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LFE5 - Using geomembranes in landfill engineering

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1 Introduction

This document covers the use of geomembranes in landfill engineering and was originally developed jointly with the British Geomembrane Association.

The Landfill Directive uses the terms bottom liner (Annex 1 paragraph 3(2)(a)) and artificial sealing liner (Annex 1 paragraph 3(6)). You should interpret these as being the same element. The overall environmental protection required by the Directive should be provided by combining an underlying geological barrier with an artificial sealing liner. The requirement for an artificial sealing liner will be met by using a liner system such as a geomembrane. We also recommend such sealing liners for capping landfills.

The term 'geomembrane' refers to a specific group of geosynthetics. They are flexible polymeric sheets which can be welded together to form a continuous 'bowl' in a landfill site. Geomembranes are used in a wide variety of civil engineering applications, generally as barriers to moisture and gas flow. Geomembranes are frequently used as an element in lining and capping systems for waste disposal facilities. The design, installation and quality assurance of geomembranes requires particular care to ensure the liner provides a continuous seal across the site.

For European CEN standard purposes the term 'geosynthetic barrier' includes polymeric and bituminous geomembranes and geosynthetic clay liners. Collectively these materials are referred to as polymeric geosynthetic barriers, bituminous geosynthetic barriers and clay geosynthetic barriers respectively. This document specifically deals with polymeric geosynthetic barriers, referred to as geomembranes from here on.

2 Background and scope

We recognise that total containment of wastes is not practicable, accordingly we expect the underlying approach to any landfill engineering works will be one of 'Landfill by design'. Landfill by design requires that any engineering proposals should be designed specifically using scientific techniques and calculations, for the particular environment they are intended to protect. To ensure landfills are designed and built with an appropriate level of environmental protection, designs must not be 'off the shelf' or 'cobbled together'. Instead they should take a detailed risk assessment as their starting point. This risk assessment must be based on the source-pathway-receptor principle.

This document is not intended to be an exhaustive design manual but we recommend that any designer or Environment Agency officer involved in assessing geomembranes for engineering purposes be familiar with this document. There are also several excellent text books on designing with geosynthetics which provide detailed technical information on the subject.

Geomembranes are available in a range of synthetic materials, sizes and thicknesses. Engineering experience of using different products, coupled with the long life required of landfill liners has restricted the choice to a small number of materials. However, current research and development is opening up possibilities for new materials or previously less favoured ones (Selecting materials is covered in a later section). Sheet sizes depend to a large extent on the composition and manufacturing method of the geomembrane. Larger sheets require less on-site welding, but can be more difficult to handle or fit to complex subgrade shapes. Regarding thickness, the thinnest plastic sheets may well have a lower permeability than a compacted natural clay, but are more susceptible to damage during installation and operation. They can also be more difficult to weld.

Geomembranes are normally incorporated as part of a composite or multiple lining system. Usually, reliance won't be placed on using a geomembrane as the sole barrier. This is due to their lack of robustness and their potential for damage. However, a geomembrane can (depending on the detailed risk assessment) be part of a single liner system within a cap which consists of at least the prepared ground, the membrane itself, and a protective cover. All of these elements must be carefully designed, installed and quality assured.

3 Quality

3.1 Manufacturing quality control (MQC)

If installation of a geomembrane is to be successful, quality products must be used. There are currently no standards in the UK for the MQC of geomembranes, however the Geosynthetic Research Institute provide guidelines, which cover geomembranes. These standards are reproduced as Appendix B. We have not officially adopted these guidelines, but we've included them for guidance and information. CEN (Technical committee 189) have developed standards and test methods for geomembranes in support of CE marking. As a result, we now require a CE registration certificate to accompany materials used in landfill engineering.

3.2 Construction quality control (CQC)

We will require assurance that only suitably qualified and experienced staff install the components of a flexible membrane liner.

Such staff must hold a current, independent certification for welding and installation to a recognised Environment Agency or industry standard.

An acceptable example is the British Geomembrane Association (BGA)/Thermal Welding Institute (TWI/CSWIP) third party accreditation scheme.

3.3 Supervising quality assurance

A quality approach is vital to successfully developing a landfill. Quality assurance (QA) has a role to play in all aspects of landfill engineering. Whilst QA techniques don't guarantee works have been carried out in accordance with the specifications, they should provide confidence that the following requirements have been met:

i) Effective mechanisms are in place to ensure the construction of the engineered systems will be to standards and specifications agreed with us through the environmental permitting process, and the materials and workmanship used are of an appropriate quality.

ii) The design, construction and quality assurance processes are well documented for regulatory purposes and to provide public confidence in the works.

Independent, third party construction quality assurance (CQA) provides confidence these requirements have been met. Where an environmental permit specifies a containment system, we will require validation by a suitably qualified and experienced independent engineer that the works have been carried out to the agreed standards.

3.4 Construction quality assurance plan (CQA plan)

Once we grant an environmental permit, operators must submit an acceptable proposed CQA plan on a cell by cell basis, prior to installing the liner.

The CQA plan must contain the following information for each geomembrane product proposed:

i) A summary of the required quality control procedures with a list of characteristics to be tested.

ii) Details of the planned geomembrane storage on site prior to installation.

iii) The handling equipment and techniques for the geomembrane on the site.

iv) Details of the installation staffs' accreditations.

v) Details of the conformance tests the CQA engineer will undertake on the liner material delivered to site. These must include measuring thickness, a visual inspection and removal of a sample for later testing. Samples must be stored in conditions that will not compromise later testing. Table 1 details the further CQA testing we require. A UKAS accredited laboratory must carry out these tests. The lab must be accredited for each test to be carried out.

vi) Rejection criteria of the geomembrane sheets, for example unacceptable physical characteristics, limits on thickness tolerances.

vii) Details of actions to take in the event of non-compliance with any part of the design or CQA plan.

viii) The methods for approving the subgrade.

ix) Measures to take to protect the liner if inclement weather occurs during installation.

x) Procedure for inspecting, testing and sampling welds, including the details of the nominated geosynthetic laboratory for off-site testing

xi) Action to take in the event of a defective weld, including re-test procedures.

xii) Rejection criteria of the laid geomembrane if test results indicate failure.

xiii) Method for presenting an installation record for the geomembrane , welding and weld tests to the Environment Agency. The source roll for each panel must be recorded along with the time and date of installation, weather conditions and site operatives.

xiv) Means of protecting the geomembrane sheets following installation.

xv) The proposed level of supervision and quality control.

xvi) Details of information to be kept in the engineer's daily log, including: -

a) placing low permeability material and sub-grade layers;

b) conformance to panel layout design;

c) geomembrane handling equipment;

d) type of welding equipment used, with details of any mechanical breakdowns since previous visit;

e) weather conditions, and whether the works are being undertaken with the weather windows specified with in the working plan;

f) details of visits by the supervising engineer (hours on site for example);

g) testing procedure and reports of field tests;

h) remedial action on geomembrane defects or weld defects;

i) daily and weekly records;

j) records of liner protection installation;

k) site visits by regulatory or other parties interested in the construction;

l) any other matters detailed in the CQA plan.

We must agree in advance, any deviation from the CQA Plan or any element of the works specified in the environmental permit. .

3.5 Contract documents

As the site owner/operator, you may let a contract for the construction of a cell in which you leave the choice and source of the materials to the contractor. However, this practice can cause you difficulties if there are discrepancies between the contract and the CQA plan. Obviously, we will enforce the approved design and CQA plan rather than the contract. It is your responsibility to ensure there is no confusion and no discrepancies.

3.6 CQA testing

Table 1 below provides guidance on the test properties and frequencies we expect for geomembranes. We offer these test frequencies as guidance, you can vary them where you can make a technical case for doing so. We must stress that the testing defined in Table 1 must be performed on samples taken from actual materials delivered to site under the CQA engineer's supervision. This testing must be performed in laboratories having UKAS accreditation for each of the specific tests. The relationship between the prescribed test method and the service life of the geomembrane is discussed our R&D Technical Report P1-500 – The likely medium to long-term generation of defects in geomembrane liners (2003).

Table 1 Guidance on CQA testing for geomembranes

Property	Test	Frequency
Conformance sampling and testing Thickness Density Puncture resistance Tear resistance Carbon black content Carbon black dispersion Tensile properties (yield and break stress, yield and break elongation)	See Appendix B	One sample per 5000 m^2, or every five rolls delivered to site whichever is the greatest number of tests. In the event that materials from different resin sources or manufacturing lines are supplied, at least one additional sample of this material must be taken and tested.
Stress crack resistance Oxidative induction time	See Appendix B	One sample per 10,000 m^2, or resin type or manufacturing run
Start-up test weld - welding equipment and welding operative	See Appendix A	Daily at start of works, and after all stoppages of greater than one hour. Also after significant changes in welding conditions.
Non destructive weld testing Dual track weld extrusion weld	Air pressure test Vacuum box, spark testing, ultrasonics	Continuous - every weld
Destructive weld testing i) On site ii) Off site – weld seam strength in peel and shear	ASTM D 6392-99 failure mode only (Film tear bond) by hand tensiometer in peel and shear. ASTM D 6392-99	Every weld One per 200m of seam
Subgrade	Smooth and firm Particle size	Five per hectare (see section 5) Continuous
CQA engineer Visual inspection of geomembrane Thickness of geomembrane (taken at the edge of the sheet)	Tears, holes, stretching Micrometer	Every roll Five per 100m, 10 – 20m apart

Note: The omission from this table of any test does not preclude its use.

4 Materials

4.1 Types of geomembranes

An increasingly wide range of geomembrane materials are available for use as liners. They include a variety of single or co-polymer membranes and blends of two or more polymer materials to provide the required characteristics. Geomembrane materials are also made as composites of two or more polymer types bonded together or may be reinforced with a fabric or net. Additives such as plasticisers and carbon black are sometimes incorporated to modify the physical or long term ageing characteristics of the geomembrane material.

Most polymer materials used in the construction of geomembranes are thermoplastics because they are easier to weld and repair on site. The most common membranes used in landfill engineering are polyethylenes due to their resistance to a wide range of chemicals.

You may consider using other materials for geomembranes where the material meets the performance requirements set out by the designer provided we accept the technical case for its use.

Geomembranes may have increased strength if they are composed of a polymer with a higher crystallinity, higher molecular weight or if the liner is of a greater thickness. However, this can reduce the flexibility of the material and increase it's susceptibility to brittle fracture. The geomembrane may have to operate at elevated temperatures for a portion of its life due to the heat generated during biological degradation of waste, which can cause temperatures of 40 - 70˚C. You must provide scientific and technical data for the material properties of your proposed liner at elevated temperatures (minimum 50˚C). If you're in any doubt as to whether the geomembrane is fit for purpose, you must seek the advice of a suitably qualified and experienced engineer.

Your designer must provide us with information that indicates that the liner will be sufficiently resistant to the chemicals it may come into contact with. The exact composition of any leachate on a landfill (particularly on sites accepting hazardous wastes) is difficult to predict. As a result the liner must have some resistance to a comprehensive range of chemicals, over long periods of exposure. Liner manufacturers usually carry out index chemical immersion tests on their geomembranes. You should make this information available to both your designer and us.

4.2 Permeability

Liquids and gases permeate geomembranes as vapours or gases on a molecular scale by diffusion. The rate of permeation depends on the solubility of the liquid and the diffusibility of the dissolved molecule in the geomembrane.

A molecular concentration or partial pressure gradient across the geomembrane will be the driving force for the direction and rate of transfer. This is in contrast to soils and clays, which are porous where the main driving force is the hydraulic head.

Gas permeability varies greatly according to geomembrane type and the nature of the gas. For example, the permeability of a sample of HDPE under test at 23˚C was found to be five times greater for carbon dioxide than methane.

Tests have been carried out on the permeability of geomembranes to organics aqueous solutions, simulating leachates containing small amounts of organics. The results concluded that significant quantities of an organic compound can permeate through a geomembrane due to selective permeation, even when the organics are present in the leachate at very low concentrations.

4.3 Physical stress

The geomembrane will be subject to physical stresses during transport, site handling, installation and during its life. Some of these stresses can be evaluated from the liner design, for example anchorage arrangements. Other stresses may result from temperature such as induced expansion/contraction.

The geomembrane must be able to withstand the physical, biological and chemical stresses it will be subjected during its installation design life. Factors which affect the physical requirements are site topography, types (physical forms) of waste, depth of waste to be accommodated, anticipated compaction equipment and hydrology/hydrogeology of the site.

You must provide quantitative evidence to establish that the geomembrane will bear the stress that will be placed on it. Pay particular attention to the apex of any slopes within the site or any other abrupt changes of gradient. These areas may require either some strengthening or modification to soften the angle.

4.4 Environmental stress cracking

A stress crack is defined as either an external or internal crack in a plastic that is caused by a tensile stress less than its mechanical strength. Under conditions of simultaneous stress and exposure to chemicals (such as, soaps, oils and detergents) polyethylene geomembranes can fail mechanically by cracking.

Tests can be performed to indicate the susceptibility of a geomembrane to stress cracking by using the notched constant tension load test (D5397) mentioned in Table 1. The opportunity for stress cracking to develop can be reduced by good design and good installation practices.

4.5 Chemical stress

Due to the variety of wastes likely within a landfill, the effects of chemical stress on the liner system is of primary concern, particularly in the long term. The effects of chemical stress may result in:

- degradation of the base polymer
- depolymerisation
- absorption of waste constituents
- extraction of components of the original geomembrane formulation such as antioxidants

The effects of chemical stress may take many decades to appear.

EPA Method 9090 is intended to determine the effects of leachate chemistry on the physical properties of a geomembrane material. The test immerses the liner material in leachate for a minimum period of 120 days, at both room temperature and 50˚C. If you expect higher temperatures, the immersion testing should be at an increased temperature. Comparisons of measurements of the membrane's physical properties, taken periodically before and after contact with the waste fluid, is used to estimate the compatibility of the liner with the waste over time.

4.6 Biological stress

Contact of a geomembrane sheet with a soil or liquid will potentially expose it to biological stress. Little lab or field data is available to show that biological factors have contributed to failure or have had adverse effects on geomembrane performance. There is a need for further research in this area.

In general, high molecular weight polymers are highly resistant to biodegradation. Biological attack has been observed with some plasticised geomembrane compositions due to the susceptibility of some plasticisers and other monomeric constituents of the compound to biodegradation. The resin portion of a geomembrane is usually resistant to bacteria in that it doesn't provide a carbon source for bacterial growth.

Fungal growth can occur on the surface of a geomembrane without degrading the mass of its composition.

Attack by rodents (and similar pests) on the liner system can't be ruled out and burrowing activities by other animals can damage the subgrade or protective layers of geomembranes.

5 Designing and installing geomembranes

5.1 Introduction

In recent years there has been a tendency towards using high density polyethylene (HDPE) for basal lining and either HDPE or linear low density polyethylene (LLDPE) for capping. This is because of their high resistance to chemical attack and the wide experience of their use in landfills in North America and Europe. This should not prevent you from considering other polymeric liners, since HDPE also has some properties that don't make it ideal. In particular it's potential for thermal expansion and environmental stress cracking can reduce its long-term flexibility and tensile behaviour. At present, various alternative polymers are being developed specifically for use as landfill liners where a combination of high chemical resistance, strength, flexibility, temperature stability and robustness are required. Increasingly, you should consider the performance and chemical resistance of other geomembranes as a wider range of products becomes available. Balancing ultimate chemical resistance with alternative physical properties may provide a better engineered and less risky scheme in many circumstances.

You should choose a geomembrane that provides adequate tensile strength and is robust enough to survive installation. On side slopes, design care must be taken to avoid exceeding any material specific stress or strain characteristics.

5.2 Selecting geomembranes

Table 2 provides a guide for choosing geomembranes. The contents of the table are not exhaustive, use it as a guide to the various steps and procedures you should include during selection.

Step 1 Containment application - Geomembrane selection must be influenced by the proposed use of the material, as basal, sidewall and capping liners will all be subject to different levels of chemical, physical and biological stress. You must give careful attention to assessing the use in its overall setting.

Step 2 Assess the environmental framework - At this stage undertake a detailed site specific assessment to ensure the properties of your selected membrane will protect the environment with an adequate factor of safety.

Step 3 Assess the physical stresses – Assess physical, chemical and biological stresses the liner is likely experience at this stage.

Step 4 Select the most appropriate geomembrane – Once you've calculated the various applications and environmental stresses, compare these to the material properties of the available products. Select the best material based on your comparison.

Table 2 Geomembrane selection

STEP 1

CONTAINMENT APPLICATION	
Capping liners Basal liners Sidewall liners Secondary liners	-Gas, liquid and solid waste containment

STEP 2

ASSESS ENVIRONMENTAL FRAMEWORK
-Required design life -Overall design framework -Site specific considerations such as slope angles -risk assessment including the consequences of failure

STEP 3

ASSESS ENVIRONMENTAL STRESSES		
Physical/mechanical	Chemical	Biological
-Required design life -Interface properties with other liner elements -magnitude and extent of settlement -construction and installation stresses -predicted loadings -predicted temperature	-Required design life -Waste types and likely by-products of waste -Potential attack by volatiles in gases -predicted temperatures	-Required design life -assess macro and micro biological exposure

STEP 4

MEMBRANE SELECTION
Select membrane to match environmental setting with a suitable factor of safety (see step 1 of this standard)

5.3 Geomembrane delivery and handling

The CQA engineer must supervise the delivery of the liner material. They should supervise the unloading and make arrangements for safe storage. Appropriate machinery must be available on the site for lifting and transporting the membrane. Lifting and carrying should use slings or core bars. Under no circumstances can the membrane be handled with the tines of a forklift machine, the bucket of an excavator or any similar equipment. The storage area must be prepared to minimise the potential for damage.

5.4 Design issues

Slope stability - Slopes are restricted more by subgrade preparation than by the geomembrane installation. Sheets can be unrolled and installed against very steep or vertical walls but in most situations the walls are not smooth enough to be in contact with a geomembrane, risking severe damage when in use. Several methods have been developed by installers and operators to overcome this problem including using gabions, rock bolted frames and vertical formers to provide a surface against which to install the sheet. Not all geomembranes are suitable for vertical and subvertical installation. Your designer should provide additional technical information on sheet properties where this is proposed. There have been failures in subvertical systems due to poor design and installation.

The shear strength of a geomembrane/soil interface is low and to enable the design of steeper slopes in landfill, and greatly increase the available volume for waste disposal, textured sheets have been developed. Textures include roughness or protuberances on one or both sides of the geomembrane. The methods used may reduce the strength or other physical properties of the sheet compared with the equivalent smooth sheet. The texturing process must be compatible with the membrane. This ensures the texturing provided is robust and gives confidence in slope stability. Different texturing processes will give different residual shear strengths, you will need to consider this if these are critical to the design. Obtain friction angles between the geomembrane and other ancillary materials such as geotextiles from the manufacturer. If relevant test data is unavailable, you will need to carry out actual shear box tests to gather the data.

The shear forces imposed on geomembranes can become critical during construction and you must consider this possibility. This needs to include the method of placement of any cover materials and the types of installation devices you plan to use. If the stresses induced indicate instability, even when using a friction geomembrane, your design is likely to require soil veneer reinforcement.

Stresses – Stresses can be induced into the geomembrane by a number of factors during transport, installation and the membrane's operational life. Designers must consider the potential sources and magnitudes of such stresses, ensuring that where possible choose lining materials and elements to eliminate these stresses (for example, interface shear between different materials). Features such as anchor trenches must be designed to provide a degree of pullout resistance, but they must fail well before the membrane. The material you choose must therefore give a good factor of safety over the anchorage strength.

Leachate monitoring and extraction points - must be designed so they spread loads and don't overstress or puncture the geomembrane. Structure and pipe penetrations through the liner are difficult design problems often causing installation difficulties and potential points of weakness, avoid them at all costs. Successful design requires a detailed knowledge of both the available techniques and the practical aspects of installation.

Desiccation under geomembrane Liners - evidence is emerging of two processes which may cause desiccation of mineral liners under geomembranes. The first is due to diurnal heating and cooling causing evaporation of moisture from the mineral liner. This moisture then condenses on the lower surface of the geomembrane and runs downhill causing an additional problem of water trapped between the membrane and the mineral liner. Desiccation caused in this way can cause severe and permanent damage to the mineral liner, and require the repair of the geomembrane to remove the water. One proposed solution to this problem is to immediately cover laid geomembranes to ensure that the geomembrane is in intimate contact with the mineral liners and that temperature variations are minimised.

The second process is due to temperature and moisture gradients (between the cooler ground and the warmer waste body) at the base of an active site. Rowe (1998) considers that moisture will migrate from higher temperature and moisture states to lower temperature and moisture states until a balance is reached. Evidence for this second process is still being collected, designers should however consider that the process could lead to mineral liner desiccation

5.5 Subgrade

The essential requirements for installing a geomembrane are a smooth, dry and clean working surface. For compacted mineral liners in good weather conditions this is readily achievable. However, for conditions such as sheer rock faces, the preferred methods of treatment are re-profiling and/or placing suitable engineering materials or structures against the face with an appropriate gradient. In the latter case a design must address the matter of potential subsequent settlement (including differential settlement against the quarry face) to minimise the risk of membrane rupture.

The subgrade design aspects which require the most detailed attention are: -

i) Grain size and angularity - the subgrade (that is, the material immediately beneath the membrane) should be free for a depth of at least 150 mm of any objects which may puncture the membrane. The subgrade material therefore requires particular attention in its specification. For 2.0 mm thickness HDPE, the maximum particle dimension (in a material with a broad particle size distribution such as 40 % less than 1 mm) in contact with the membrane is 20mm (according to BS5930:1999) assuming rounded material (not angular or crushed). For 1.0 mm thickness HDPE the maximum particle dimension is 10 mm under the same conditions. If your design uses angular, crushed, or narrow particle size distribution subgrade material, the maximum permissible particle dimension is reduced by 50% in each case. Any stone protruding above the surface of the subgrade must be stone picked and the indentation filled and compacted with suitable material.

ii) Chemical composition - the sub-grade should be free from any contamination which may chemically affect the selected geomembrane material.

iii) Surface finish - the surface onto which the membrane is to be laid must be as flat as possible. Undulations require complex cutting and welding of the membrane, and since the joints are potentially the weakest parts of the geomembrane your design should minimise their number.

There should be no sharp angles in the subgrade which exceed ±10mm under a 1000mm lath (for example at changes of grade due to rutting), and no large rounded irregularity should exceed ±50mm under a 3000mm lath). As detailed in Table1, you should take measurements of smoothness and flatness at a rate of five per hectare and recorded in the CQA report.

iv) Thickness - there should be a specified minimum thickness of sub-grade over hard rock or stone. In the case of a composite liner this condition will be fulfilled by the mineral liner element, but otherwise you may use another suitable material. The thickness your design specifies will depend on the composition of the sub-grade, the smoothness or otherwise of the underlying surface and the depth of waste to be placed. Your design must also take account of any potential for differential settlement and of the need to achieve minimum slope angles.

v) Compaction - the sub-grade must be sufficiently well compacted to prevent localised settlement and possible elongation and rupture of the membrane after construction when the weight of the waste is applied. If you've any doubt regarding the degree of compaction of the subgrade, undertake field testing to demonstrate that compaction is in excess of 95% of the maximum dry density using a 4.5kg rammer.

vi) Shear strength – Designers must calculate the required shear strength of the sub-grade on a site specific basis from the material properties and the waste overburden properties. As a minimum, this should normally exceed 50 kN/m^2. Designers should provide you with technical calculations including a factor of safety demonstrating the subgrade specification will not fail).

vii) Bearing capacity - the subgrade and underlying ground must be capable of bearing the total and differential loads applied by structures such as pumping chambers.

viii) Maximum slope angle - the maximum slope angle will normally be on the side slopes and should be determined in relation to the stability and shear strength of the natural ground and any placed sub-grade material. Designers must also consider coefficients of friction between different elements of the liner system, together with the practicality of machine access.

Bear in mind that any slippage of the cover material over a membrane, for example, in storm conditions, could cause a sympathetic slip of a placed sub-grade layer, which can only be rectified by re-laying the entire system. A similar effect may be caused by moving plant coming to a sudden stop or accelerating sharply while moving over the cover layer. Slope angles should be designed to prevent such effects.

Generally, a slope angle which exceeds 1:2.5 (40%) is unlikely to be acceptable to us except where the design has installed engineered structures allow steeper slopes to be lined.

ix) Minimum slope angle - the smallest slope angles are likely to be at the base of a landfill. Even here a certain gradient is necessary to ensure efficient movement of leachate through the under drainage system to a collection point. The thickness of the sub-grade over any hard rock will need to be adequate to provide such falls.

x) Anchor trenches – see section 5.7

xi) Tests, test methods and acceptance criteria - in general, you must use laboratory tests to assess material properties, and survey techniques to determine thickness and slope angles. It's important your design establishes acceptance criteria. For laboratory tests this will normally be expressed in terms of the percentage of samples which must achieve the predetermined target for any given property. This is important not only for overall quality control purposes, but also to enable the membrane supplier/installer to be assured that their work (possibly under a separate contract or sub-contract) is not jeopardised by the standard of the sub-grade.

Following completion of the subgrade, the CQA engineer must carry out a visual inspection and check any surface irregularities using a lath (one metre straight edge). The CQA engineer should then confirm the suitability of the subgrade as set out in the CQA plan.

5.6 Installing geomembranes

Layout plan - the arrangement of sheets should be according to your predetermined plan in order to minimise the amount of on-site welding needed. Attempts to fit a membrane in any irregularly shaped site without benefit of a plan will inevitably cause buckling or creasing of the material, requiring extra cutting and welding. Layout plans are not rigid, the installer is likely to adjust a number of details depending on the geometry of the site once the subgrade has been constructed.

HDPE, which is the most commonly used material at present, is delivered to site as rolls of up to 250m length and five to ten metres wide. It is difficult to deploy larger rolls than this on site without damaging the subgrade. The nature of the membrane will determine the layout of the sheets. Our basic requirement is to minimise the number of welds and amount of patching. Welds should run down a slope or be on the flat base. You must patch any holes left in the liner during installation at junctions and locations where samples have been removed for testing as soon as possible, these holes can allow the ingress of rainwater or cause local desiccation of the mineral liner.

In windy conditions, you should weight sheets down with sandbags or similar immediately after unrolling to prevent the sheet moving during welding. You must not use any materials which could scratch the geomembrane, your CQA engineer must visually check for such damage.

Similarly, you should weigh down all exposed edges of the liner at the end of each working day. If the geomembrane becomes displaced due to wind (or suffers wind damage), you may need to reject the material due to the likelihood of over-stressing having occurred.

5.7 Anchor trenches

At the top of any slope the membrane will need to be bedded into an anchor trench to prevent slipping and creasing. Your design of anchor trench geometry should consider constructability, to ensure easy installation. Consider v-shaped trenches, with a fall along their length to prevent the ponding of water. A normal minimum requirement is that the trench must be at least one metre back from the top edge of the slope. The membrane should be laid on the inside wall and base of the trench only (you may need to change this layout to allow for a geophysical leak location test). The trench should be backfilled as soon as possible, with low permeability soils and compacted to provide a secure anchorage system. Your design must not use these trenches as a component of a perimeter surface-water management system. Anchor trenches should always be pumped dry to prevent water seeping into the subgrade and causing slope stability problems.

Table 3 Factors that could contribute to geomembrane failure

Factor	Failure mechanism
Material	Defects in geomembrane Sensitivity of the selected material to the service environment Chemical incompatibility Inadequate UV resistance Environmental stress cracking Inadequate physical properties Creep Dimensional instability (shrinkage) Crazing, cracking Inadequate seaming system
Site	Subsidence Gas formation caused by decomposition of organic materials in soil High water table (reverse hydrostatic pressure) Chemical reactivity of subsoil (such as solubility in acids)
Design	Improper selection of materials Inadequate specification of materials Inadequate compatibility testing Improper use of materials Supporting structure problems Stress fatigue and cracking Inadequate protection against ice
Construction	Inadequate subgrade compaction Inadequate subgrade finishing Poor quality of seams Inadequate anchoring Inadequate sealing around structures Inadequate techniques for the application of covering materials Imposed shear forces by construction methods
QC,QA,CQA	Inadequate inspection of construction, Allowing poor construction quality Inadequate inspection of materials
Other	Attack by weathering, ozone Chemical attack by constituents of the waste Attack by wind or fire Biological attack, including biodegradation Attack by animals and insects
Operations	Inadequate maintenance of protective cover Inadequate control of incoming wastes Inadequate control of methods of placing waste Improper cleaning procedures Vandalism

5.8 Welding geomembranes

With all geomembranes the less field welding to be carried out the better because of the possible problems of poor weather and ground conditions and the resulting quality control difficulties.

The extent of overlap of adjacent sheets will depend largely on the manufacturer's recommendations and the method of welding you adopt. As a general rule, the overlap should be no less than 100mm.

The weld surfaces must be clean. The cleaning method will depend on how well you've protected the material from soiling during site handling. Loose, dry sand may be removed with a brush or cloth but anything more than this must be removed with water and the appropriate utensils. Some manufacturers apply a removable tape to the edges of the geomembrane which you remove just prior to welding. This improvement is extremely useful on muddy or dusty sites.

Prior to extrusion welding, the surfaces to be welded must be carefully abraded with a handheld electric sander or wire brush to remove surface oxidation or any processing contaminants such as lubricants. Abrasion must not cause any significant thinning of the liner or excessive scratches which could act as stress crack initiators.

Welding methods

The available welding methods fall into two groups, namely solvent methods (including adhesives) and thermal methods. Solvents are used with PVC and CPE and are generally formulated by the membrane manufacturer. These methods are not commonly used in landfills so are not detailed further here.

There are various thermal welding methods available and they fall into two groups, thermal fusion (melt bonding) and extrusion welding. In the first, the surfaces of the liner material are melted, generally by contact with a hot shoe or wedge and pressed together, In the second a strip of additional polymer material (usually of the same composition as the sheet) is applied to the prepared joint surfaces.

The hot wedge welding machines that have been developed either produce a single continuous weld, between 20 and 50 mm wide or two parallel continuous welds, typically 20-25mm with a 25-30mm air channel in between. We strongly recommend that all main welds be double continuous welds with an intervening air channel. The test method for this weld is the quickest and most reliable.

We prefer hot wedge welding for all main joints between adjacent sheets of the liner, because they rely on truly melting together the two surfaces. This may incur some thinning of the material, but provided the overall weld thickness is still greater than that of a single sheet we don't consider this to be a disadvantage.

Although fusion methods are preferable, the machinery can't negotiate tight curves or direction changes. As a result extrusion methods are currently used for welding seams in awkward areas such as for patch repairs. Generally, the two sheets to be joined are tacked together using a hot air gun and then the surface over which extrudate is to be applied is lightly ground to remove contaminants and the oxide layer. At this stage if the weld is to be spark tested, a copper wire is tacked along the centre of the seam. The extrusion welder melts a separate supply of polymer (either from a reservoir of granules, or from a roll on a cable reel). The extrudate is then applied by passing the welder over the joint surfaces. Discard the initial extrudate as this will have been overheated. The extrudate applied must completely cover the ground areas to prevent weak points forming. Carry out all lengths of welding as continuously as possible. If it is necessary to stop the weld in the middle of a length, and start again later, take special care to ensure no gap is left in the weld. Mark any such ‘stop-start' positions for extra careful checking.

Carefully control the temperature and speed of welding according to the nature and thickness of the material and the ambient air temperature. If the weld temperature is too low a poor weld will result; if too high, the material can burn, flake or melt excessively.

Welding of any one joint should be carried out in one direction only. Using two machines welding towards each other may result in unequal lengths of material to be joined where the two meet causing unnecessary cutting and patching.

All welds need to cool to the ambient air temperature before reaching their full strength.

Ensure there are no creases or folds present, cut out and re-weld any left in the material after welding, inserting patches if necessary. Exercising care should during laying will minimise the need for such repairs.

Weld testing

Weld testing methods fall into two categories; destructive and non-destructive. Destructive methods clearly indicate seam integrity by attempting to mechanically part the seams, and are similar for all methods of welding. Non-destructive methods aim to assess the seam integrity without damaging the seam, the methods used differ according to the type of weld being tested.

We consider compressed air testing of double continuous welds to be the most reliable technique, it’s also the quickest way of testing long weld lengths. However, care must be taken to avoid over-stressing the weld. Use a pressure gauge at both ends of the weld wherever possible to ensure bridging of the air channel by excess material does not occur.

Destructive methods

Destructive tests on start up welds carried out in the field involve placing a strip taken across a welded seam into the jaws of a tensiometer and pulling the jaws apart. Samples are tested in both peel and shear modes. The seam should not part and the material should not fail in the sheet rather than at the seam. The procedure for such tests is described in Appendix A. You must send samples of your production weld seams for destructive testing at a UKAS accredited laboratory in accordance with Table 1.

Non-destructive methods

We consider air pressure testing (APT) of double continuous welds to be the most reliable non-destructive method. APT involves the channel between two welds being pressurised by introducing compressed air to a predetermined pressure. If the channel holds this pressure over a set time period, the weld has passed. However, take care not to over-stress the weld with excessive air pressures. It is preferable to use a pressure gauge at both ends of the weld to ensure bridging of the air channel by excess material has not occurred. Alternatively, deflate the channel by removing the plug from the end furthest from where you introduced the compressed air.

Extrusion welds around patches or repairs must be tested by a combination of visual inspection, spark testing or vacuum box testing. In the case of spark testing a copper wire is placed in the centre of the seam area prior to welding. After welding, an electrostatically charged brush (the spark gun) is passed over the seam, areas where the wire is exposed or where insufficient extrudate is present are indicated by visible sparks between the copper wire and the brush. This test does not give any indication of weld strength, or continuity of seal, it only relates to the thickness of extrudate applied over the copper wire. Continuity of the seal will be assured by correctly placing the copper wire within the seam, in accordance with ASTM D6395. In vacuum box testing, a soap solution is applied to a short length of welded seam. A vacuum box (equipped with a vacuum gauge, a clear glass view panel on top and a soft rubber gasket on the edge of the open bottom) is then placed over the area to be tested and partially evacuated. Bubbles in the solution indicate holes. Although this method clearly identifies leaks, in practice it is difficult to seal the edges of the box.

As much as possible of the complete length of all welds on the site should be tested to ensure no leachate seepage will occur. The test must therefore relate to the integrity of the welds rather than their strength alone.

5.9 Geophysical test methods

Further integrity tests you can employ use geophysical methods relying on the membrane being an electrical insulator. Since geomembranes can suffer considerable damage by placing overlying materials, geophysical testing should be carried out after you've installed the protection/drainage media. You can find further advice on geophysical methods in other guidance we've produced.

5.10 Protection layers

i) Requirements - immediately after completely installing any section of liner (normally once you've completed all CQA testing) cover the section with a layer of suitable material to protect it against damage (site damage, temperature extremes, oxidation, UV light, animals, vandalism and other stress agents).

ii) Protection material - the most commonly used protection materials are granular materials such as sand, silt or a geosynthetic material. The important factors to consider when using mineral protectors are grain size and angularity. In general, the maximum particle size in a broadly graded material should be tow to five mm, particles should not be hard or angular). In the case of geosynthetics performance tests can be undertaken which indicate their suitability. Using otherwise unsuitable materials may be possible by placing a suitable geosynthetic over the liner before laying the cover, subject to testing.

iii) Protector thickness - the protection system includes the materials immediately adjacent to the geomembrane, the leachate drainage blanket and the first layer of waste. Each element must be carefully specified and have appropriate CQA checks applied. Geosynthetic protectors are normally five to ten– mm thick, whilst mineral protectors are at least 250mm - 1000mm thick depending on the material used and the traffic over it. Control and check the thickness of the cover material by survey techniques, rather than by any form of physical probing, which could damage the liner.

iv) Placing protection systems – Carefully place the protection materials on the liner ensuring any potential for geomembrane damage is minimised.

Under no circumstances may a machine or truck track directly on the liner material once laid to its specification. Determine the minimum thickness of protective material by assessing the likely stresses imposed by the waste body and the ground pressure that will be applied by the plant laying the cover.

Lay cover layers greater than 300mm thickness in thin layers to maximise compaction and minimise subsequent settlement.

5.11 Leachate drainage layers

Leachate drainage systems normally consist of a blanket of coarse granular material directly over the protection layer. For geomembranes, it's essential a cover or protection layer of finer material (or a suitable geotextile) underlies the coarse drainage material to prevent puncturing. If using a fine material the design needs to prevent the possibility of fines washing into the drainage blanket.

5.12 Strengthening and sealing around structures

Some parts of the geomembrane may require extra strengthening or reinforcement, under inspection chambers and around leachate sumps for example. Designers must pay careful attention to these areas and provide detailed design calculations and engineering drawings to us to assure us the membrane will not be punctured during its design life.

5.13 Check List

Use the following as a checklist while installing a geomembrane;

a) Geomembrane must be deployed without tension

b) Pressures on the geomembrane must be less than 55 kPa (8 psi.) if the subgrade conforms with section 5.5 (iii)

c) Geomembrane (not ambient) temperature must be specified

d) Geomembranes should be just taut at minimum service temperature or covering temperature

e) Avoid scratching geomembranes (through dragging and so on) as even shallow scratches can initiate stress cracks.

f) Ensure geomembranes are ballasted against wind uplift

g) Place no horizontal seams on slopes

h) Minimise seaming in corners

i) Avoid re-seaming geomembranes as the thermal history of the sheet changes during welding.

j) Avoid overgrinding geomembranes

k) Ensure the grinding orientation doesn't jeopardise the welding process

l) Examine textured sheet edges to ensure the texture will not jeopardise the welding process

m) Patch all penetrations - even pinholes

n) Peel test both tracks of a dual track wedge weld.

6 Validation report

A validation report for a geomembrane must include the following: -

i) The results of all testing. This includes field and laboratory tests and the records of any failed tests with details of the remedial action taken, referenced to the appropriate secondary testing. Accompany any test results which fail due to either poor sampling, specimen preparation or defective testing with a written explanation from the soils laboratory or the quality assurance engineer. The results must be clearly presented, with graphs and tables used where necessary.

ii) Plans showing the location of all tests and samples

iii) As-built plans and sections of the works

iv) Copies of the site engineer's and or QA inspector's daily records (including, for example, plant in use, work done, problems experienced, weather conditions, conditions of materials and so on)

v) Records of non-compliance and their solution (note – agree your proposed solution in advance with the Environment Agency)

vi) Results of any geophysical testing

vii) Any other site specific information you consider relevant to proving the integrity of the geomembrane

viii) Validation by the independent QA engineer that all the works subject to QA and CQA procedures have been carried out in accordance with the method statement, designs and specifications agreed with the Environment Agency

As built drawings and supporting documentation should include:

- Layout of individual liner sheets with roll numbers
- Dates of sheet installation
- Type of weld, date of weld and test type, date and welding technician
- Sample points annotated with sample type and number
- Repairs
- Welding personnel accreditation certificate

Appendix A - start-up test weld

You must undertake a start up weld test: -

- at the start of each day
- after any welding stoppage exceeding one hour
- where weather conditions have changed, affecting the welding efficiency of the machinery

If any of the above conditions exist, carry out the following sequence of testing under the supervision of the third party independent quality assurance inspector or engineer:

a) A test weld greater than 3m in length. The test must be carried out under the same conditions as exist for the membrane welding. Mark the test weld with the time, date, ambient temperature, geomembrane temperature and welding machine type and number.

b) Cut six specimens, each 25mm wide and at least 105mm long from the weld. Test three in peel and three in shear using a hand tensiometer to confirm failure of the weld takes place in the Film Tear Bond Mode (as per ASTM D6392-99). For fusion welds, test both tracks of the weld in peel.

c) If any specimen fails, repeat the entire operation.

d) If any of the additional specimens fail, inspect the welding equipment reporting any defects and the corrective action taken. If you can correct the problem, the equipment may be used after two further consecutive full trial seams are achieved without failure

e) If the equipment fails five times in any 48 hour period, returned it for repair keeping records of the service.

f) A record of the results must form part of the validation report.

Appendix B – manufacturing quality control for geomembranes

These tables are reproduced from GRI standards GM13 and GM17. These standards are included for information and guidance.

High density polyethylene (HDPE) geomembrane – smooth

Properties	Test method	Test value							Testing frequency (minimum)
		0.75 mm	1.00 mm	1.25 mm	1.50 mm	2.00 mm	2.50 mm	3.00 mm	
Thickness – mils (min, avg.) ● Lowest individual of 10 values	D5199	Nom. (mil) - 10%	Nom. (mil) - 10%	Nom. (mil) - 10%	Nom. (mil) - 10%	Nom. (mil) - 10%	Nom. (mil) - 10%	Nom. (mil) - 10%	Per roll
Density (min.)	D1505/D 792	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	90,000 kg
Tensile properties (1) (min, avg) ● Yield strength ● Break strength ● Yield elongation ● break elongation	D 6693 Type IV	 11 kN/m 20 kN/m 12% 700%	 15 kN/m 27 kN/m 12% 700%	 18 kN/m 33 kN/m 12% 700%	 22 kN/m 40 kN/m 12% 700%	 29 kN/m 53 kN/m 12% 700%	 37 kN/m 67 kN/m 12% 700%	 44 kN/m 80 kN/m 12% 700%	9,000 kg
Tear Resistance (min.ave.)	D 1004	93 N	125 N	156 N	187 N	249 N	311 N	374 N	20,000 kg
Puncture Resistance (min.ave.)	D 4833	240 N	320 N	400 N	480 N	640 N	800 N	960 N	20,000 kg
Stress Crack Resistance (2)	D 5397 (App.)	300 hr.	300 hr.	300 hr.	300 hr.	300 hr.	300 hr.	300 hr.	Per GRI GM -10
Carbon Black Content - %	D 1603 (3)	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	9,000 kg
Carbon Black Dispersion	D5596	Note (4)	Note (4)	Note (4)	Note (4)	Note (4)	Note (4)	Note (4)	20, 000 kg
Oxidative Induction Time (OIT) (min, avg.) (5) (a) Standard OIT - or – (b) High Pressure OIT	 D 3895 D 5885	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	90,000 kg
Oven Aging at 85°C (5), (6) (a) Standard OIT (min, avg.) - % retained after 90 days - or – (b) High pressure OIT (min, avg.) - % retained after 90 days	D 5721 D 3895 D 5885	 55 % 80 %	 55 % 80 %	 5 % 80 %	 55 % 80 %	 55 % 80 %	 55 % 80 %	 55 % 80 %	Per each formulation
UV Resistance (7) (a) Standard OIT (min, avg.) - or – (b) High pressure OIT (min, avg.) - % retained after 1600hrs (9)	 D 3895 D 5885	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	Per each formulation

(1) Machine Direction (MD) and cross machine direction (XMD) average values should be on the basis of 5 test specimens each direction
Yield elongation is calculated using a gage length of 33 mm
Break elongation is calculated using a gage length of 50mm
(2) The yield stress used to calculate the applied load for the SP-NCTL test should be the manufacturer's mean value via MQC testing.
(3) Other methods such as D 4218 (muffle furnace) or microwave methods are acceptable if an appropriate correlation to D 1603 (tube furnace) can be established.
(4) Carbon black dispersion (only near spherical agglomerates) for 10 different views:
9 in category 1 or 2 and in Category 3
(5) The manufacturer has the option to select either one of the OIT methods listed to evaluate the antioxidant content in the geomembrane.
(6) It is also recommended to the evaluate samples at 30 and 60 days to compare with the 90 day response
(7) The condition of the test should be 20hr. UV cycle at 75°C followed by 4hr. Condensation at 60°C.
(8) Not recommended since the high temperature of the Std-OIT test produces an unrealistic result for some of the antioxidant sin the exposed samples.
(9) UV resistance is based on percent retained value regardless of the original HP-OIT value.

High density polyethylene (HDPE) geomembrane – textured

Properties	Test method	Test value							Testing frequency (minimum)
		0.75 mm	1.00 mm	1.25 mm	1.50 mm	2.00 mm	2.50 mm	3.00 mm	
Thickness – mils (min.ave.) ● Lowest individual for 8 out of 10 values ● Lowest individual for any of the 10 values	D 5994	nom. (-5%) - 10% - 15%	nom. (-5%) - 10% - 15%	nom. (-5%) - 10% - 15%	nom. (-5%) - 10% - 15%	nom. (-5%) - 10% - 15%	nom. (-5%) - 10% - 15%	nom. (-5%) - 10% - 15%	Per roll
Asperity Height mils (min, avg.) (1)	GM 12	0.25 mm	0.25 mm	0.25 mm	0.25 mm	0.25 mm	0.25 mm	0.25 mm	90,000 kg
Density (min.ave.)	D 1505/D 792	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	Every2nd roll (2)
Tensile Properties (min, avg.) (3) • Yield strength • Break strength • Yield elongation • Break elongation	D 6693 Type IV	11 kN/m 8 kN/m 12% 100%	15 kN/m 10 kN/m 12% 100%	18 kN/m 13 kN/m 12% 100%	22 kN/m 16 kN/m 12% 100%	29 kN/m 21 kN/m 12% 100%	37kN/m 26 kN/m 12% 100%	44 kN/m 32 kN/m 12% 100%	9,000 kg
Tear Resistance (min.ave.)	D 1004	93 N	125 N	156 N	187 N	249 N	311 N	374 N	20,000 kg
Puncture Resistance (min.ave.)	D 4833	200 N	267 N	333 N	400 N	534 N	667 N	800 N	20,000 kg
Stress Crack Resistance (4)	D 5397 (App.)	300 hr.	300 hr.	300 hr.	300 hr.	300 hr.	300 hr.	300 hr.	Per GRI GM 10
Carbon Black Content (range)	D 1603 (5)	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	2.0 – 3.0%	9,000 kg
Carbon Black Dispersion	D5596	Note (6)	Note (4)	Note (4)	Note (4)	Note (4)	Note (4)	Note (4)	20, 000 kg
Oxidative Induction Time (OIT) (min, avg.) (7) (a) Standard OIT - or – (b) High Pressure OIT	 D 3895 D 5885	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	90,000 kg
Oven Aging at 85°C (7), (8) (a) Standard OIT (min, avg) - % retained after 90 days - or – (b) High Pressure OIT (min, avg) - % retained after 90 days	D 5721 D 3895 D 5885	 55 % 80 %	 55 % 80 %	 5 % 80 %	 55 % 80 %	 55 % 80 %	 55 % 80 %	 55 % 80 %	Per each formulation
UV Resistance (9) (a) Standard OIT (min, avg) - or – (b) High pressure OIT (min, avg) - % retained after 1600hrs (11)	GM11 D 3895 D 5885	 N. R. (10) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	 N. R. (8) 50 %	Per each formulation

(1) Of 10 readings; 8 out of 10 must be ≥ 0.18 mm, and lowest individual reading must be ≥ 0.13mm
(2) Alternate the measurement side for double sided textured sheet
(3) Machine direction (MD) and cross machine direction (XMD) average values should be on the basis of 5 test specimens each direction.
Yield elongation is calculated using a gage length of 33mm
Break elongation is calculated using a gage length of 50mm
(4) The SP-NCTL test is not appropriate for testing geomembranes with textured or irregular rough surfaces. Test should be conducted on smooth edges of textured rolls or on smooth sheets the same formulation as being used for the textured sheet materials. The yield stress used to calculate the applied load for the SP-NCTL test should be the manufacturer's mean value Via MQC testing.
(5) Other methods such as D 4218 (muffle furnace) or microwave methods are acceptable if an appropriate correlation to D 1603 (tube furnace) can be established)
(6) Carbon black dispersion (only near spherical agglomerates) 10 different views:
9 in categories 1 or 2 and 1 in category 3
(7) The manufacturer has the option to select either one of the OIT methods listed to evaluate the antioxidant content in the geomembrane.
(8) It is also recommended to evaluate samples at 30 and 60 days to compare with the 90 day response.
(9) The condition of the test should be 20 hr. UV cycle at 75°C followed by 4 hr. condensation at 60°C
(10) Not recommended since the high temperature of the Std-OIT test produces an unrealistic result for some of the antioxidants in the UV exposed samples.
(11) UV resistance is based on percent retained value regardless of the original HP-OIT value

Linear low density polyethylene (LLDPE) geomembrane - smooth

Properties	Test Method	Test Value								Testing Frequency (minimum)
		0.50 mm	0.75 mm	1.0 mm	1.25 mm	1.50 mm	2.00 mm	2.5 mm	3.0mm	
Thickness – mm (min, avg)	D5199	Nom.	Nom.	Nom.	Nom.	Nom.	Nom.	Nom.	Nom.	Per roll
• Lowest individual of 10 values		-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	
Density g/ml (max.)	D1505/D 792	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	90,000 kg
Tensile properties *(1)* (min, avg) • Break strength N/mm • Break elongation - %	D 6693 Type IV	13 800	20 800	27 800	33 800	40 800	53 800	66 800	80 800	9,000 kg
2% Modulus – N/mm (max.)	D 5323	210	370	420	520	630	840	1050	1260	per formulation
Tear Resistance – N (min, avg)	D 1004	50	70	100	120	150	200	250	300	20,000 kg
Puncture Resistance – N (min, avg)	D 4833	120	190	250	310	370	500	620	750	20,000 kg
Axi-symmetric Break Resistance Strain - % (min)	D 5617	30	30	30	30	30	30	30	30	per formulation
Carbon Black Content - %	D 1603 *(3)*	2.0 – 3.0	2.0 – 3.0	2.0 – 3.0	2.0 – 3.0	2.0 – 3.0	2.0 – 3.0	2.0 – 3.0	2.0 – 3.0	20,000 kg
Carbon Black Dispersion	D5596	note *(3)*	note *(3)*	note *(3)*	note *(3)*	note *(3)*	note *(3)*	note *(3)*	note *(3)*	20,000 kg
Oxidative Induction Time (OIT) (min, avg) (4) (a) Standard OIT - or - (b) High pressure OIT	D 3895 D 5885	100 400	100 400	100 400	100 400	100 400	100 400	100 400	100 400	90,000 kg
Oven Aging at 85°C *(5)* (a) Standard OIT (min, avg) - % retained after 90 days - or - (b) High pressure OIT (min, avg) - % retained after 90 days	D 5721 D 3895 D 5885	35 60	35 60	35 60	35 60	35 60	35 60	35 60	35 60	per formulation
UV Resistance *(6)* (a) Standard OIT (min, avg) - or - (b) High pressure OIT (min, avg) – % retained after 1600hrs *(8)*	D 3895 D 5885	N. R. *(7)* 35	N. R. *(7)* 35	N. R. *(7)* 35	N. R. *(7)* 35	N. R. *(7)* 35	N. R. *(7)* 35	N. R. *(7)* 35	N. R. *(7)* 35	per formulation

(1) Machine Direction (MD) and cross machine direction (XMD) average values should be on the basis of 5 test specimens each direction
- Break elongation is calculated using a gage length of 50 mm/min.

(2) Other methods such as D 4218 (muffle furnace) or microwave methods are acceptable if an appropriate correlation to D 1603 (tube furnace) can be established.
(3) Carbon black dispersion (only near spherical agglomerates) for 10 different views:
- 9 in categories 1 or 2 in Category 3

(4) The manufacturer has the option to select either one OIT methods listed to evaluate the antioxidant content in the geomembrane.
(5) It is also recommended to the evaluate samples at 30 and 60 days to compare with 90 day response
(6) The condition of the test should be 20hr. UV cycle at 75°C followed by a 4hr. Condensation at 60°C.
(7) Not recommended since the high temperature of the Std-OIT test produces an unrealistic result for some of the antioxidants in the UV exposed samples.
(8) UV resistance is based on percent retained value regardless of the original HP-OIT value.

Linear low density polyethylene (LLDPE) geomembrane - textured

Properties	Test method	Test Value								Testing frequency (minimum)
		0.50mm	0.75 mm	1.0mm	1.25mm	1.50mm	2.00mm	2.5mm	3.0mm	
Thickness mils (min.ave.) • Lowest individual for 8 out of 10 values • Lowest individual for any of the 10 values	D 5994	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	Nom. (-5%) -10% -15%	per roll
Asperity Height mm (min, avg) (1)	GM 12	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	every 2nd roll (2)
Density g/ml (max.)	D 1505/D 792	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	90,000 kg
Tensile properties (3) (min, avg) • Break strength – N/mm • Break elongation - %	D 6693 Type IV	5 250	9 250	11 250	13 250	16 250	21 250	26 250	31 250	90,000 kg
2% Modulus – N/mm (max.)	D 5323	210	370	420	520	630	840	1050	1260	per formulation
Tear resistance – N (min, avg)	D 1004	50	70	100	120	150	200	250	300	20,000kg
Puncture Resistance – N (min, avg)	D 4833	100	150	200	250	300	400	500	600	20,000kg
Axi – Symmetric Break Resistance Strain - % (min)	D 5617	30	30	30	30	30	30	30	30	per formulation
Carbon Black Content - %	D 1603 *(4)*	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	20,000kg
Carbon Black Dispersion	D 5596	note *(5)*	note *(5)*	note *(5)*	note *(5)*	note *(5)*	note *(5)*	note *(5)*	note *(5)*	20,000kg
Oxidative Induction Time (OIT) (min, avg) (6) (a) Standard OIT - or – (b) High pressure OIT	D 3895 D 5885	100 400	100 400	100 400	100 400	100 400	100 400	100 400	100 400	90,000 kg
Oven Aging at 80°C (7) (a) Standard OIT (min, avg) - % retained after 90 days - or - (b) High pressure OIT (min, avg) - % retained after 90 days	D 5721 D 3895 D 5885	35 60	35 60	35 60	35 60	35 60	35 60	35 60	35 60	per formulation
UV Resistance (8) (a) Standard OIT (min, avg) - or - (b) High Pressure OIT (min, avg) - % retained after 1600 hrs (10)	D 3895 D 5885	N. R. *(9)* 35	N. R. *(9)* 35	N. R. *(9)* 35	N. R. *(9)* 35	N. R. *(9)* 35	N. R. *(9)* 35	N. R. *(9)* 35	N. R. *(9)* 35	per formulation

(1) Of 10 readings; 8 out of 10 must be ≥0.18mm, and lowest individual reading must be ≥0.13mm
(2) Alternative the measurements side for double sided textured sheet
(3) Machine direction (MD) and cross machine direction (XMD) average values should be on the basis of 5 test specimens each direction.

- Break elongation is calculated using a gage length of 50mm at 50mm/min.

(4) Other methods such as D 4218 (muffle furnace) or microwave methods are acceptable if an appropriate correlation to D 1603 (tube furnace) can be established.
(5) Carbon black dispersion (only near spherical agglomerates) for 10 different views:

- 9 in Categories 1 or 2 and 1 in Category 3

(6) The manufacturer has the option to select either one of the OIT methods listed to evaluate the antioxidant content in the geomembrane
(7) It is also recommended to evaluate samples at 30 and 60 days to compare with the 90 day response.
(8) The condition of the test should be 20 hr. UV cycle at 75°C followed by 4 hr. condensation at 60°C.
(9) Not recommended since the high temperature of the Std-OIT test produces an unrealistic result for some of the antioxidants in the UV exposed samples.
(10) UV resistance is based on percent retained value regardless of the original HP-OIT value.