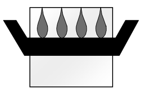
# Geomembranes

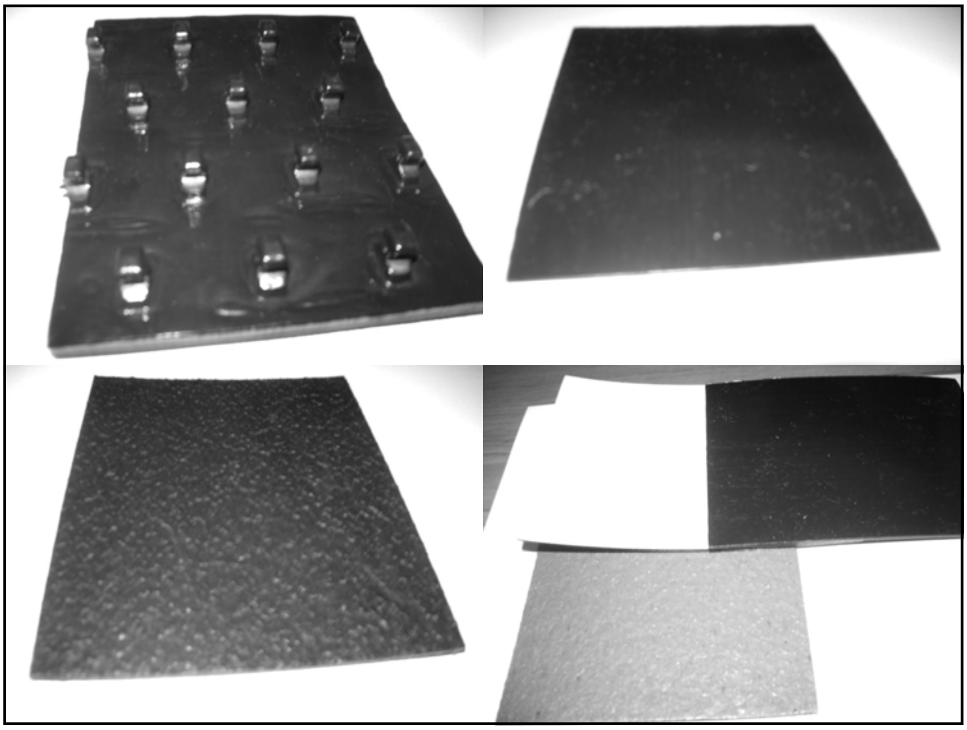
## Geomembrane

• A planar, relatively impermeable, polymeric (synthetic) membrane with a minimum thickness of 1.0 mm.

- Acts as a barrier to fluids
  - Both liquids and gases
  - Function is always containment
  - Many types: HDPE, LLDPE, PVC, EPDM, etc.
- Rolls are field seamed
- Required by regulations for waste containment



Waterproofing

# Comments

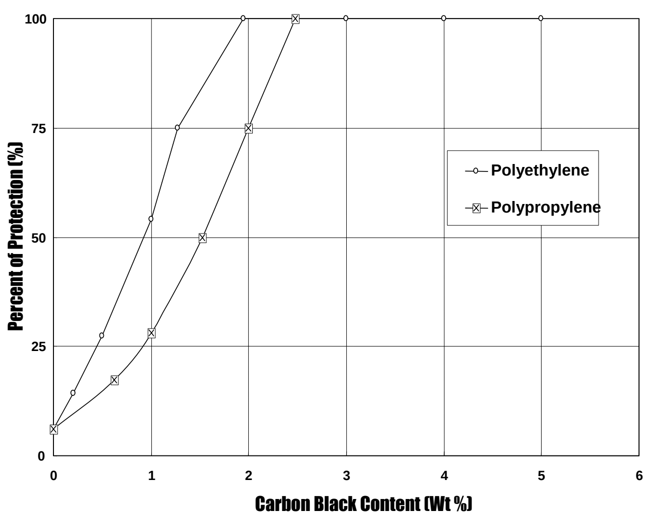
- Name is associated with resin type
- All have some amount of additives
- Hence they are formulations: definition of "formulation"= The mixture of a unique combination of ingredients identified by type, properties and quantity. Ex: for HDPE geomembranes a formulation is defined as the exact percentages and types of resin(s), additives and carbon black.
- Additives can vary from 2% to 60%
- They are critical to proper performance
- Challenged via performance oriented specs.

# Approximate Formulations

| Type | Resin | Plasticizer | Fillers | C.B. | additives |
|---|---|---|---|---|---|
| HDPE | 95-98 | 0 | 0 | 2-3 | 0.5-1* |
| LLDPE | 94-96 | 0 | 0 | 2-3 | 1-4* |
| PVC | 50-70 | 25-35 | 0-10 | 2-5 | 2-5 |
| EPDM | 25-30 | 0 | 20-40 | 20-40 | 1-5 |

* Additives are various antioxidants

## Effect of Carbon Black on Resistance to UV Light for Polyethylene and Polypropylene



# Controlling Factors (1)

- Quality of design
  - Material selection
  - Avoidance of tensile stresses
  - Slope stability and subgrade integrity
  - Adequate protection to liner
  - In landfills, waste settlement effects
  - Thorough site-specific specification
  - Do not make the installers job difficult!

# Controlling Factors (2)

- Physical damage
  - Vulnerable to damage at all stages
- Material degradation
  - Oxidation, UV, aggressive chemicals
- Stress cracking ( mainly HDPE)

## Geomembrane Requirements and Characteristics

- **Physical** (e.g. thickness and density)
- **Mechanical** (e.g. tensile strength, tear resistance, impact resistance, puncture resistance, stress cracking, friction)
- **Endurance** (e.g. resistance against ultraviolet light, biological, chemical and thermal degradation)

- HDPE is the most common resin because of its good chemical resistance
- Typical thicknesses are 1 to 3 mm (lower values used for caps and upper values for basal systems)
- Surfaces are smooth, textured or profiled depending on the surface friction requirements
- LDPE, VLDPE are used in caps due to increased flexibility, hence they can respond better to differential settlement of waste

## Design Philosophy for Geomembranes

- **Minimise stresses and hence strains in the geomembrane**

- **Check that the resin used is not sensitive to *stress cracking* which can occur in materials such as HDPE. Stress cracking is brittle cracking under tensile stress less than its short-term mechanical strength**

- **Both aim to ensure the long-term integrity of the geomembrane and hence minimise any leakage**

# Stress Crack Resistance

- Although in many circumstances HDPE responds as a ductile material, it is susceptible to a brittle failure mechanism referred to as stress cracking (or slow crack growth).
- Stress cracking occurs under sustained tensile stresses that may be much lower than the short term strength

## Three conditions must exist for stress cracking to occur

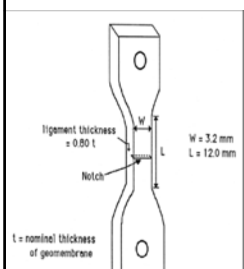
1- Defect in the material which serves to initiate the crack
  - Defects may be induced by the seaming process, construction damage (e.g., scratches, punctures) and material flaws in the GM

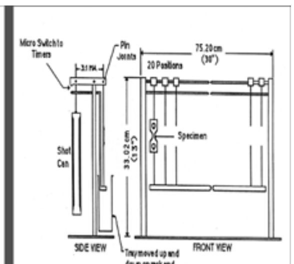
2- Microstructure that will allow the propagation of the crack

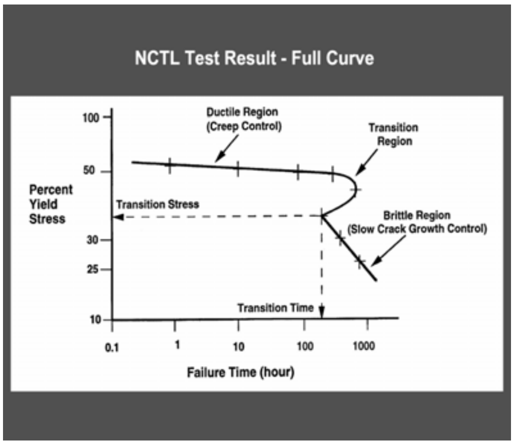
3- Sustained tensile stresses. These tend to promote rapid crack propagation to the stage of failure.

# Stress Crack Resistance

- Stress Cracking test is called Notched Constant Tension Load (NCTL) test, ASTM D5397
  - It places centrally notched dumbell-shaped test specimens under a constant load (@%of their yield stress ASTM 638) in a surface wetting agent (Igepal) at an elevated temperature (50ºC)
- Also SP-NCTL test (Single point), see Appendix to ASTM D5397

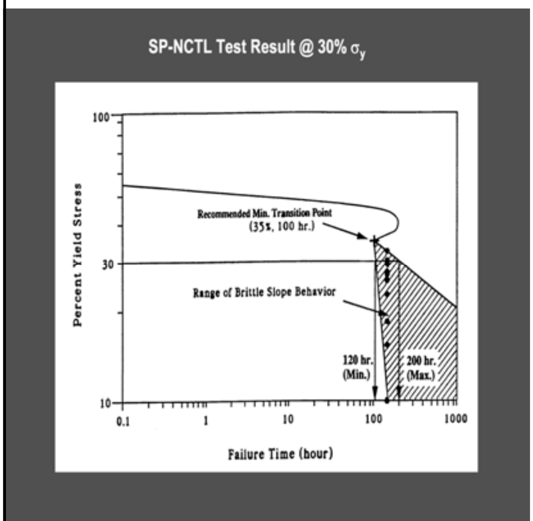



**Current recommendation for an acceptable stress crack resistant HDPE is transition time T ≥ 100 hr**

**Note: 100 hrs based on field retrieved samples, the highest T was 97 hrs. If additional field samples which fail in stress cracking are found with T>100 hrs, then recommended value will have to be raised higher.**




**SP NTCL can be used only for quality control.**

**Same set up as NTCL, but select only one specific value of yield stress (i.e. 30%).**

**If specimen does not fail within 200 hours means that transition time for the full curve is at least 100 hours.**

## Stress Crack Resistance

### Summary

To reduce the potential of stress cracking it is important to:

1- Have material with good stress crack resistance (as minimum see GRI-GM13 table)

2- Limit long term tension in the geomembrane

3- Limit surface damage to the geomembrane to the maximal practical extent (e.g. by providing appropriate geomembrane protection)

## DURABILITY

- Even a well designed and properly constructed geomembrane may be expected to experience some degradation or ageing over its lifetime. Eventually this degradation can lead to failure.

- For a GM liner used as part of a barrier system, failure is said to have occurred when the GM no longer acts as an effective hydraulic or diffusive barrier against contaminant

- Rate of degradation depends on GM properties including thickness and properties of the polymer. It also depends on the exposure conditions, chemical concentration and applied mechanical stresses.

- ≠ 1 Most frequently asked question is; "how long will the geosynthetic last"?
- "Long" or "very long" is an inadequate response for most users
- Alternatively, one could ask "how long does the geosynthetic have to last"?
- Thus, the issue is "lifetime prediction"…

## Expected lifetimes (in years) for various covered geosynthetic applications

| GS type | Roads/Drains | Walls/Slopes | Dams/Tunnels | Landfills |
|---|---|---|---|---|
| GT & GG | 30-50 | 75-100 | 100-200 | 30-1,000 |
| GM & GCL | n/a | n/a | 100-200 | 30-1,000 |
| GN & GC | n/a | n/a | 100-200 | 30-1,000 |

## Degradation and Lifetime Prediction

### Degradation Mechanisms

- oxidation (all types)
- hydrolytic (all types)
- chemical (all types)
- plasticizer extraction (PVC only)
- ultraviolet (exposed only)

## Investigative Options

### (a) "Try, wait and see"

- without monitoring
- with monitoring

### (b) Let others "try, wait and see"

- without monitoring
- with monitoring

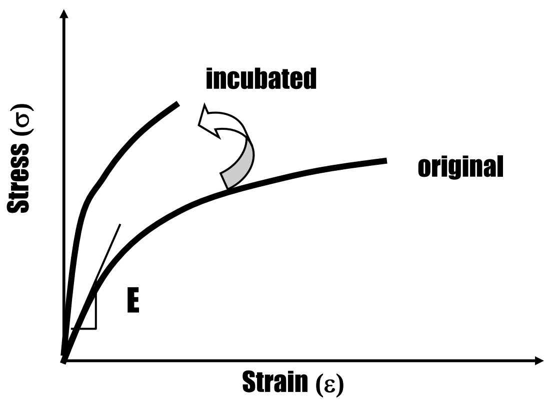
### (c) Perform accelerated laboratory studies

# Time-Temperature Superposition

- Most (all?) degradation mechanisms occur proportionate to temperature
- Higher the temperature; faster the reaction
- Holds for oxidation, hydrolysis, chemical, ultraviolet, migration, biological, radioactive mechanisms (but does not apply to stress)
- Target is a predetermined change in some engineering property, e.g., "50% failure strain"

# In General:

Reaction will cause ductile-to-brittle behavior




$\varepsilon_f$ decreases

E increases

$\sigma_f$ increases then decreases

Thus, a limit could be the time required for a 50% reduction in "$\varepsilon_f$"; this is called a "half-life" value and is a good target

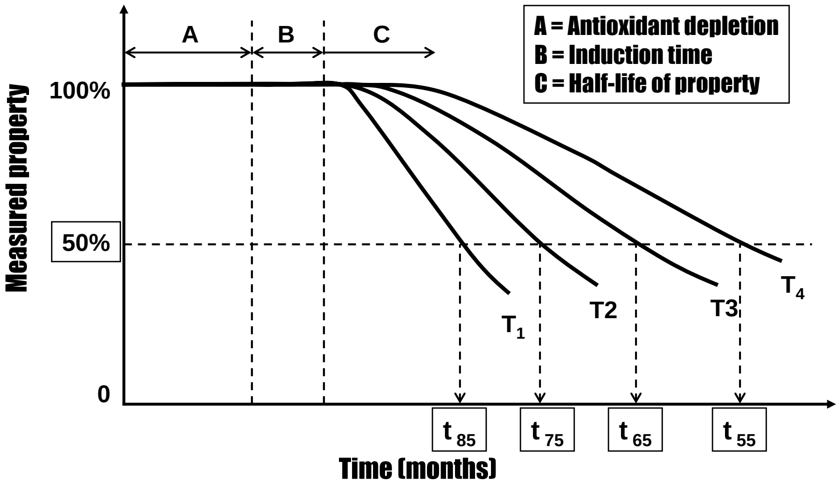
Geosynthetic polymer formulations and lifetime prediction methodology

- Identification comes from resin type
- Yet, all GS are formulations
- Additives are the major uncertainty
- They consist of heat stabilzers (for processing) and antioxidants (for long term durability)
- Some also have CB and fillers
- Additive package is proprietary

# Lifetime Prediction

- Following is common for many materials, including plastics (100's of references)
- Uses time-temperature superposition
- Then plots data on Arrhenius graph for extrapolation down to the site-specific temperature
- 3-stages are defined...

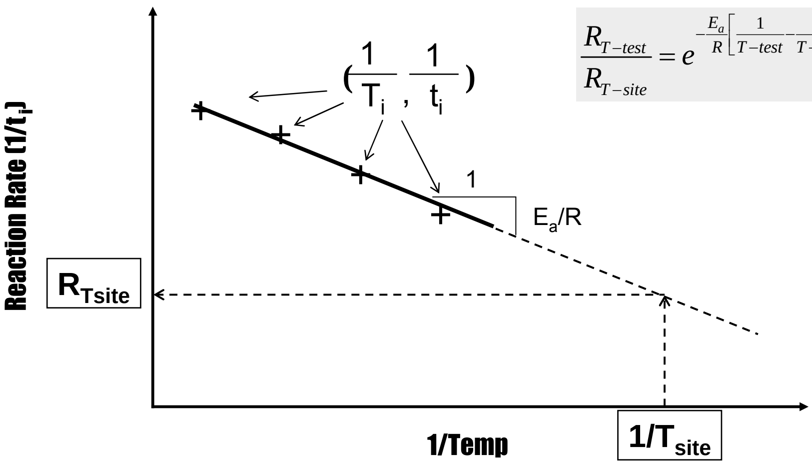
# Incubated Property Behaviour




# Arrhenius Plot for Stage "C" (1/2 Life)

Equation for extrapolation

$$\frac{R_{T-test}}{R_{T-site}} = e^{-\frac{E_a}{R}\left[\frac{1}{T-test} - \frac{1}{T-site}\right]}$$



# In General…

- **Above is for HDPE, LLDPE, and fPP**

**A = Antioxidant depletion (time to deplete the antioxydants by consumption and/or extraction)**
**B = Induction time to the onset of polymer degradation**
**C = Half-life of property (time for degradation of the polymer to decrease some property to 50% of the original value)**

- **For PVC; Stage A is plasticizer migration**

# Oxidative Induction Time

✓ **OIT is the time required for the geomembrane test specimen to be oxidized under a specific pressure and temperature**

✓ **The length of OIT indicates the amount of antioxidants present in the test specimen (i.e. the higher the OIT, the greater the amount of antioxidant)**

**<u>Note:</u> The maximum effective temperature of hindered amines is below 150°C.**

**At 200°C, hindered amine molecules rapidly volatilize from the geomembrane thus losing their apparent effect.**

**As a result, geomembranes with hindered amine antioxidants will exhibit a shorter OIT value than those without.**

| Test | Advantages | Disadvantages |
|---|---|---|
| STD-OIT 200°C, 35kPa ASTM D3895 | • short testing time (~100min.).<br>• standard test apparatus. | • high temperature may bias the test results for certain types of antioxidants. (Ex. hindered amine types of antioxidants) |
| HP-OIT 150°C, 3,500kPa ASTM D5885 | • able to distinguish the stabilization effect of different types of antioxidants in the geomembrane.<br>• lower temperature relates closer to service conditions. | • long testing time(〉 300min.).<br>• special testing cell and set up are required. |

# Service life of Geomembrane

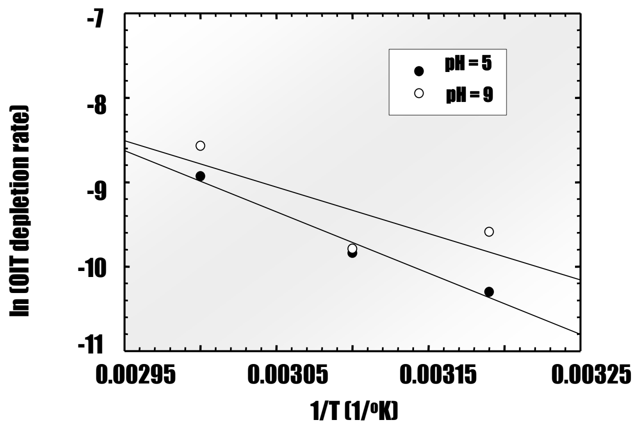
Summary

| Stage | Description | Duration (years) |
|---|---|---|
| A | Antioxidant Depletion | x |
| B | Induction Time | y |
| C | Halflife of Engineering property | z |
| Total | Lifetime Estimate | ~ x+y+z |

Example (Based on results from Sangam & Rowe, 2002)

| | | 25ºC | 15ºC |
|---|---|---|---|
| Temperature: | | 25ºC | 15ºC |
| Exposure medium: Leachate and water, | | A=50 years | 100 years |
| | | B=15 years | 25 years (estimated based on Viebke 1994) |
| | | C=25 years | 25 years (assumed based on Rowe, 1998) |
| | Total: | 90 years | 150 years |

## Arrhenius plot of Std-OIT (Bouazza et al., 2007)

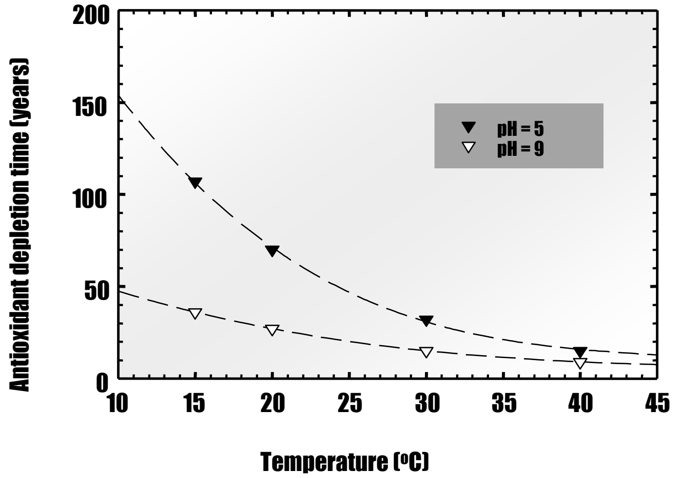



**Arrhenius equation and deduced activation energy**

| Solution pH | Arrhenius Equations | $E_a$ (kJ/mol) | $R^2$ |
|---|---|---|---|
| 5 | ln(s) = 12.306 – 7104 1/T | 59.0 | 0.975 |
| 9 | ln(s) = 6.834 – 5216 1/T | 43.4 | 0.701 |

## Variation of estimated antioxidant depletion time with temperature for geomembrane exposed to mild acidic and alkaline solutions

(Bouazza et al., 2007)



## Geomembrane Lifetime Prediction

- Its all time-temperature superposition
- Followed by Arrhenius plotting
- Governs entire plastics industry
- Focus has been on nonexposed HDPE (it was driven by landfill concerns)

## Exposed Durability and Lifetime

- Degradation mechanisms are the same as nonexposed “plus” ultraviolet and high ambient temperatures
- Both are more severe than other mechanisms
- Experimental approach is completely different
- Laboratory weatherometers are used which impose UV, elevated temperature and moisture

# Thermal Aging

**Forced air oven (@85°C for 90 days)**

**Thermal incubation= simulation of GM exposed to air (1st stage of construction )**

**Oven aging + OIT measurements= info on long term performance of antioxidant package**

→ **durability of the GM**

**Std.-OIT Results of oven aged HDPE geomembrane samples (Bouazza et al. , 2007)**

| Std-OIT (minutes) | | OIT Retention |
|---|---|---|
| Original | Oven aged (90 days) | (%) |
| 163.7 ± 6.0% | 123.7 ± 8.8% | 75.6 |

$$OIT_r = \frac{OIT}{OIT_{org}} \times 100$$ **> 55% (if Std-OIT)**

**GM has enough antioxidants to ensure its long term oxidation stability under field condition**

SI (METRIC UNITS)

**Table 2(b) – 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.)<br>• lowest individual for 8 out of 10 values<br>• lowest individual for any of the 10 values | D 5994 | nom. (-5%)<br>-10%<br>-15% | nom. (-5%)<br>-10%<br>-15% | nom. (-5%)<br>-10%<br>-15% | nom. (-5%)<br>-10%<br>-15% | nom. (-5%)<br>-10%<br>-15% | nom. (-5%)<br>-10%<br>-15% | nom. (-5%)<br>-10%<br>-15% | per roll |
| Asperity Height mils (min. ave.) *(1)* | GM 12 | 0.25 mm | 0.25 mm | 0.25 mm | 0.25 mm | 0.25 mm | 0.25 mm | 0.25 mm | every 2nd roll *(2)* |
| 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 | 90,000 kg |
| Tensile Properties (min. ave.) *(3)*<br>• yield strength<br>• break strength<br>• yield elongation<br>• break elongation | D 6693<br>Type IV | 11 kN/m<br>8 kN/m<br>12%<br>100% | 15 kN/m<br>10 kN/m<br>12%<br>100% | 18 kN/m<br>13 kN/m<br>12%<br>100% | 22 kN/m<br>16 kN/m<br>12%<br>100% | 29 kN/m<br>21 kN/m<br>12%<br>100% | 37 kN/m<br>26 kN/m<br>12%<br>100% | 44 kN/m<br>32 kN/m<br>12%<br>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 | 200N | 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 GM10 |
| 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 | D 5596 | note *(6)* | note *(6)* | note *(6)* | note *(6)* | note *(6)* | note *(6)* | note *(6)* | 20,000 kg |
| Oxidative Induction Time (OIT) (min. ave.) *(7)*<br>(a) Standard OIT<br>— or —<br>(b) High Pressure OIT | D 3895<br>D 5885 | 100 min.<br>400 min. | 100 min.<br>400 min. | 100 min.<br>400 min. | 100 min.<br>400 min. | 100 min.<br>400 min. | 100 min.<br>400 min. | 100 min.<br>400 min. | 90,000 kg |
| Oven Aging at 85°C *(7)*, *(8)*<br>(a) Standard OIT (min. ave.) - % retained after 90 days<br>— or —<br>(b) High Pressure OIT (min. ave.) - % retained after 90 days | D 5721<br>D 3895<br>D 5885 | 55%<br>80% | 55%<br>80% | 55%<br>80% | 55%<br>80% | 55%<br>80% | 55%<br>80% | 55%<br>80% | per each formulation |
| UV Resistance *(9)*<br>(a) Standard OIT (min. ave.)<br>— or —<br>(b) High Pressure OIT (min. ave.) - % retained after 1600 hrs *(11)* | GM11<br>D 3895<br>D 5885 | N.R. *(10)*<br>50% | N.R. *(10)*<br>50% | N.R. *(10)*<br>50% | N.R. *(10)*<br>50% | N.R. *(10)*<br>50% | N.R. *(10)*<br>50% | N.R. *(10)*<br>50% | per each formulation |

*(1)* Of 10 readings; 8 out of 10 must be ≥ 0.18 mm, and lowest individual reading must be ≥ 0.13 mm
*(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 33 mm
Break elongation is calculated using a gage length of 50 mm
*(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 made from 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) for 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.

**SI (METRIC) UNITS**

**Table 1(b) – High Density Polyethylene (HPDE) 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. ave.)<br>• 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.) | 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 | 90,000 kg |
| Tensile Properties *(1)* (min. ave.)<br>• yield strength<br>• break strength<br>• yield elongation<br>• break elongation | D 6693 Type IV | 11 kN/m<br>20kN/m<br>12%<br>700% | 15 kN/m<br>27 kN/m<br>12%<br>700% | 18 kN/m<br>33 kN/m<br>12%<br>700% | 22 kN/m<br>40 kN/m<br>12%<br>700% | 29 kN/m<br>53 kN/m<br>12%<br>700% | 37 kN/m<br>67 kN/m<br>12%<br>700% | 44 kN/m<br>80 kN/m<br>12%<br>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 | D 5596 | note *(4)* | note *(4)* | note *(4)* | note *(4)* | note *(4)* | note *(4)* | note *(4)* | 20,000 kg |
| Oxidative Induction Time (OIT) (min. ave.) *(5)*<br>(a) Standard OIT<br>— or —<br>(b) High Pressure OIT | D 3895<br><br>D 5885 | 100 min.<br><br>400 min. | 100 min.<br><br>400 min. | 100 min.<br><br>400 min. | 100 min.<br><br>400 min. | 100 min.<br><br>400 min. | 100 min.<br><br>400 min. | 100 min.<br><br>400 min. | 90,000 kg |
| Oven Aging at 85°C *(5)*, *(6)*<br>(a) Standard OIT (min. ave.) - % retained after 90 days<br>— or —<br>(b) High Pressure OIT (min. ave.) - % retained after 90 days | D 5721<br>D 3895<br><br>D 5885 | 55%<br><br>80% | 55%<br><br>80% | 55%<br><br>80% | 55%<br><br>80% | 55%<br><br>80% | 55%<br><br>80% | 55%<br><br>80% | per each formulation |
| UV Resistance *(7)*<br>(a) Standard OIT (min. ave.)<br>— or —<br>(b) High Pressure OIT (min. ave.) - % retained after 1600 hrs *(9)* | D 3895<br><br>D 5885 | N. R. *(8)*<br><br>50% | N.R. *(8)*<br><br>50% | N.R. *(8)*<br><br>50% | N.R. *(8)*<br><br>50% | N.R. *(8)*<br><br>50% | N.R. *(8)*<br><br>50% | N.R. *(8)*<br><br>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 50 mm
*(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.
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*(6)* It is also recommended to evaluate samples at 30 and 60 days to compare with the 90 day response.
*(7)* The condition of the test should be 20 hr. UV cycle at 75°C followed by 4 hr. condensation at 60°C.
*(8)* 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.
*(9)* UV resistance is based on percent retained value regardless of the original HP-OIT value.




- **Performance in field is controlled by leakage**
- **Leakage may be due to poor field seams, poor factory seams, pinholes from manufacture, and puncture holes from handling, placement, or in-service loads**

## Potential Sources of puncture

- Construction

  * Accidental (i.e., trucks turning, etc.)

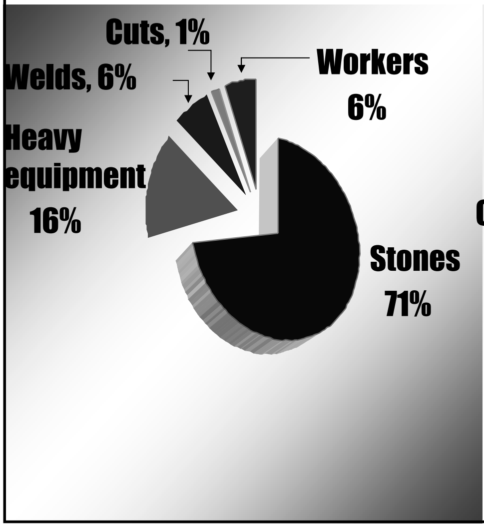
- Operations

  * Penetration of large pieces of contained material (waste), through the drainage/protection layers

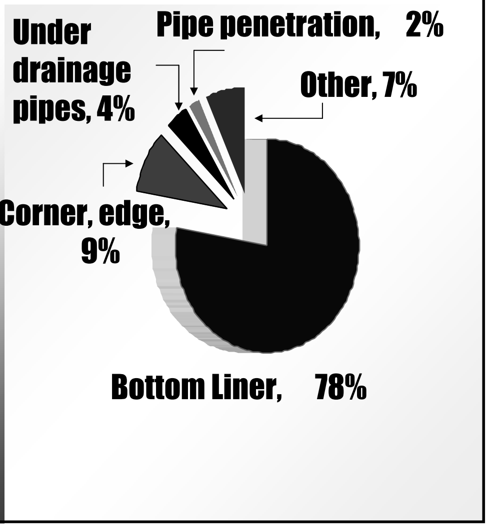
- Materials interaction

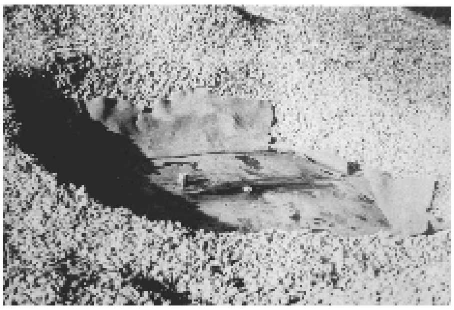
  * Granular material protuberances

**Cause of damage in geomembrane liners (data from Nosko & Touze-Foltz 2000)**




**Location of damage in geomembrane liners (data from Nosko & Touze-Foltz 2000)**






## Construction related puncture

- Cannot be completely avoided

- Considered in design: leak rate (number/surface of holes per $m^2$) proposed based on observations

- Leak design value could potentially be reduced if a construction leak survey is incorporated (after installation of the drainage layer)

## Operation related puncture

- Thickness of drainage layer

- If landfill, selected waste on first fill

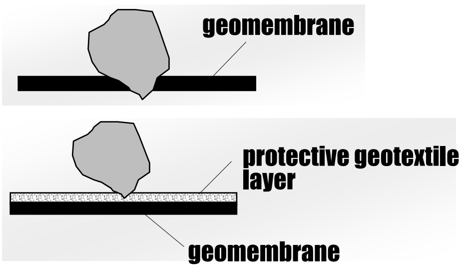
## Material Interaction related puncture

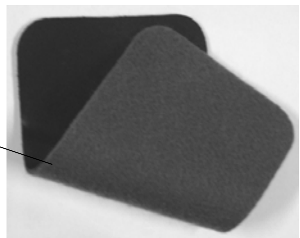
- Influenced by:
  - stress
  - Granular material (drainage layer)
  - Subgrade
  - Nature of the protection layer/cushion

# Problem Remediation

- **Construction:**
  - CQA
- **Operations:**
  - Supervision
- **Materials Interaction:**
  - Consider an appropriate design method

# Geotextiles for geomembrane protection

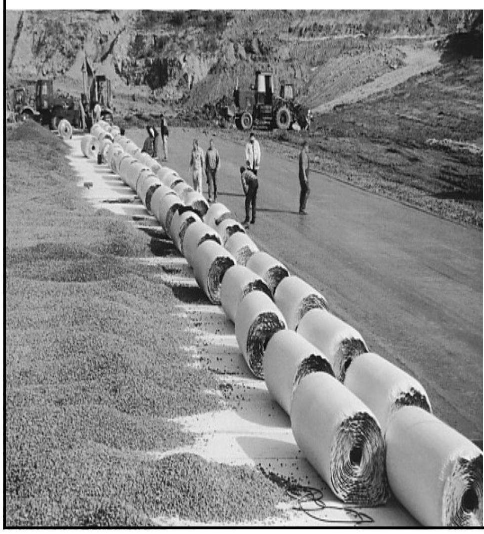


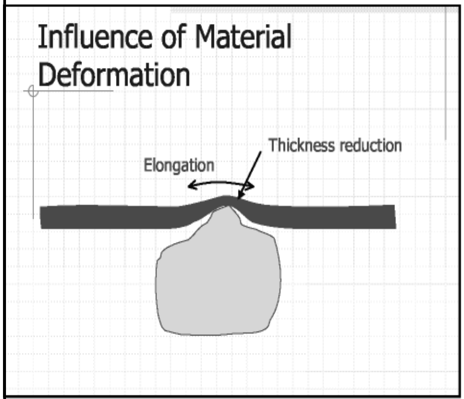
- Geotextiles are used to protect the geomembrane from both mechanical damage and straining under applied loads
- Non-woven geotextiles are commonly used (e.g. needle punched non-woven geotextiles)
- Efficiency of protection is dependent upon: fibre type (e.g. length), fibre quality and manufacturing method (e.g. type and amount of needling)
- The weight of a geotextile should not be used to specify a protection layer

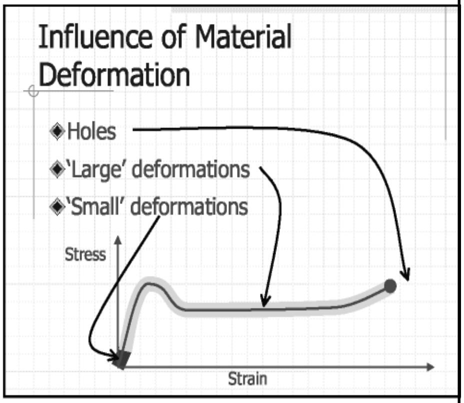
# Gravel Placed on a Geotextile Protection Layer

Sand Filled Geotextile
Mattress Protection Layer



Concrete Filled Geotextile
Mattress Protection Layer




## Influence of Material Deformation

- No leak (no open holes) on a short term basis
- Potential development of leaks on a long term basis
  - Stress cracking
  - Durability reduced locally (less material available/reduced time to complete oxidation of the material)

## Protection Design methods

- Vendor/Manufacturer Design
- Empirical based Design (short term behaviour)
- Experimental based Design (Long term behaviour)

## Vendor/Manufacturer Design

- Use a non woven geotextile needle punched geotextile:
  - X $g/m^2$ for normal conditions
  - Y $g/m^2$ for critical conditions (this one was used on another similar project)
  - Z $g/m^2$ for extremely critical conditions
- On site verification of the geotextile performance with a pit trial:
  - Valid for evaluation of (a few types of) installation damage
  - Long term protection efficiency ignored

Avoid this design

# The other two methods.....

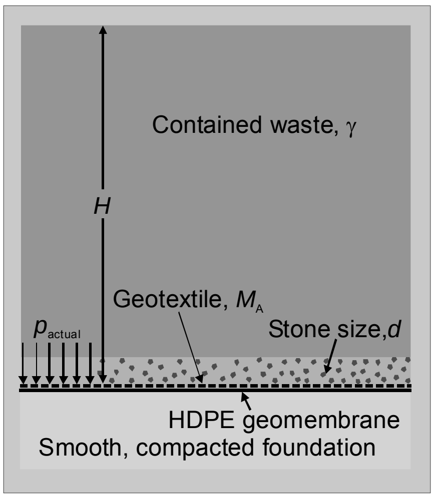
**North American practice**

- Prevention of localised yield stresses in HDPE geomembrane
- More tolerant compared with European approach, consequently:
  - A given geotextile protection is fully mobilised
- Empirical relationship to determine geotextile protection properties
  - But, a large factor of safety is used in the calculation!!

**European practice**

- Prevention of possibility of stress cracking in HDPE geomembrane
- More restrictive compared with North American approach, consequently:
  - A given geotextile does not show the same level of protection
  - Results in heavier protection layers
- Based on laboratory test that gives a pass/fail result

# Model used to analyse geotextile protection for geomembrane liner




- Both North American and European practice utilise the same analysis model
- The weight of the contained waste exerts localised stresses on the base geomembrane liner through the stone in the base drainage layer
- The presence of the geotextile protection of a specific mass per unit area provides the required protection to the geomembrane liner

# North American approach – use of an empirical relationship

$$p'_{allow} = FS \times p_{applied}$$

$$p'_{allow} = \frac{M_{Areqd} \times 450}{H^2 \times MF_S \times MF_{PD} \times MF_A \times FS_{CR} \times FS_{CBD}}$$

- $M_{Areqd}$: Mass per unit area of protection geotextile
- $FS_{CR}$: Partial FS for creep
- $FS_{CBD}$: Partial FS degradation
- $H$: Effective stone height (0.5 of max size of the gravel)
- $MF_S$: Modification factor for protrusion shape
- $MF_{PD}$: Modification factor for packing density
- $MF_A$: Modification factor for soil arching

Geotextiles selection (Narejo et al., 1996)

## Modification and safety factors as recommended by (Narejo et al., 1996) & Koerner et al. (1996)

| Factor | Value |
|---|---|
| Particle shape, $MF_S$ | |
| Angular | 1.0 |
| Subrounded | 0.5 |
| Rounded | 0.25 |
| Packing density, $MF_{PD}$ | |
| Isolated protrusions | 1.0 |
| Packed gravel | 0.5 |
| Soil Arching, $MF_A$ | |
| None | 1.0 |
| Moderate | 0.75 |
| Maximum | 0.5 |
| Creep, $FS_{CR}$ | |
| $M_A = 270\ g/m^2$ | 1.5[a], >1.5[b] |
| $M_A = 550\ g/m^2$ | 1.2[a], 1.3[b], 1.5[c] |
| $M_A = 1100\ g/m^2$ | 1.0[a], 1.1[b], 1.2[c], 1.3[d] |
| $M_A > 1100\ g/m^2$ | 1.0[b], 1.1[c], 1.2[d] |
| Degradation, $FS_{CBD}$ | 1.5 |
| Global factor safety, FS | minimum recommended values (GM thickness=1.5mm) |
| Isolated protrusions | 3[a], 4.5[b], 7[c], 10[d] |
| Packed gravel (Hp ≤38 mm) | 3 |

[a,b,c,d] Protrusion height, $H_p$ = 6,12,25,38 mm, respectively.

**Example:**

**The base of a landfill is lined with a 1.5 mm HDPE geomembrane, the applied pressure acting above the geomembrane is equal to 130 kPa. A drainage layer consisting of angular gravel is to be placed on top of the geomembrane. The maximum particle size of the overlying gravel is 76 mm, thus giving an effective protrusion height of $H_p$ = 38 mm** (Max part. size= 2 x effective protrusion height).

**From previous table $M_{FS}$ = 1 mm for angular particles, $M_{FPD}$ = 0.5 with packed gravel (as opposed to isolated protrusions), $M_{FA}$ =1 since there will be no reduction from arching, $FS_{CR}$ = 1.3 and $FS_{CBD}$ =1.5 would require a NWGT with $M_A$= 850 g/m$^2$ to provide a factor of safety of 3. However, Narejo et al. (1996) recommended that GT no lighter than 1100 g/m$^2$ be used where $H_p$ is 38 mm.**

# Protection Tests: Mechanical Damage

- Tests to assess the ability of materials to protect against mechanical damage (short-term loading) include the following index tests:
  - Resistance to static puncture
  - Pyramid puncture
  - Dynamic puncture test
  - Impact resistance

# Protection Test

- Truncated cone test ASTM 5514
- Three truncated cones mount out of a sand subgrade over which a protection geotextile and geomembrane is placed and additionally covered with sand.
- The pressure vessel is then loaded with a hydrostatic water pressure at a rate of 7 kPa per minute.
- Once the geomembrane is punctured water penetrates through the geomembrane and activates two electrically conducting probes.
- The time and pressure can be obtained with this index test.

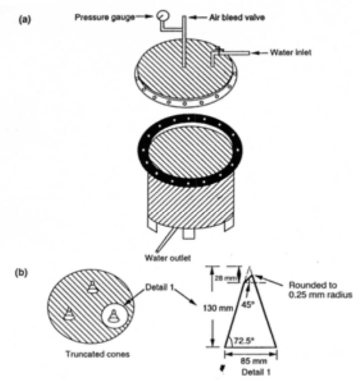



Figure 1. Details of the hydrostatic pressure truncated cone puncture test: (a) pressure vessel for the truncated cone and pyramid puncture tests; (b) protrusions for the truncated cone puncture test.

# Truncated cone test ASTM 5514

**Maximum pressure on a 1.5mm thick HDPE geomembrane protected with a nonwoven needle-punched geotextile (for packed stone), Koerner et al, 1996, "Puncture Protection of Geomembranes, Part 3, Examples", Geosynthetics International, Vol3.**

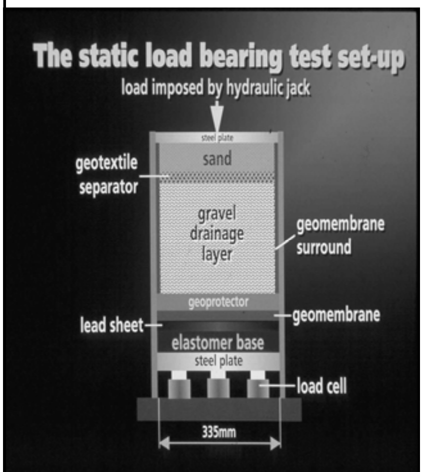
| max. stone size (mm) | Geotextile mass per unit area ($g/m^2$) | Maximum pressure (height of solid waste in metres) (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | No arching | | | Moderate Arching | | | Maximum Arching | | |
| | | Angular stone | Subrnd stone | Rounded stone | Angular stone | Subrnd stone | Rounded stone | Angular stone | Subrnd stone | Rounded stone |
| 3 | 270 | 84 | 170 | 340 | 112 | 226 | 454 | 168 | 340 | 680 |
| | 550 | 216 | 432 | 862 | 288 | 576 | 1150 | 432 | 864 | 1724 |
| 6 | 270 | 21 | 42 | 84 | 28 | 56 | 112 | 42 | 84 | 168 |
| | 550 | 50 | 100 | 200 | 67 | 133 | 267 | 100 | 200 | 400 |
| | 1100 | 118 | 236 | 472 | 157 | 315 | 420 | 236 | 472 | 944 |
| 12.5 | 550 | 10 | 20 | 40 | 13 | 27 | 53 | 20 | 40 | 80 |
| | 1100 | 25 | 50 | 100 | 33 | 67 | 133 | 50 | 100 | 200 |
| | 2200 | 54 | 108 | 216 | 72 | 144 | 288 | 108 | 216 | 432 |
| 19 | 1100 | 10 | 20 | 40 | 13 | 27 | 53 | 20 | 40 | 80 |
| | 2200 | 22 | 44 | 88 | 29 | 59 | 117 | 44 | 88 | 176 |

Note: *Maximum stone size = 2 x effective protrusion heigth. Unit weight of solid waste = 11.8 $kN/m^3$.

## Protection Tests: Long-term Loading

- Protection efficiency for geomembranes under long-term loading, and hence straining that could result in stress cracking, can be assessed using a compression test. Performance type tests can be conducted using site specific geosynthetic and mineral materials.
- The full test entails subjecting the geomembrane, protection layer, gravel layer system to the design load for 1000 hours at a temperature of 40°C
- A layer of rubber is used to simulate a compacted clay layer beneath the geomembrane

## Experimental based design method: pass/fail method

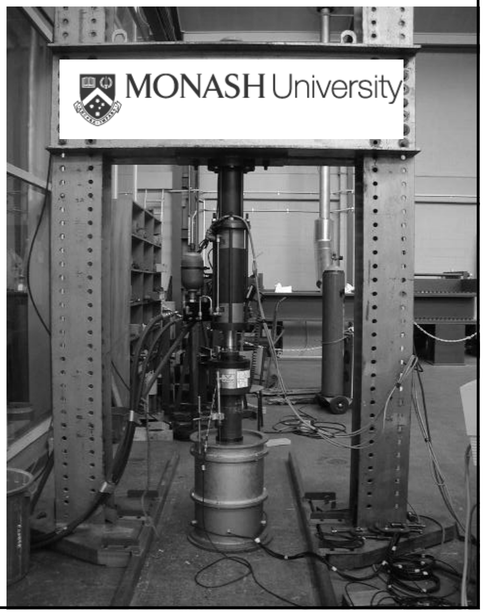



| Temperature | Duration of load |
|---|---|
| 40°C | 1000 hrs, 1.5 x design load |
| 23°C | 1000 hrs, 2.25 x design load |
| 23°C | 100 hrs, 2.5 x design load |

Pass: local strains in soft metal sheet less than 0.25%

+ No damage to GM upper surface (cracks or nicks), no sharp angled deformation

# Compression Test Set Up




**German geotextile recommendations according to compression test method based on the use of gravel (16 - 32 mm)**

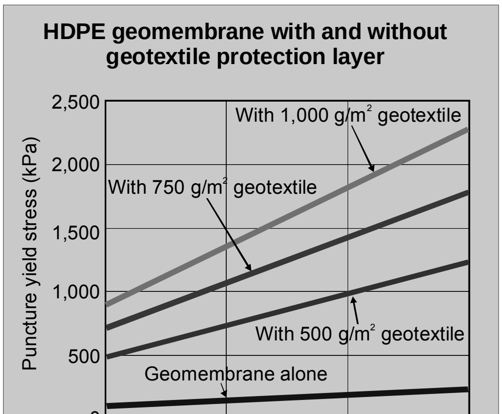
| Waste height (m) | Geosynthetic | $M_A$ (g/m²)_ |
|---|---|---|
| 0 ≤ h ≤2 | Nonwoven GT | 600 |
| 2 ≤ h ≤ 10 | Nonwoven GT | 1800 |
| 10 ≤ h ≤ 25 | Composite material consisting of nonwoven/woven GT | 3000<br><br>4200 |
| 2 ≤ h ≤ 10<br>H > 25 | GCLComposite material to be filled on site with mineral material | >52,000 |

# Summary of approach to geotextile protection for geomembranes

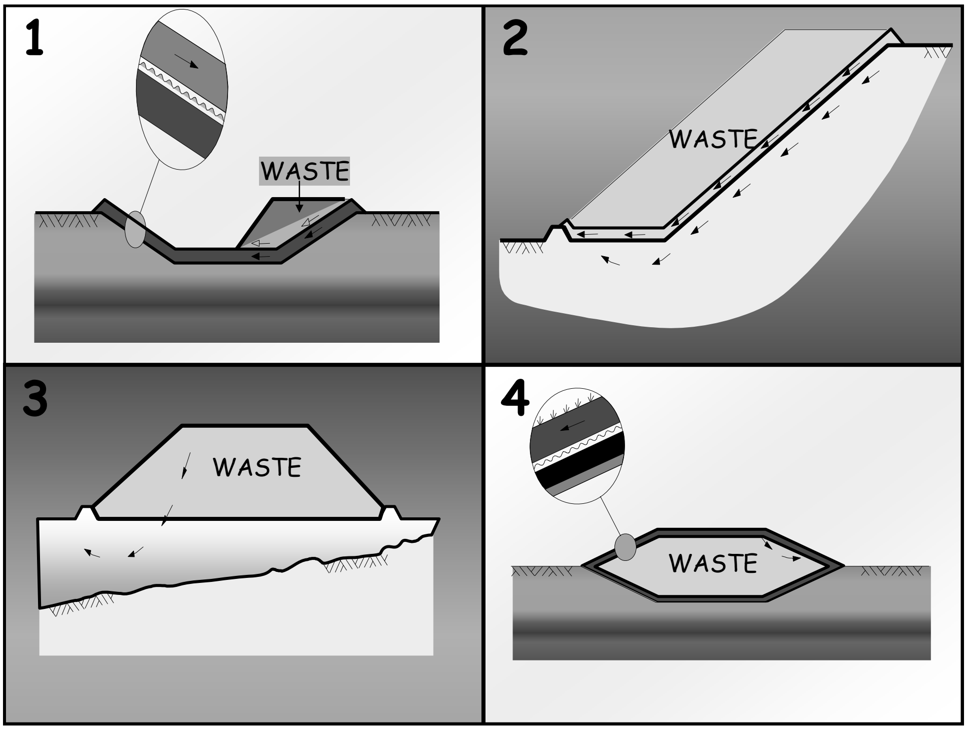
- ***North American practice:***
  - Limiting localised yield strain in HDPE geomembrane (does not limit deformation)
  - Based on empirical relationship
  - Loading and stone size according to application
  - Temperature and time accounted for by factors
  - Large overall safety factor used
  - Nonwoven geotextiles with $M_A \geq 500$ $g/m^2$ used
  - Approach seeks to prevent short term puncture of GM & aims to prevent local elongation past the yield point

- ***European practice:***
  - Limiting localised strain to 0.25% in HDPE geomembrane and 3% maximum global strain
  - Based on pass/fail laboratory test
  - Stone size according to application
  - Standardised temperature and time
  - Load varies according to application
  - Nonwoven geotextiles with $M_A \geq$ 1,000 $g/m^2$ used
  - Approach seeks to ensure the GM long term performance & limit the development of local strains within the GM due to a combination of pressures

# Effect of geotextile protection on geomembrane liners




- The major geotextile protection performance parameter is mass per unit area, with puncture resistance being important for comparison within the same mode of geotextile manufacture
- Two approaches to geotextile protection:
  - *North American:* Protection layer limits local deformations in HDPE geomembrane to prevent localised yield stresses from developing
  - *European:* Protection layer limits local deformations in HDPE geomembrane to prevent possibility of environmental stress cracking (ESC)




## Kettleman Hills (California, USA) landfill failure

- Hazardous waste landfill
- Slope Height = 27 m
- Bowl-shaped volume
- Side slopes – 2H:1V (26º) to 3H:1V (18.5º)
- Waste placement began in 1987
- Failure occurred on March 1988
- 0.5 m avg. leachate level in LCS


Kettleman Hills Landfill
N
Waste


Kettleman Hills (California, USA) landfill failure
Waste mass slid 10.5 m horizontally & slumped
4.2m vertically


## Frictional Properties

- The interaction between geosynthetics and between geosynthetics and soil is fundamental to the stability of landfill lining systems
- Information is required on the frictional strength on the interface between all materials that could comprise a lining system (e.g. compacted clay, geomembrane, GCL, geotextile, geogrid and granular soil)
- Interface shear strength is measured using:
  - Direct shear
  - Inclined plane

## Potential Interfaces for sliding

- Sliding will occur along weakest interface (s) !!!!

  GM-CCL, GM-GCL

  Internal shear in GCL

  GM-granular soil, GM-geonet, GM-GTX

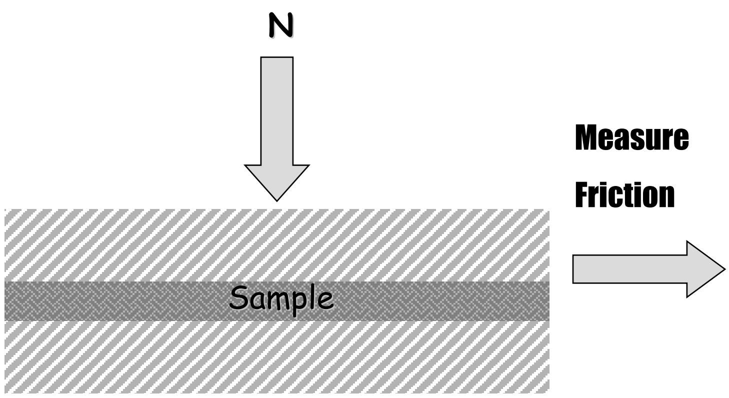
- TESTING REQUIRED

  - Shear strength of every interface (both peak and residual)

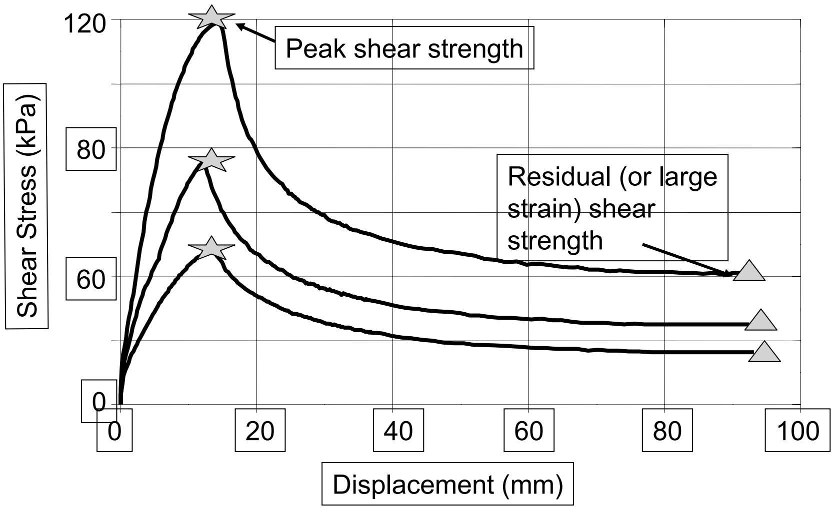
  - Wide width tensile strength of every geosynthetic

## Laboratory Testing

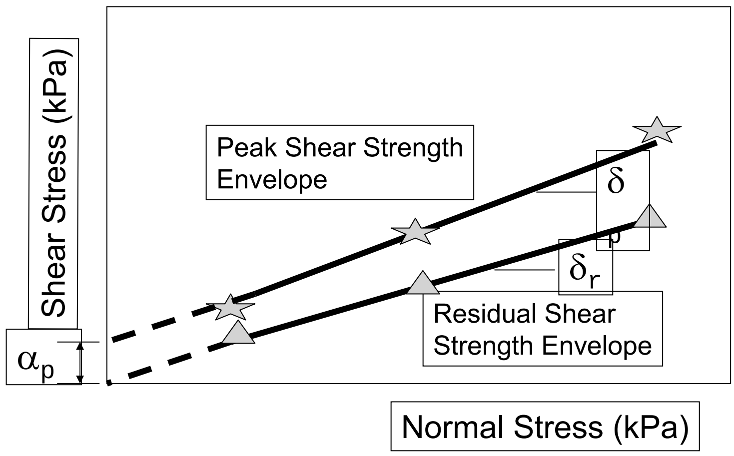
- Direct shear box, large scale direct shear box, Tilt table, Torsional ring shear device



## Measurement of Peak and Residual Shear Strength




## Calculation of Shear Strength Parameters



## Recommendations for evaluating interface strength

- Perform site specific shear testing at representative normal stresses for interface of concern.
- Use a shear rate that is representative of field conditions (slower apparently more conservative)
- Displace interfaces far enough to obtain large displacement or residual behaviour.

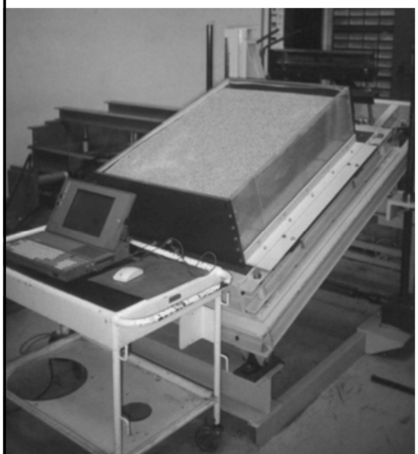
- If soil involved (i.e.CCL): Prepare soil samples to representative moisture contents and densities (and account for variability in field).
- Perform both undrained (rapid) and drained (slow) tests on interfaces with clay to identify critical conditon
- Consider ALL possible failure surfaces

**BE WARY OF EXISTING DATA**

## Key Factors Influencing Measured Strengths

- ✓ Design of direct shear device….
- ✓ Test set up (e.g. method of clamping/restraining the geosynthetic, gap size between top and bottom boxes, dry or submerged conditions, material in top box used to transmit normal stress to interface, shearing rate, temperature, normal stress range….)
- ✓ Variability of materials, direction of shearing, number of tests….
- ✓ SOIL MECHANICS ! (density, maximum particle size, consolidation, drained or undrained shearing, pore water pressures, volume changes….)

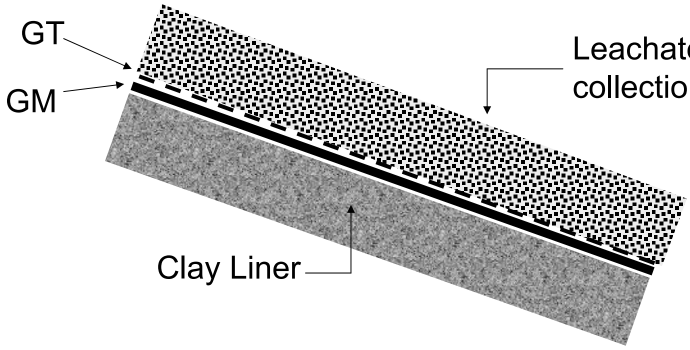
## Inclined Plane Test



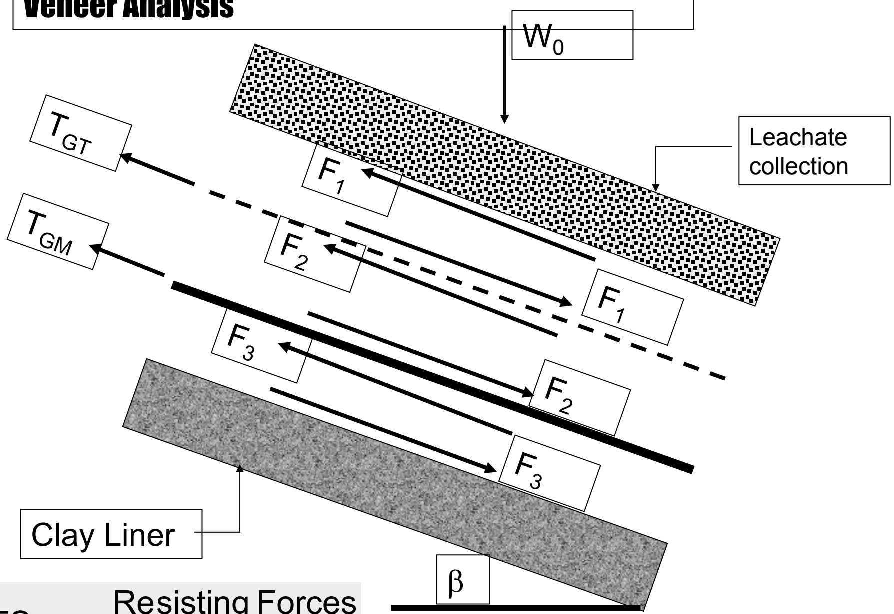
- ✓Used for tests at low normal stresses (i.e. applicable to capping systems and basal systems during construction)
- ✓Stress controlled test, hence it can be used to assess creep

## Interfaces and Stability

**Geomembranes and Geotextiles tend to introduce slippery interfaces into lining systems. These interfaces require local and global stability analysis. A local veneer analysis is provided here.**




## Veneer Analysis




$$FS_{\substack{along\\slope}} = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

**$W_o$ = weight of overburden (waste, etc.)**

**$W_L$ = weight of LCS**

**$\delta_{a\text{-}b}$ = interface friction angle between materials a and b.**

**T = tension in a geosynthetic layer.**

Geotextile:

$$F_1 = \min \begin{bmatrix} (W_o + W_L)\sin\beta \\ (W_o + W_L)\cos\beta \tan\delta_{LCS-GT} \end{bmatrix}$$

$$F_2 = \min \begin{bmatrix} F_1 \\ (W_o + W_L)\cos\beta \tan\delta_{GT-GM} \end{bmatrix}$$

$$T_{GT} = F_1 - F_2$$

**Geomembrane:**

$$F_3 = \min \begin{bmatrix} F_2 \\ (W_o + W_L)\cos\beta \tan\delta_{GM-Clay} \end{bmatrix}$$

**Or, if undrained strength of geomembrane-clay interface ($S_{gm\text{-}clay}$) is provided rather than $\delta_{GM\text{-}clay}$**

$$F_3 = \min \begin{bmatrix} F_2 \\ S_{gm-clay} L_s \end{bmatrix}$$

where $L_s$ is the length of the slope.

$$T_{GM} = F_2 - F_3$$

**Check strength of geosynthetics:**

$$T_{GT} \leq \frac{T_{w,GT}}{FS}$$

$$T_{GM} \leq \frac{T_{w,GM}}{FS}$$

**where $T_w$ is the wide-strip tensile strength of the geosynthetics and FS is a factor of safety (2-5).**