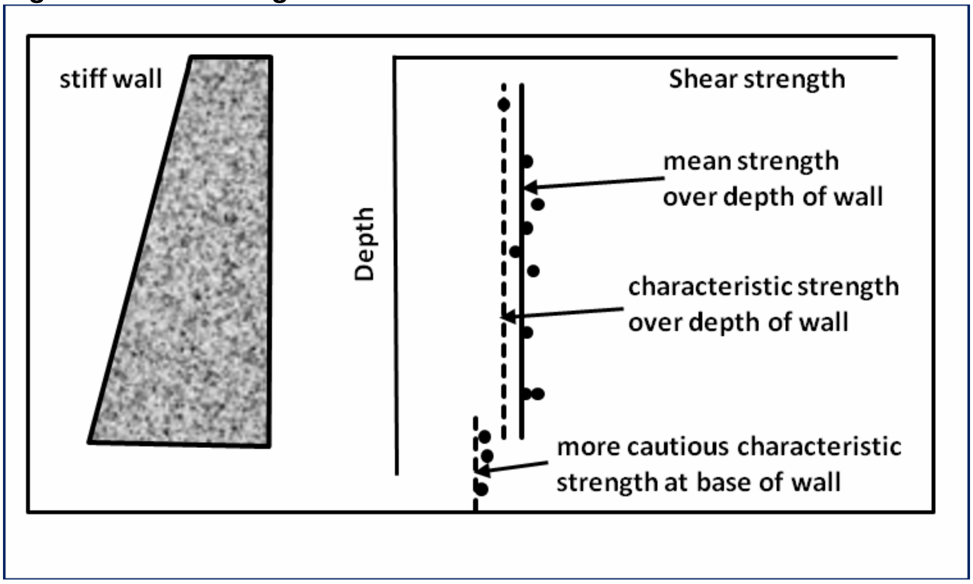
   The selection of characteristic values for geotechnical parameters shall be based on results and derived values from laboratory and field tests, complemented by well-established experience.

6. There are two main steps in deciding the characteristic values for the relevant geotechnical parameters:
   i. establish the values of the appropriate ground properties
   ii. from these select the characteristic value as a cautious estimate of the value affecting the occurrence of the limit state

7. The aspects to consider when selecting the characteristic value are:
   i. **The amount of and degree of confidence in, the ground properties**. The difference between the selected characteristic value and the test results will obviously be greater if the test results show a large amount of scatter.
   ii. **The soil volume involved in the particular limit state**. The zone of ground governing the behaviour of a geotechnical structure at a limit state is usually much larger than a test sample or the zone of ground affected in an in situ or laboratory test. The test results need to be averaged over the volume of soil involved in the limit state being considered.
   iii. **The ability of the structure to transfer loads**. Stiff structures may be able to transfer loads from weaker zones to stronger zones provided the soil is ductile.

iv. Hence, where a large soil volume is involved together with a stiff structure and ductile soil then the limit state will be controlled by a characteristic value close to the mean value of the soil parameter. For example, consider the retaining wall shown in Figure B1:

Figure B1: Retaining wall - characteristic values



The active pressures on the back of the wall are derived from the characteristic value derived from the mean strength of the ground over the full depth of the wall.

v. However, where a smaller soil volume is involved then the limit state will be controlled by a characteristic value close to the (randomly occurring) lowest values of the soil parameter because the failure surface may develop mainly within a volume of weak soil. Hence, the characteristic value of soil strength for derivation of the passive pressure distribution on the front of the wall and for foundation analysis will be close to the lowest test results at the base of the wall.

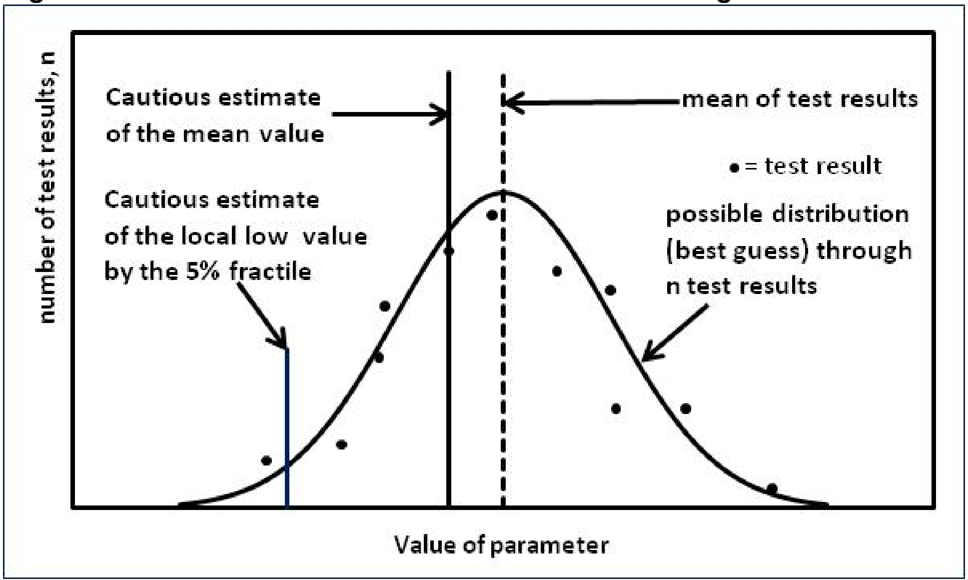
vi. To reiterate, the same soil can have different characteristic values depending upon the limit state being considered, the amount and quality of the data, the strength and stiffness of the structure and the volume and ductility of the ground involved in the limit state.

8. When using standard tables of characteristic values, the characteristic value shall be selected as an extremely cautious value.

9. Statistical methods may be used when selecting characteristic values of geotechnical parameters but they are not mandatory. The use of statistics requires a sufficient number of test results which can include test data from previous experience of the site and area. Parameter values are gathered in statistical populations of samples:
   i. **local population** – test results from the site
   ii. **regional population** – tests on the same soil or rock formation from a larger area than the site from previous investigations that may or may not be in the public domain
   iii. the two populations can be combined statistically [see EN 1990, clause D7.1(5) and also the designers' guides to both EN 1990 and EC 7-1] to derive parameter values and then characteristic values.

10. When using statistical methods, EC7 recommends that the calculated probability of a worse value governing the occurrence of the limit state considered should not be greater than 5%.
    i. If the limit state is governed by a large soil volume and the structure can redistribute stresses (see above), then the characteristic value should be selected as a cautious estimate of the mean value of the ground parameter. The mean is unknown, however, and the statistical analysis is required to give an estimate of the mean such that there is a 95% confidence that it will be more favourable than the derived characteristic value (see Figure B2).

Figure B2 – Derivation of characteristic values using statistics



    ii. If the limit state is governed by a small soil volume and there are few test results, if any, in the soil volume, then the characteristic value should be selected such that there is only a 5% chance that somewhere in the ground there is a value less favourable than the characteristic value ie the characteristic value should be selected as the 5% fractile (see Figure B2).

11. The terms "favourable" and "unfavourable" are used because sometimes the characteristic value may be lower than the mean parameter value (eg bearing capacity of foundations or pressures on retaining structures) and sometimes it can be higher (eg permeability or downdrag on leachate chimneys).

12. Some limit states are governed more by differences between higher and lower characteristic values than the mean values. For example differential settlements require consideration of differences between weaker and stronger zones and their extents in relation to the structure when deciding on the characteristic values.

13. When little or no local data is available, the selection of characteristic values may be based mainly on regional or previous data from the site (eg earlier phases of the landfill). However, for landfill engineering, this approach should be used only for preliminary design: The assumed characteristic values should be confirmed at a later stage by local testing.

Appendix C - Setting an Earthworks Specification

Introduction

The specification is drafted by the designer in order that:

a. the earthworks will be constructed in accordance with the design

b. the contractor will know the requirements and will therefore be able to price appropriately

c. the CQA Engineer will be able to certify the quality of the works

There are two approaches available for specification:

1. End-Product Specification

2. Method Specification

End-Product Specification for a landfill clay liner

This is the only methodology suitable for landfill clay liners (and also the mineral component of landfill caps) but can be used in any earthworks where there is a tight set of specification criteria required e.g. for fill behind retaining structures or a reinforced earth bund.

The end-product specification gives the various properties required to be achieved by the compacted material and the contractor is required to demonstrate by means of compaction trials that his chosen methodology is appropriate for their achievement. A limit is usually placed on layer thickness in order to keep control of the works and to provide adequate compaction. The works are then controlled by frequent testing which allows the methodology to be amended if necessary as the works proceed.

For general earthworks it may be adequate to provide a specification comprising grading, compacted in-situ moisture content range and minimum dry density or even, for clays, just grading and undrained shear strength range.

For construction of a landfill liner, hydraulic conductivity is a critical factor and performance is required over much longer timescales than say for highway construction. This requires that many more material properties are defined and controlled during construction to ensure long term performance. The process of specification of a clay material as used in a mineral liner is discussed below but the process can be used for any end-product specification for earthworks.

The most practical method of setting a specification is by setting a series of classification requirements and then deriving an acceptance envelope on the moisture content v dry density (compaction) graph.

Material Properties
We recommend some of the material property requirements but others are needed for control. The basic classification/material properties including particle size distribution, clay

particle content, fines content, large particle content, plasticity indices, and particle density need to be specified.

Compaction Characteristics

The soil's compaction characteristics are fundamental to the specification and control process. The 2.5kg compaction test (BS 1377 Part 4 1990 Test 3.3 and 3.4 - known as the Proctor test in the USA) is the most widely used in earthworks. The 4.5kg (or heavy) test (BS 1377 1990 Part 4 Test 3.5 and 3.6) has been used but the level of compaction generally achieved with modern plant is between the levels in these two tests. There is no special magic in either test as they represent arbitrary energy levels chosen by history and practicality. In geotechnical engineering, practitioners have much more experience of the 2.5kg test results and this test is recommended for this reason as judgement is improved. Several tests should be carried out to ensure consistency or to separate groups of materials with their own compaction requirements. Carrying out a few 4.5kg tests may assist in understanding the behaviour of the soil but generally are not necessary.

Moisture Content Range

Assess a realistic range of moisture contents likely to be achieved on site. Test the effects of this moisture range on permeability and shear strength and if necessary reduce the range to best meet the specification and practical considerations. Ideally the most sustainable situation is to place the soil at its natural moisture content i.e. the mean moisture content of the stockpile or the as-dug moisture content. As the soil may dry out a few percentage points in dry weather or wet up in rain, a range close to the natural moisture content is preferred.

Also consider the moisture content prevalent in the general environment, i.e. the moisture content of the soils immediately adjacent to those being placed. Wetting up clay to meet a specification and placing it on a subgrade of much drier material is not realistic as there will be equalisation of moisture content over time, bringing the wetter layer down in moisture content and possibly desiccating it.

It may be that the range of moisture contents achievable on site will not allow the required material properties to be achieved. In this case it may be preferable from a sustainability viewpoint to change the design e.g. a thicker liner using a higher permeability material available on site is preferable to import of higher quality material.

There are other factors which define the acceptable moisture content range as described below.

Percentage Air Voids Lines

Compaction needs to be adequate to provide a low permeability soil with high enough shear strength and for it not to consolidate significantly. Experience has shown that 10% air voids is the least dense specification that can provide this performance and 5% air voids will provide significantly better performance (Arup 2007). An air voids line of 5% or 10% is therefore generally one of the limits chosen for a landfill liner and a defined boundary on any plotted specification envelope/ acceptance envelope (see Figure C1).

From the mean particle density the 0% air voids line can be calculated as can the 5% and 10% air voids which should be plotted on the compaction curve graph. Note that these are theoretical lines based on the reported mean particle density (PD). These lines are not definitive as PD is determined on relatively small samples generally from the matrix of the soil. The lines are, however, very useful in interpretation of soil performance.

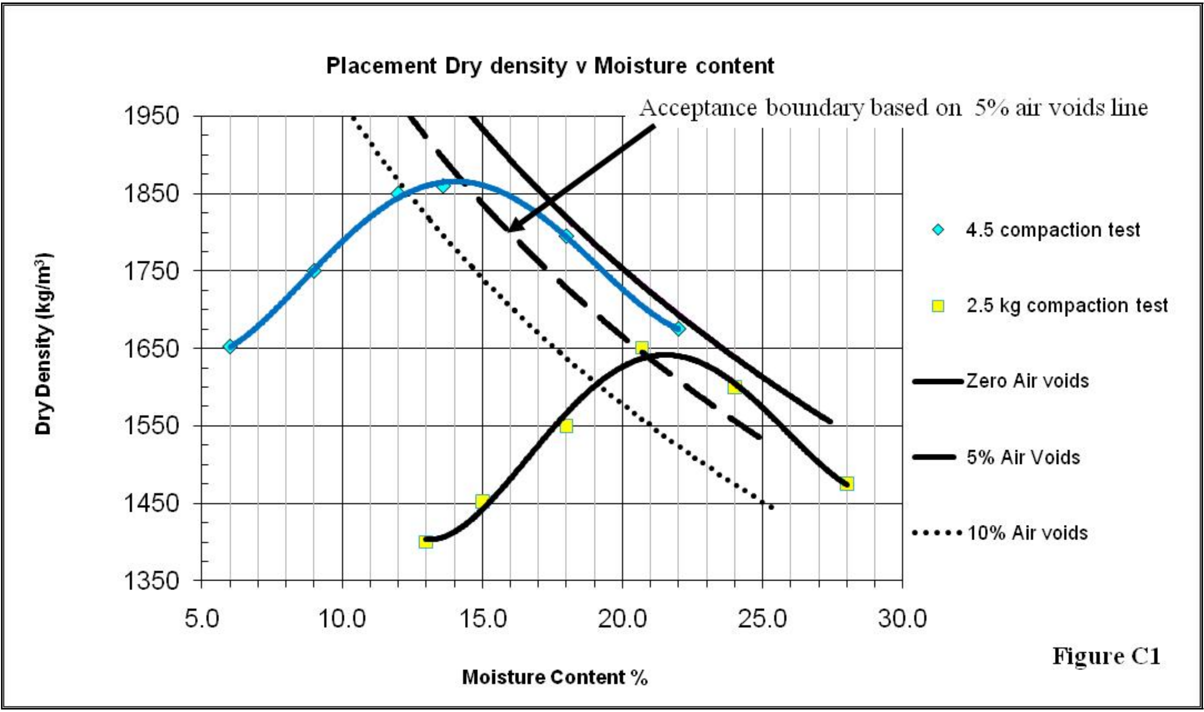


Figure C1

Note that some soils may have fairly consistent PD, e.g. a weathered Oxford Clay, where the majority of weathered soil matrix has virtually the same mineralogy as the remaining lithorelics. However other soils, such as glacial tills, may have a diverse selection of erratics which may be from rocks with significantly higher PD. This will cause some samples from the latter soil type to plot above the 0% air voids line, which whilst theoretically impossible is statistically inevitable due to normal testing error and also inclusion of the high PD particles in a core cutter or within the volume of soil tested by a nuclear density meter. The statistics are discussed in Appendix D.

Once the basic material properties and its compaction characteristics are determined, the liner specification must be defined in terms of hydraulic conductivity, shear strength and ductility which are the primarily controls of the performance of a clay liner.

Shear Strength and the Definition of the Maximum Moisture Content

Shear strength is important because if it is too high it will be too stiff to allow remoulding of the clods into a reworked homogenous material leaving inter-clod voids which will increase permeability. If it is too low the soil will not lay well, will stick to the roller and severe rutting will be caused by construction plant. The layer also has to support dynamic construction and operational loads and static loads from increasing and phased overburden loadings, loads from in-cell infrastructure such as leachate manholes, and if at or close to a side slope, loads from slope stability shearing.

Assuming reasonable compaction of the clay, shear strength is a function of the moisture content. In order not to cause significant problems in terms of sticking and rutting a minimum shear strength of about 50 kPa is required for clay. Other values may be justified dependent upon site specific conditions and loading conditions. By specifying samples with dry density/moisture content points along the chosen % Air Voids (AV) line (say 5%) a moisture content v shear strength relationship can be plotted and the maximum moisture content defined by the 50 kPa (or other site specifically defined value) intercept (Figure C2). This provides the maximum moisture content boundary to the Acceptance Envelope.

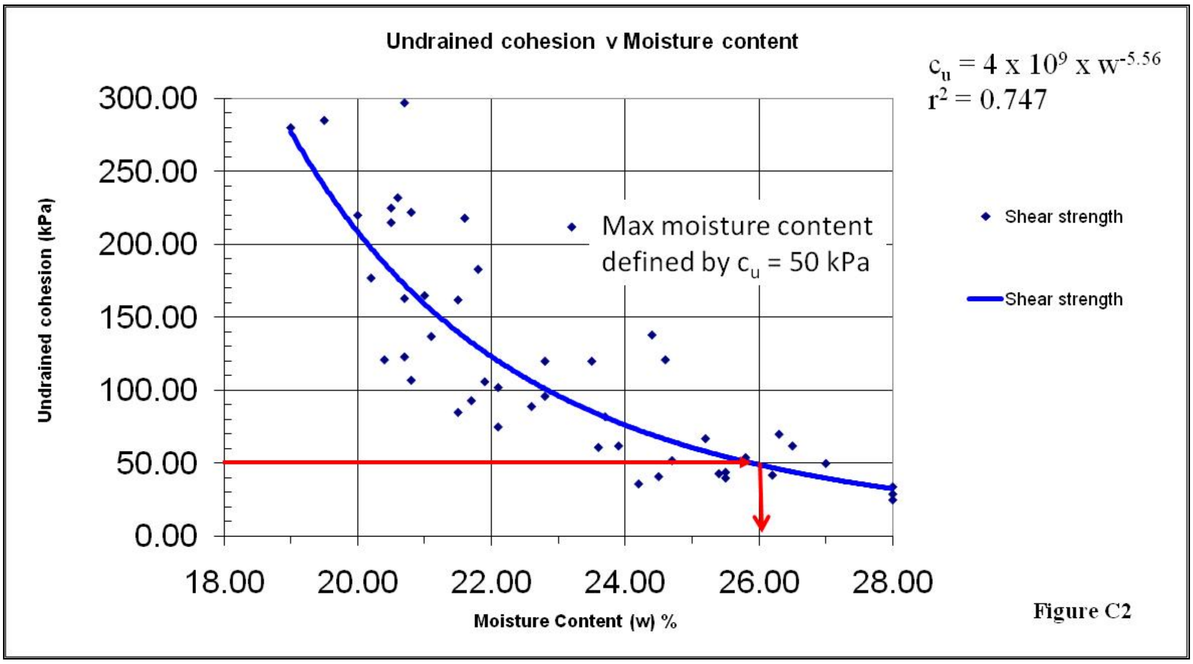


Figure C2

Hydraulic Conductivity

The required maximum hydraulic conductivity is specified by the Regulations (as equivalent to 1 m thickness of permeability = 1×10^{-9} m/s) and/or the Hydrogeological Risk Assessment (HRA). However, it is common to carry out several tests early in a laboratory testing programme to check that the clay fill is capable of meeting this criterion. Any defining envelope in a specification will have to be proven to provide hydraulic conductivity below the limiting value for the thickness of liner to be used in the design.

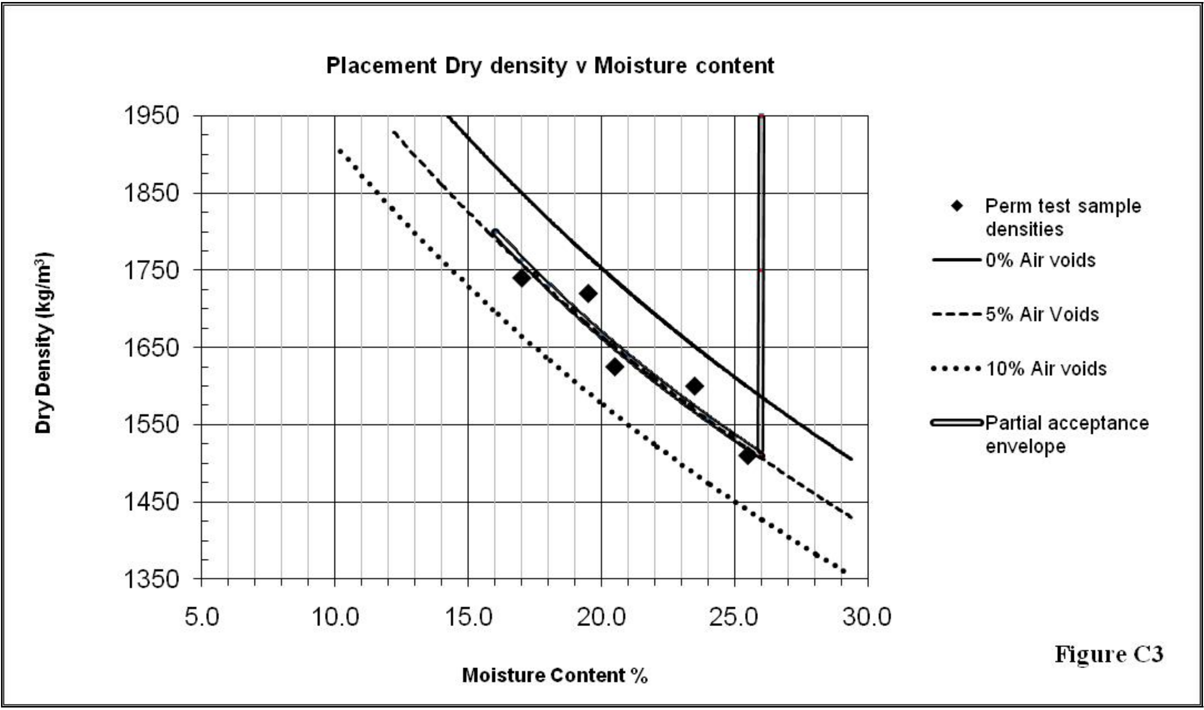


Figure C3

Figure C3 shows a series of points chosen along the lower edge of the Acceptance Envelope. The combinations of moisture content and dry density at these points are those at which samples should be compacted in the laboratory for the permeability tests. Further samples should be taken both inside and outside the envelope but a series of permeability tests chosen this way with results below the permeability criteria demonstrates the adequacy of the chosen envelope. The characterisation/source evaluation testing for permeability against moisture content shall give recognition to the variability of the test results, which is about half an order of magnitude, and also recognise that laboratory results are typically lower than those in the field by a similar amount. In order to demonstrate that the required permeability target of say 1×10^{-9} m/s can be achieved in the field during the works at the dry density/moisture content combinations to be specified, it is suggested that a suitable buffer could be used so for example:

a. the characteristic permeability of each moisture content set tested in the laboratory shall ≤ 5×10^{-10} m/sec and
b. the maximum value of each moisture content set tested in the laboratory shall ≤ 5×10^{-9} m/sec
c. These values are for the designer to decide with reference to the HRA and his judgement of the material and its compaction behaviour.

Ductility and Definition of the Minimum Moisture Content

A minimum moisture content is chosen to ensure that the clay:

1. Is mouldable by the available plant to breakdown clods and produce a homogenous material
2. Is ductile enough to ensure that any anticipated strains do not change the permeability by brittle or semi-brittle micro-fracturing.

If it is too dry it will have shear strength too high to allow the available compaction plant to remould the clods into a homogenous layer. Shear strength in excess of 200 kPa is accepted as too high but this requires confirmation by field trial. The specification should take into consideration the natural moisture content range, in order to be sustainable, and the likely variation due to weather conditions and the moisture content of the sub-grade materials.

This lower limit should also take into consideration ductility of the clay which could become semi brittle and fissured if stressed or too dry and this may significantly alter the permeability in such a zone. Fortunately most landfill design aims at minimal strains by designing conservative slopes and particularly if geosynthetics are to be incorporated in the design.

Unfortunately there is no suitable commercial testing available for ductility. The Plastic Limit (BS 1377 Part 2 Test 5) has in the past been used to define the change from brittle to plastic behaviour but is not a definitive test. There is a zone of semi brittle behaviour between brittle and plastic states. The Plastic Limit test is a classification test that was never designed to determine ductility, is considered too imprecise and not repeatable with accuracy by geotechnical engineers (Sherwood 1970 and most inter-laboratory proficiency comparison tests). Furthermore, the Plastic Limit test is carried out on a clay sample at a very different scale (2mm thickness test sample rather than 1000 mm liner). A clay liner at the Plastic Limit will be plastic and experience shows that it will still be so at several percent below that value. The Highways Agency stopped using the Plastic Limit some years ago as a criterion for defining limiting moisture content for this reason.

If a designer wants to specify the mean Plastic Limit as the minimum moisture content then that is acceptable without further testing being required. If the designer wants to specify a lower moisture content then testing should be carried out to demonstrate that this lower moisture content will not prejudice the permeability requirement.

The critical issue is that when the liner is strained:

- does the hydraulic conductivity increase because the clay is acting in a brittle manner and possibly allowing micro-fissures to open, or
- does the clay still act in a plastic manner because no micro-fissuring occurs or has no substantial effect

Research testing has shown very small changes to permeability (significantly less than one order of magnitude) but always within the variability of commercial testing results (Arch *et al* 1996 and Edelmann *et al* 1999) caused by shear strains comparable to those acting in landfill liners. The brittle behaviour of the clay at different moisture contents can be determined by subjecting a triaxial sample to strain and then measuring the hydraulic conductivity. A methodology is under development to do this testing using standard soil laboratory methods and equipment. To define the strains needed for these tests it was reported by designers that 3 to 4% was the largest shear strains calculated for liners excluding near vertical liners (modelled by finite difference software) - also see Table 2 of the main guidance document. It is conservative to test clays with a factor of safety of strain and adding 50% was considered reasonable i.e. 6% strain has been adopted as a default value for this test at the time of writing. If a near vertical liner were to be designed where high strains were likely, suitable analyses should be carried out to demonstrate the likely maximum strains and the test modified to provide similar factors of safety.

Therefore, if a designer wishes to specify a soil at moisture content below its Plastic Limit then samples are made up at these moisture contents and at dry densities that would plot the sample on the lower edge of an acceptance envelope. The samples are then strained in a triaxial frame before their permeability is determined. If the results demonstrate the required permeability criterion is met then the lower moisture content can be used in the specification. This test is required only if the chosen moisture content range is below the mean plastic limit.

Acceptance Envelope

An acceptance envelope plotted as a graph such as the example in Figure C4 (partial acceptance envelope) and Figure C5 which puts these three limits together.

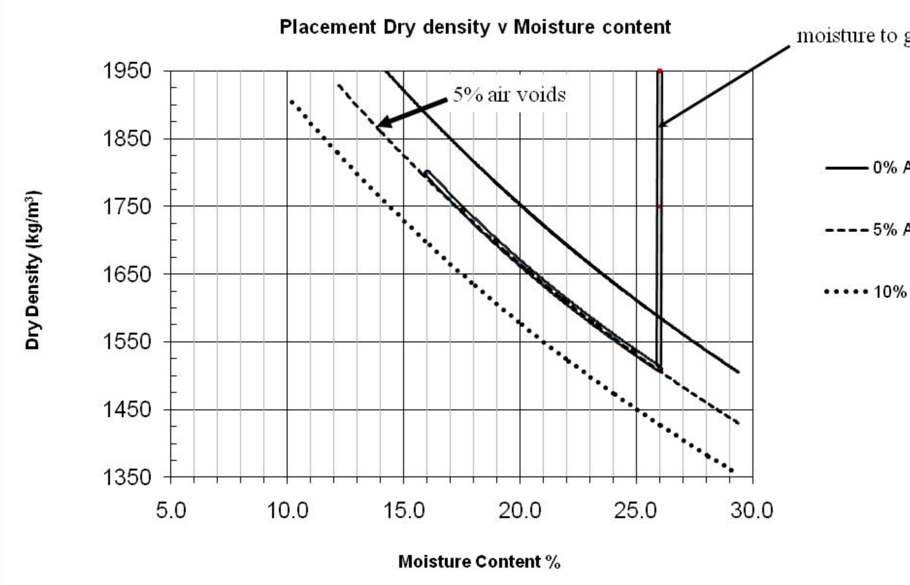


Figure C4

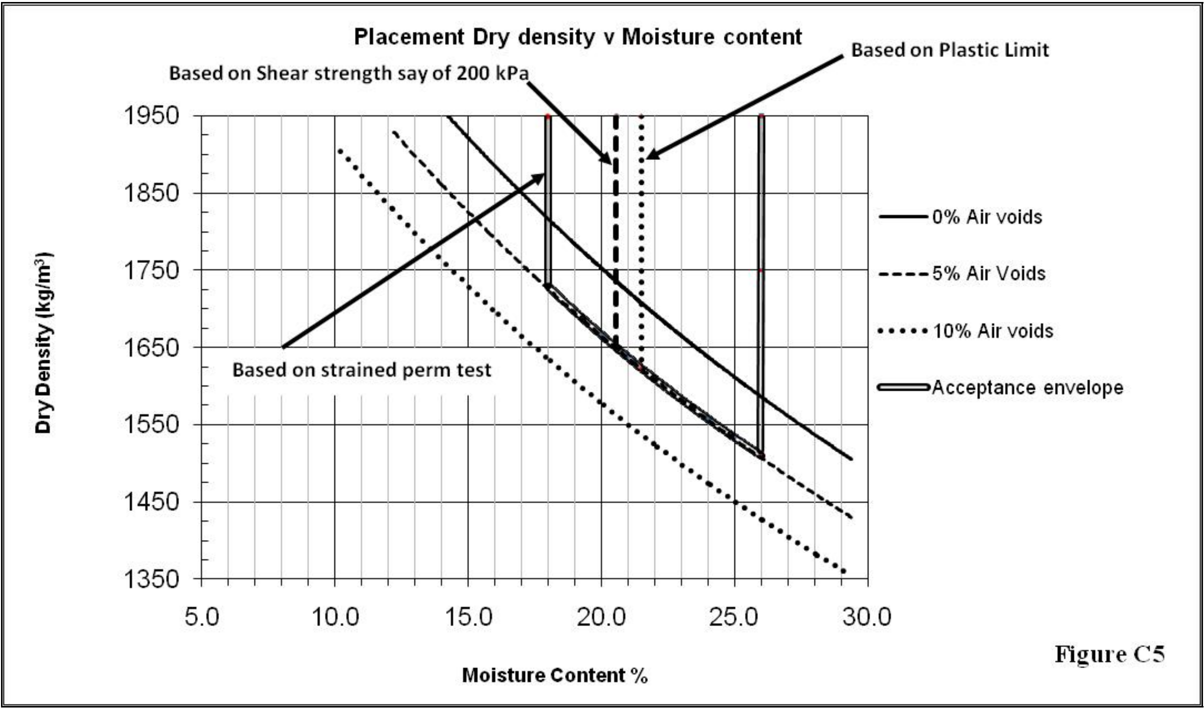


Figure C5

Control on site is by measuring dry density and moisture content, using a nuclear density meter, core cutter or by sand or water replacement, plotting the result on the graph and appraising pass or fail with this zone (see Appendix D).

Table C1 - Example Specification based on the example above for a clay liner where the target is 1 m thickness at a permeability of 1 x 10^{-9} m/s – can be amended by the Design Engineer with our agreement

Property	Requirement	Test
Permeability/ Hydraulic conductivity to be measured during source evaluation and trial liner testing and early in the main liner construction	The characteristic permeability of all samples tested in the laboratory shall ≤ 5 x 10^{-10} m/sec and The maximum value of all samples tested in the laboratory shall ≤ 5 x 10^{-9} m/sec	BS1377 : 1990 , Part 6 : Method 6
Minimum moisture content (see Figure C5)	≥ 18%	BS1377 1990, Part 2 Method 3.2
Maximum moisture content (see Figure C5)	≤ 26 %	BS1377 1990, Part 2 Method 3.2
% Air voids	The percentage of accepted test results with air voids ≤ 5% shall be ≥ A %. (see Section 6.5 and Appendix E)	
Remoulded Shear strength	Typically ≥ 50 kN/m^2 or other site specifically defined value	BS1377 : 1990, Part 7 : Method 8
Plasticity index (I_p)	10% ≤ I_P ≤ 65%	BS1377:1990:Part 2: Methods 4.3 and 5.3
Liquid Limit	≤ 90%	
Percentage fines <0.063mm (63 μm)	≥ 20 % but with a minimum clay content (particles < 2 μm) of 8 %.	BS1377 : 1990, Part 2 : Method 9.2, 9.5)
Percentage gravel	≤ 30%	
Maximum particle (stone) size	2/3rd compacted layer thickness Typically 125 mm but must not prejudice the liner, for instance by particles sticking together to form larger lumps.	BS1377 : 1990, Part 2 : Method 9.2, 9.5)

Method Specification for general earthworks

Method specification became the norm for all general fill for UK highways from the early 1970s onwards. The principle is that soils are grouped into general classes based on grading and plasticity and the method of compaction is standard for each class. The method of compaction for each class (layer thickness, moisture content range, weight and type of compaction plant and the number of passes of the plant) was derived from site results and was designed to give 10 % air voids or less in the body of the earthworks. Site control was therefore much simplified and less costly with a much lower amount of testing required to confirm the material class and acceptability. Extra tests could be carried out in areas where level of compaction appeared not to meet the specification.

The materials are classified following the Specification for Highway Works (SHW) Table 6/1 and 6/2 and then the standard compaction methods can be used as described in Table 6/4.

One point regularly omitted in many specifications is the moisture content range for the material to be acceptable for compaction. At the wet end of the range this will ensure adequate shear strength to avoid the compaction damaging the layer and at the dry end the "mould-ability" of the soil. The range is determined in the same way as for an end product specification, however for general earthworks permeability is probably not the critical parameter but rather shear strength and settlement.

For general earthworks the Specifications for Highways Works (SHW) and BS 6031 Code of Practice for Earthworks provide good practice guidance.

The materials on your site might not naturally conform to the standard highway classification. This is not a major problem but does require appropriate laboratory testing to determine the parameters needed to classify the material albeit to a quasi standard class. A field trial will then be required to derive the method of compaction that will give the required level of compaction with this "new" material.

Clay Fill

For general earthworks in clays an acceptance envelope may be defined by a combination of say:

- maximum moisture content defined by shear strength ≥ 50 kPa (requires laboratory test data for verification)

- minimum moisture content defined by shear strength ≤ 200 kPa (requires laboratory test data for verification)

- maximum air voids content = 10 % (to reduce risk of collapse settlement)

- minimum dry density = 90 % maximum dry density (2.5 kg rammer test) - (requires laboratory test data for verification that shear strength and settlement are acceptable)

  (see Figure C6)

- also maximum particle size ≤ 2/3 layer thickness

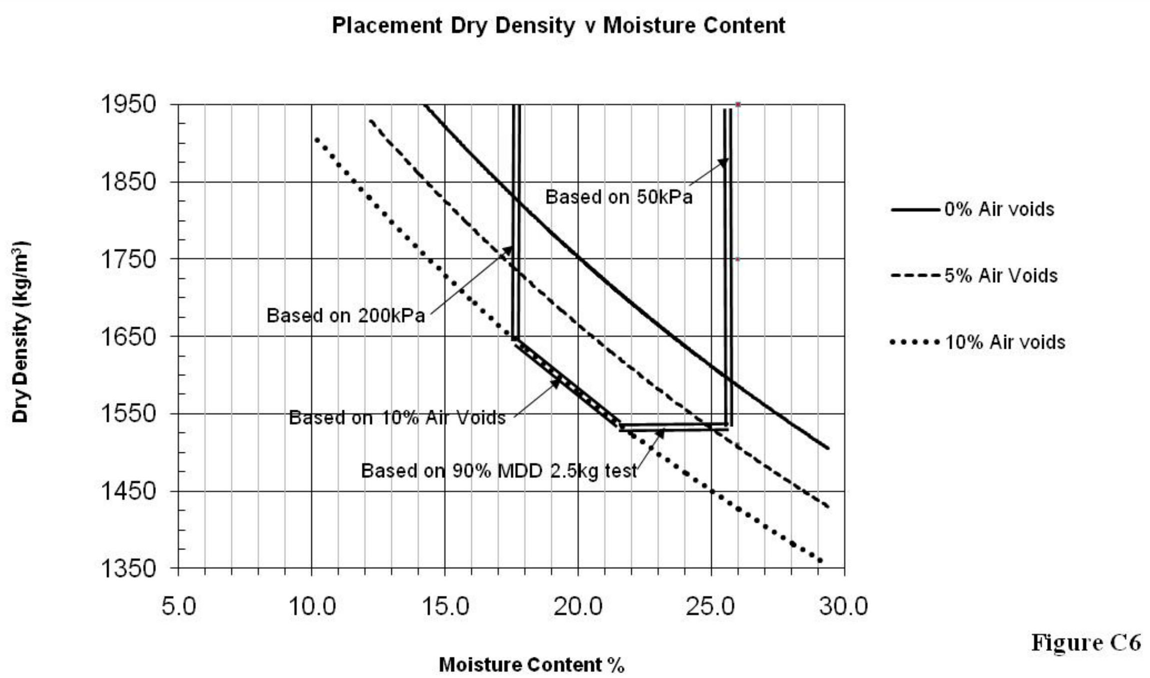


Figure C6

If the clay is described well by the standard HA classification then the HA standard method may be used without a site trial with the moisture content range determined as above because the method was designed to give the necessary level of compaction.

On-going testing is a relatively minor operation – primarily to ensure the materials are still within the specification and some testing of the compacted earthworks. It may include particle size distribution, plasticity indices and moisture content/dry density of the compacted fill.

Sand/gravel Fill
In UK conditions there is little likelihood of any collapse settlement from recompacted sand-fill and there is no problem at low moisture content. Very high moisture content could allow liquefaction but it is generally appropriate to define an acceptance envelope by a combination of say:

- maximum air voids content = 10 % (to reduce risk of collapse settlement)
- minimum dry density = 90 % maximum dry density (2.5 kg rammer test) - (requires laboratory test data for verification that shear strength and settlement are acceptable)

If the sand/gravel fill is described well by the standard HA classification then the HA standard method may be used without a site trial because the method was designed to give the necessary level of compaction.

On-going testing is a relatively minor operation – primarily to ensure the materials are still within the specification and some testing of the compacted earthworks. It may include particle size distribution and moisture content/dry density of the compacted fill.

Rock Fill

Because of the nature of the large particles of rock it is very difficult to test both in the laboratory and in the field. The void ratio should be minimised which is difficult to ensure unless very heavy compaction is used. Advice and past experience are given in the literature (Charles 1991 and Scott Wilson 1997).

Chalk Fill

Whilst chalk fill is recompacted rock fill it has its own separate behaviour. There is a wide literature on this material as it comprises a significant proportion of the infrastructure earthworks in the south east of the UK. It breaks down readily to silt sized particles in certain circumstances and can re-cement after compaction over a period of days (Lord et al 2002) but the time necessary is between half a day and two weeks. Unfortunately the process is not fully understood. Clayton (1980) provides testing methodology and discusses collapse settlement in chalk fill on inundation. This may undo the re-cementing to some extent.

The same process of ensuring low percentage air voids is essential for landfill earthworks with materials comprising chalk in the sub-grade.

Appendix D - Pass/Fail Criteria

General

Pass fail criteria are only appropriate where an end product specification is used.

Method specification

If a method specification is used then the method should ensure the required soil properties are achieved provided that:

- the soil type is correct for the method and
- moisture content is within the acceptable range and
- the method is correctly carried out

The limited amount of testing required for this method is to indicate that it is working and, if not, then trigger a change in the method and/or a tighter control of the moisture content and the other components of the method. It should be recognised that field results are more variable than those obtained from laboratory testing.

End product specification

An end product specification is often employed in landfill construction (always for an engineered clay liner), with a compaction trial carried out for each proposed material before the main earthworks to demonstrate that the proposed method will achieve the required properties. This system requires pass/fail criteria to be used to demonstrate compliance with the specification. The more extensive programme of testing with this method will pass/fail the work and if failing, specified remedial works and possibly a revision of the method can be applied.

Acceptance envelopes/control on site

Figure D1 shows the acceptance envelope (Figure C5 with some site control results plotted) that may be applicable for material to be used for an engineered clay liner where low permeability is the major requirement.

For control of the earthworks it is better to use frequent placement density and moisture content measurements (because they are measured quickly on site) using a nuclear density meter, core cutter or by sand or water replacement with a limited amount of permeability testing used as confirmation that the required permeability has been achieved. This requires that permeability/moisture content/air voids content relationships are adequately defined during the source evaluation/soil characterisation phase ie before site works commence in a timely manner.

Figure D2 shows the acceptance envelope (Figure C6 with some results plotted) that may be applicable for material to be used for an engineered clay subgrade or bund where strength, low settlements and avoidance of collapse compression are the major requirements.

For control of general earthworks it is again better to use frequently measured placement density and moisture contents using a nuclear density meter, core cutter or by sand or water replacement. Other control testing could include:

- hand shear vane tests – provided that gravel content does not affect the vane
- undrained triaxial and possibly settlement testing on undisturbed core samples
- plate bearing tests

This requires that shear strength (and possibly settlement)/moisture content and density relationships are adequately defined during the source evaluation/soil characterisation phase ie before site works commence in a timely manner.

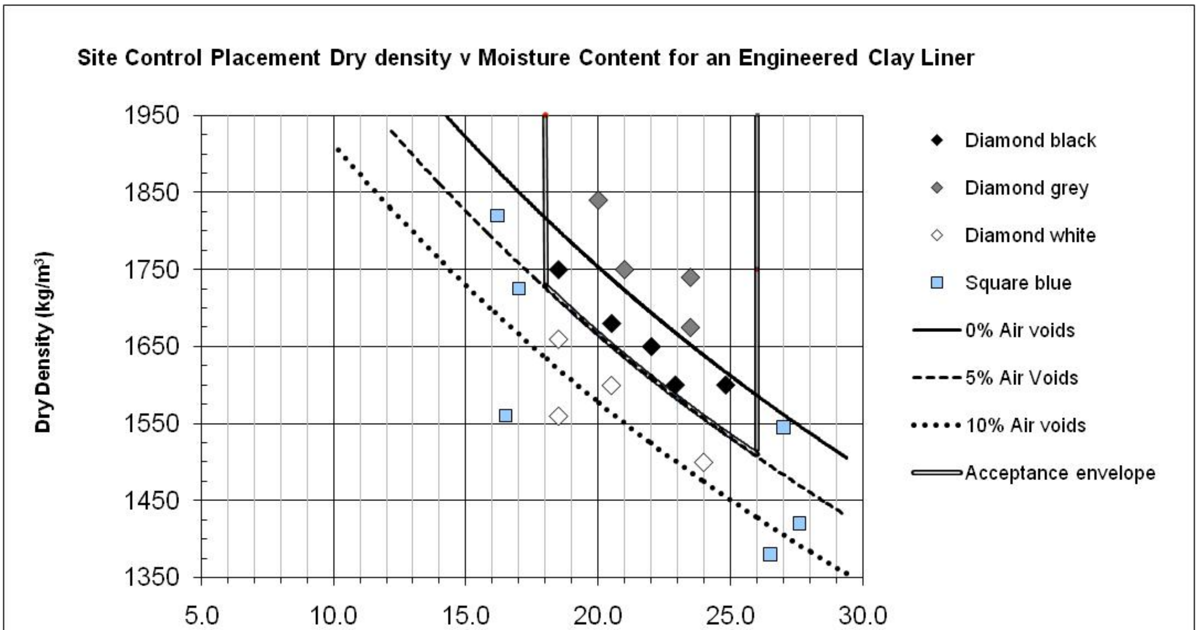


Figure D1

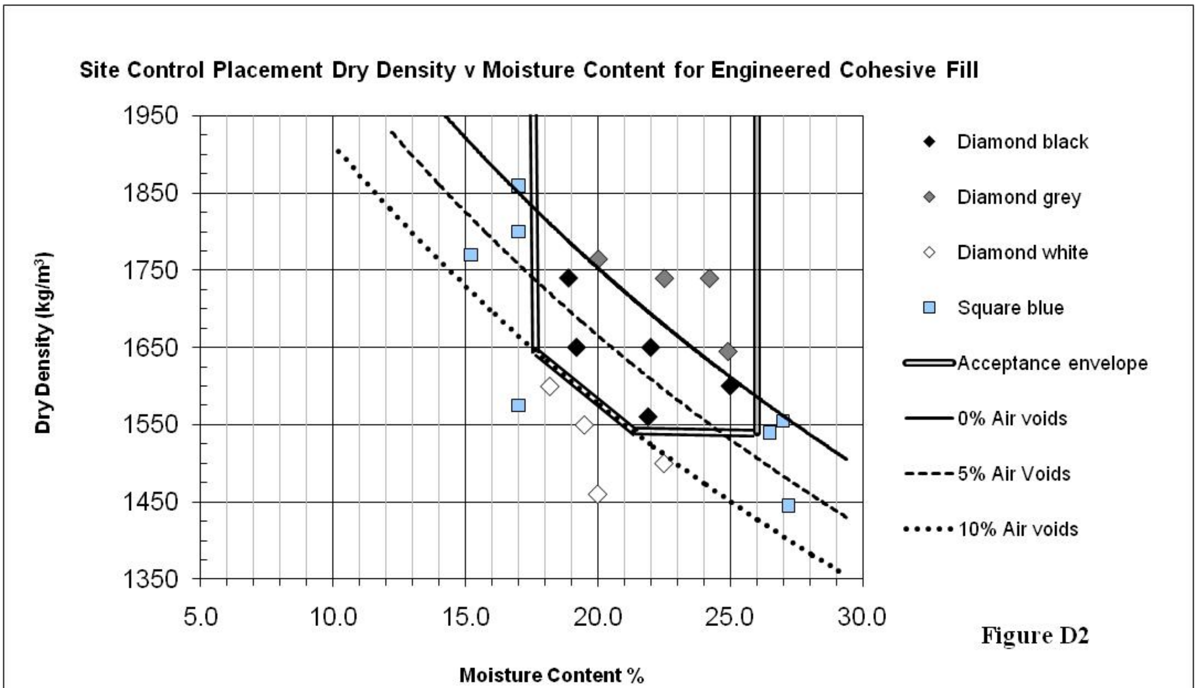


Figure D2

Method of Control

There should only be one criterion for control otherwise the situation is not logical in that the whole of the earthworks can be passed by one criterion and then failed at the end of the job by a second criterion.

- **For engineered clay liners**, as stated earlier, low permeability is the major requirement. However, because of the time taken for sampling and testing and the cost of the test, permeability testing cannot be realistically used to pass or fail earthworks without involving contractors either in delays or placing material at risk of future non-compliance and expensive remediation. Instead, full and exhaustive characterisation testing should be carried out so that the relationships between permeability/shear strength and moisture content/dry density/air voids shall be established before the earthworks commence. The control of the earthworks can then be carried out only by monitoring moisture content and density. This allows a more streamlined acceptance procedure. Permeability testing can be carried out on a limited frequency, if desired, but the results of this testing should be used purely for comfort that the methods are producing results in the right “ball park.

- **For general earthworks,** the criteria could be based on one of the following sets

    - moisture content and density
    - shear vane tests
    - plate bearing tests

  Again, full and exhaustive characterisation testing should be carried out so that the relationships between shear strength/settlement and moisture content/dry density/air voids are established before the earthworks commence.

Acceptance criteria - general

It is required that control of siteworks is to be by moisture content and density. The results are plotted on the graph (Figures D1 and D2) and they are appraised as having passed or failed.

The “Diamond black” results shown on Figures D1 and D2 could apparently be passed without a problem but thought is required for the “Diamond grey”, “Diamond white” and “Square blue” results.

Failure of a particular result to meet a specification condition shall not be assessed in an absolute fashion but with an awareness of the errors inherent in soil sampling and testing methods and the probability that the material property will vary. The “rules for failure” or pass/fail criteria shall be set out in the specification by the designer and then presented to the Environment Agency for written approval.

Note that dry density results occurring above the zero air voids line (ZAVL) are sometimes ignored because, in theory, no soil can have less than zero air voids. It is often thought that, because this is theoretically impossible, it points to poor test performance. However, if a normal distribution of test results is accepted, then up to 17% of test results can be expected above the ZAVL (see Schmertmann 1989). Results above the ZAVL should be reported and used because they probably provide information of equal value to results below the ZAVL. The CQA engineer, evaluating batches of tests, who rejects those tests above the ZAVL, will perceive a fill drier and less dense than the actual fill. There is inherent variability in the material plus density and moisture content test errors and errors in particle density tests, where results of a small number of determinations are applied to large volumes of material. The smaller the percentage of results above the ZAVL the better things may seem but up to

17 % of results above the ZAVL should not be considered abnormal. Conversely, if more than 17 % of results are above the ZAVL or if there are isolated results more than 3 standard deviations (air voids) from the mean air void then the reasons for this should be investigated e.g.:

- Has the material changed?
- Is there a geological reason?
- Are there systematic errors in the density testing?
- Are there climatic reasons for the errors?
- Have the sampling/testing personnel or equipment been changed?

Example Acceptance criteria – engineered clay liner (Figure D1):

For compliance purposes it is required that at least A % of all results within the acceptable moisture content range (including retests) plot less than 5 % air voids. Provided that anomalous readings above the ZAVL (Diamond grey results) have been resolved/rejected or repeated as necessary then this requires that the combined number of "Diamond black" and "Diamond grey" results are ≥ A % of the total number of results within the acceptable moisture content range ("Diamond black" plus "Diamond grey" plus "Diamond white" results).

The minimum value of A varies according to the location of the landfill site:

Site location	**Minimum value of A**
Non sensitive, non-aquifer sites (Secondary Aquifer B)	80
Sites over a sensitive (minor) aquifer (Secondary Aquifer A)	90
Sites over a very sensitive (major) aquifer (Principal Aquifer)	95

"Diamond white" results i.e. those within the moisture content range but with air voids > 5% can be accepted provided that A % of the total number of acceptable tests has resulted from "Diamond black" and "Diamond grey" results.

"Square blue" results i.e. those with moisture contents outside the acceptance range must be recorded as non-compliant and remedial action taken as per the specification so that the remediated material yields a compliant result when subsequently tested.

These criteria are fine for the end of a job but criteria are also required to allow acceptance/rejection as the work proceeds when, particularly at the start, there is limited data available to apply the above rules. In this situation it is recommended that:

- All "Diamond black" results are accepted.

- "Diamond grey" results are accepted but anomalous results require explanation.

- "Diamond white" results are accepted up to say 10 results (Diamond black plus Diamond grey) if the Diamond white results < 10% air voids. After 10 results the A % rule applies so air voids > 10 % can be allowed for a limited number of tests (ie < 100 - A %).

- All "Square blue" results must be recorded as non-compliant and remedial action taken as per the specification.

Example Acceptance criteria – general earthworks (Figure D2):

For compliance purposes it is required that 80 % of all results within the acceptable moisture content range (including retests) plot inside the acceptance envelope. Provided that anomalous readings above the ZAVL (Diamond grey results) have been resolved/rejected or repeated as necessary then this requires that the combined number of "Diamond black" and "Diamond grey" results are ≥ 80 % of the total number of acceptable tests ("Diamond black", "Diamond grey" and Diamond white results).

"Diamond white" results ie those within the moisture content range but with air voids > 10% and/or dry density < B % MDD (2.5 kg rammer test) can be accepted provided that 80 % of the total number of acceptable tests ("Diamond black", "Diamond grey" and Diamond white results) has resulted in "Diamond black" and "Diamond grey" results. The value of B is to be decided by the design engineer, based on his requirements, and agreed with the Environment Agency. It is expected that B will be between 85 and 95 (% MDD - 2.5 kg rammer test.

"Square blue" results i.e. those with moisture contents outside the acceptance range must be recorded as non-compliant and remedial action taken as per the specification so that the remediated material yields a compliant result when subsequently tested.

These criteria are fine for the end of a job but criteria are also required to allow acceptance/rejection as the work proceeds when, particularly at the start, there is limited data available to apply the above rules. In this situation it is recommended that:

- All "Diamond black" results are accepted.
- "Diamond grey" results are accepted but anomalous results require explanation.
- "Diamond white" results are accepted if < 10% air voids until more than 10 results (Diamond black plus Diamond grey) are available when the "80%" rule can be applied for acceptance/rejection.
- All "Square blue" results must be recorded as non-compliant and remedial action taken as per the specification.

Example Acceptance criteria – general earthworks (strength testing):

This may be adapted to suit the site specific design.

For compliance purposes of strength tests it is required that all three of the following criteria shall require satisfaction for compliance:

- The moisture content must be within the specified range.
- The average strength determined from any group of 6 consecutive test results shall exceed the specified characteristic strength (say 50 kN/m^2) by not less than 10% (eg 5 kN/m^2 hence mean strength ≥ 55 kN/m^2).

Each individual test result shall be greater than 85% of the specified characteristic strength (i.e. 85 % of 50 kN/m^2 = 42.5 kN/m^2)

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