Assessment of Maximum Allowable Strains In Polyethylene and Polypropylene Geomembranes

Ian D. Peggs[1], Bruce Schmucker[2] and Peter Carey[3]

[1]I-CORP INTERNATIONAL, Inc., 6072 N. Ocean Blvd., Ocean Ridge, FL 33435; PH (561) 369- 0795; FAX (561) 369-0895; email: icorp@geosynthetic.com
[2]EMCON/OWT Solid Waste Services, 11499 Chester Road, Cincinnati, OH 45246-4012; PH (513) 782-4700; FAX (513) 782-4807; email: bruce.schmucker@shawagrp.com
[3]P.J. Carey & Associates, 5878 Valine Way, Sugar Hill, CA 30518; PH (678) 482-5193; FAX (678) 482-5827

Abstract

Geomembranes used in separation liners between old and new waste in vertical expansions of landfills may be subject to differential settlement strains. Therefore, it is important to define a maximum allowable strain (MAS) that any given geomembrane can tolerate without compromising its required service life. In a number of instances some very low values have been proposed – as low as 0.25% and 1.0%for high density polyethylene (HDPE). Such low numbers are probably based on German regulations for HDPE landfill liners that require a maximum allowable global strain of 3% and a limiting local strain due, for example, to protruding drainage stones, of 0.25%. The low allowable strain values adopted by the German regulators have been based on products and practices utilized in the 1980's and do not reflect current conditions, nor do they address membranes other than HDPE. In this paper we present the background and reasoning for updating MAS values.

Introduction

The maximum allowable strain (MAS) in landfill lining systems has become of major importance with the increasing interest in vertical expansion. Landfill liner specifications and regulations have been based on the use of HDPE geomembranes. In other words "HDPE" is synonymous with "geomembrane". This is not a logical situation, since materials such as LLDPE and PP, although of the same polyolefin plastic family as HDPE, have very different mechanical properties that can be used to advantage in a number of applications. Therefore, they are viable candidate geomembrane materials that should be treated quite differently to HDPE.

The major reason for this difference in performance is that HDPE has a semi-crystalline microstructure that makes it susceptible to stress cracking (SC). No other common geomembrane is susceptible to SC in its as-manufactured condition. Hence the reason for limiting geomembrane strains in HDPE geomembranes. However, recent attempts to limit general strains to 0.25% and 1.0% (whatever the geomembrane material) are too restrictive and cannot be justified on a technical basis.

HDPE Mechanical Properties

The chemical resistance and high strength properties that make HDPE so appropriate as a bottom liner are a consequence of its semicrystalline microstructure. Most HDPEs are about 55% crystalline and 45% amorphous. In comparison PP is about 10% crystalline and LLDPE is about 5% crystalline. These different microstructures result in very different short term and long term mechanical performance characteristics. The reasons for the short term differences are most clearly shown in the uniaxial stress-strain curves as shown in Figure 1. HDPE has a unique point of instability – the yield point – which occurs at about 12% strain and at which the tensile specimen thins down locally and elongates like gum. For design purposes HDPE should be, and usually is, considered to have failed at the yield point.

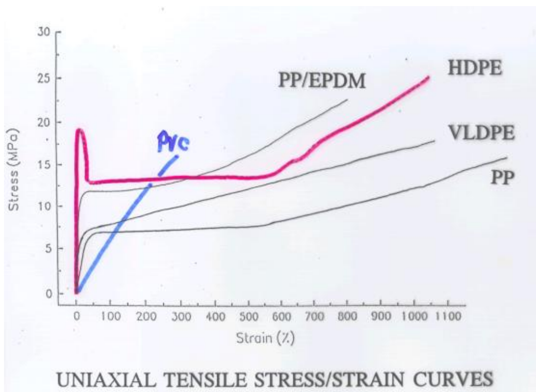

Figure 1. Uniaxial tensile stress strain curves

In comparison the uniaxial stress/strain curves for VLDPE (similar to lower density LLDPEs), PVC, and PP do not have the distinct yield point that HDPE has, so they can be considered far more stable materials. Even so, except for PVC, they do show rapidly increasing strain as stress increases above the steeper predominantly elastic region of the curve.

Multiaxial tensile properties

However, the uniaxial stress/strain curves can rarely be used for geomembrane design purposes since uniaxial stressing situations do not occur in the field. An installed geomembrane when predominantly stressed in one direction cannot elongate by drawing material from a direction perpendicular to the applied stress since that material is effectively anchored somewhere. These are typically plane strain conditions. To reproduce these conditions in the laboratory axisymmetric or multiaxial stress strain curves are generated by hydrostatically deforming large circular specimens of geomembrane clamped uniformly around the edges, thereby making the strain in the specimen uniform in all directions in the plane of the material. Figure 2 shows typically how the strains at break of several different materials are quite different, with HDPE showing the least amount of strain (typically about 30%) and PP the highest. Koch (1987), working on both HDPE pipe and geomembrane, found that biaxial strain amounted to about 25% before the first signs of yielding leading to failure were noted.

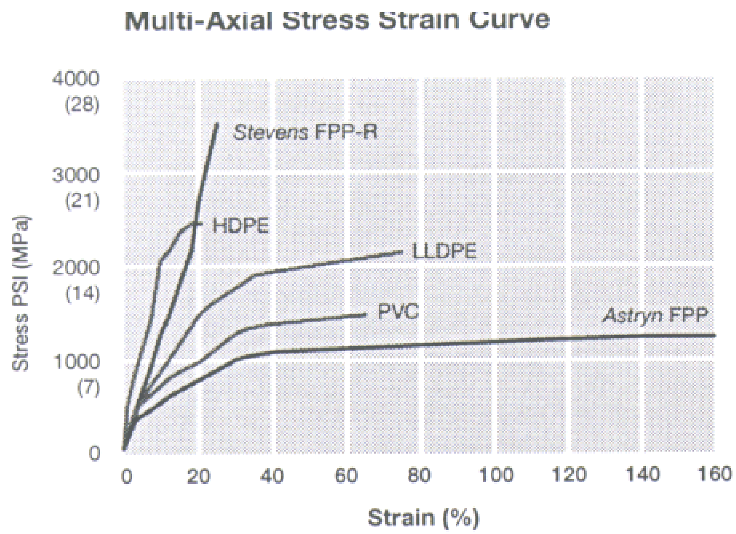

Figure 2. Typical multiaxial tensile stress/strain curves

Stress Cracking Resistance

The most significant difference between the materials is the susceptibility to SC demonstrated by HDPE but not by the other materials. This is a consequence of the semicrystalline microstructure that gives HDPE its high strength and broad chemical resistance. The stress cracking resistance (SCR) is not identical in all HDPE geomembranes. It is a function of the HDPE resin used, the molecular weight, the molecular weight distribution, and comonomer used to give each manufacturer's HDPE product the desired mechanical durability.

SC, often erroneously referred to as environmental stress cracking, is a brittle fracture that occurs under a constant stress less than the yield stress or break stress of the material. It is a fundamental property of all HDPEs. Environmental stress cracking is an acceleration of the fundamental SC phenomenon that occurs in chemical environments such as detergents, oxidizing acids, and chlorinated solvents.

In 1992 Hsuan et al. took five field samples of commercially available HDPE geomembranes and measured their SCRs according to the new (then) GRI.GM5 notched constant tensile load test. In this test different weights are added to a dogbone-type specimen in a surface-active agent at an elevated temperature (50ºC) in order to accelerate the break time. Times to break are monitored. To generate the plane strain conditions of the field, the condition necessary to generate a SC type of break, a notch (razor cut) is placed across one face of the specimen. The depth of the notch is 20% of the thickness of the geomembrane. Plane strain conditions occur at the bottom of the notch. Thus instead of performing a uniaxial tensile test or a creep test, a plane strain stress cracking test is performed. Figure 3 shows the test results.

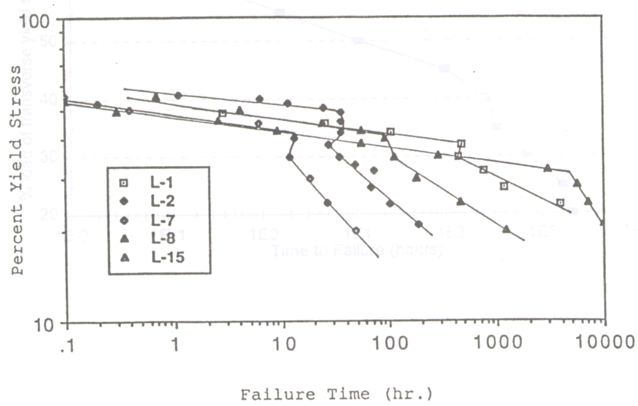

Figure 3. Stress rupture curves on five commercially available geomembranes.

At the higher loads (stresses) breaks occurred in a ductile mode to generate the shallow slope segment of the curve. However, at some critical lower stress, the curve became steeper and breaks occurred without any initial ductility – this is the stress cracking region. Thus the expected long lifetime at lower stress obtained by extrapolating the shallow segment of the curve is cut very short. It is this stress cracking phenomenon that we are trying to avoid by limiting stress, therefore strain, and also by using resins with high SCR. The SCR of the specific geomembrane is represented by the time at which the change in slope (the knee) of the curve occurs. In Figure 4 this knee occurs at times between 10 hr and 5000 hr. There are almost three orders of magnitude difference in the SCRs of the five different geomembranes.

Since then the test has been simplified for QC and QA conformance testing by applying a single stress of 30% of the room temperature yield stress (which will cause a stress cracking break) and requiring break time to exceed 200 hr, recently increased to 300 hr. There are now very few HDPE geomembranes that have SCR times less than about 500 hr and some that have times in excess of 10,000 hr.

SC is also accelerated at any given stress as temperature increases, as shown in Figure 4.

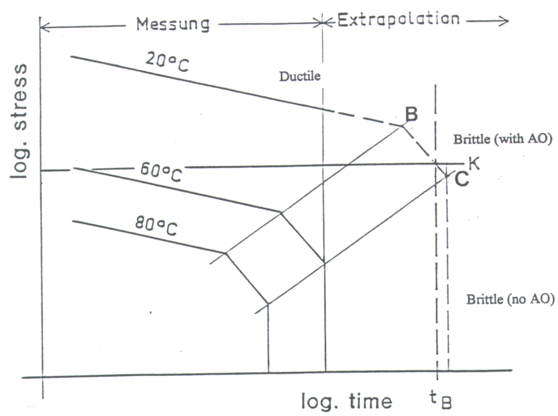

Figure 4. Stress rupture curves as a function of temperature.

It was this susceptibility to stress cracking that prompted German regulators to limit the strains to which HDPE geomembranes could be subjected. This was driven by the need to prevent damaging puncture stresses by drainage stones, and therefore to define the type of test required to assess the protection capabilities of geotextiles and other protection systems. It is important to note the differences between the German and US approaches to geomembrane protection as it affects the limiting strain. The Germans were concerned about a deformation in the geomembrane causing premature failure of the geomembrane by stress cracking some time in the future. The US approach is to assess puncture protection by determining whether complete geomembrane penetration occurs at the time of the test. Hence the German emphasis is on limiting strain, a concern that has not appeared until recently in the US.

Allowable Strain

The Germans took two approaches to arrive at a limiting strain. Initially, in 1990, three meetings were held between interested parties calling themselves the "Quo Vadis" group. They identified (Naue Fasertechnik, 1992) the basis of the test method and arbitrarily defined the limiting multiaxial strain at puncture protrusions (not complete penetrations) to be 0.25%. However for a more general strain allowance a maximum of 3% was defined. According to Jones et al. (1998), the Quo Vadis group felt that 6% total strain was the maximum allowable strain for a "satisfactory lifetime performance", which, when applying a safety factor of 2.0 became 3% allowable strain. The reason for the initial selection of 6% strain is not known, but it is comparable to a maximum strain of 5% recommended by Janson (1981) for long term performance of buried HDPE pipe. However, Jones et al. (1998) state:

> *" Clearly more research is required to establish a more rigorous scientific basis for defining this threshold"*

That this threshold is too pessimistic (too low) is also expressed by Sehrbrock (2002), a member of the original Quo Vadis group, where he states that many members of the group felt that the 3% maximum should be reserved only for settlement of the subgrade. This implies that 3 % should be allowed for differential settlement on top of a more global strain that might occur in the geomembrane.

Sehrbrock (2002) confirms that the 0.25% local strain was a compromise, simply because zero strain (their obvious target) was impossible to measure and confirm. It would also be impractical to achieve zero strain in the field.

The second approach to these limiting strains is described by Seeger and Müller (1996) of the Federal institute of Materials Research and Testing (the BAM Institute – Germany's landfill liner regulatory agency). They also identify a maximum global strain of 3% upon which a maximum additional local strain of 0.25% is allowed due to such things as protrusions by individual drainage stones. This approach is based on the excellent work done at Hoechst Aktiengesellschaft in Germany in the early 1980s on the durability testing of HDPE pipes. Koch at al. (1988) generated creep resistance (stress rupture) curves for pipes at different temperatures and internal pressures (hoop stresses) as shown in Figure 5. These curves are similar to those in Figure 3 subsequently obtained by Hsuan et al. (1992) for geomembranes.

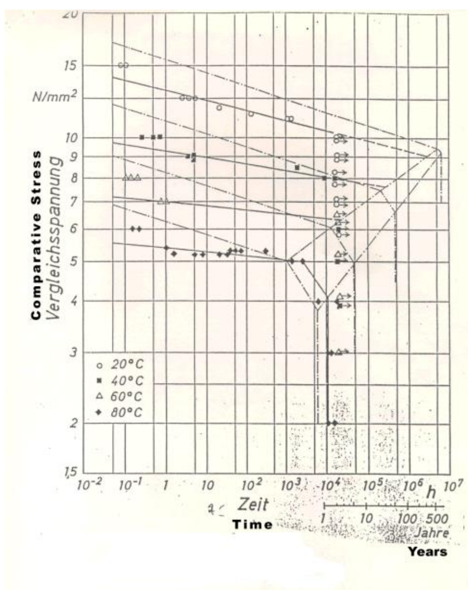

Figure 5. Creep rupture curves for two HDPE pipes made with different resins (Koch et al.)

Unlike in the pipe pressure test and in the notched constant tensile load test where the applied pressure/load is constant with time, Seeger and Müller (1996) recognized that the stress imposed on a confined geomembrane in a lining system would relax with time. Koch et al. show in Figure 6 that the stress relaxation rate is independent of initial strain between 1 and 6% strain and that the maximum stress is a function of initial strain rate; the slower the applied strain the lower the maximum stress achieved – see curves 2a, 2b, and 2c. This will be the situation in the separation liner of the a vertical expansion, where the strain, and consequently the stress, will build up slowly with time. The stress will not build to the same high level it would have done had the strain been rapidly applied. Recollect that it is the induced stress resulting from the strain, not the strain itself, that defines the material durability. Also note that Koch et al.'s (1988) stress relaxation work was done using uniaxially-stressed specimens. Stress relaxation and uniaxial/biaxial stress factors will be reviewed later.

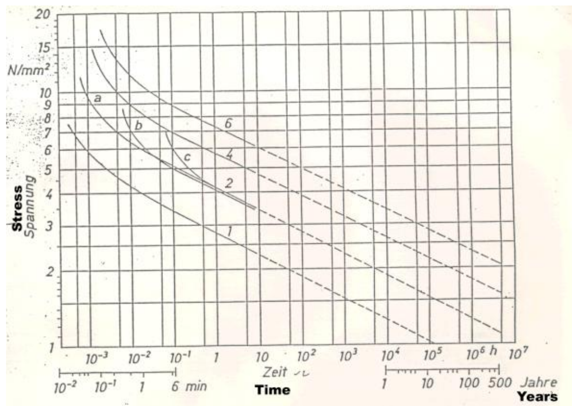

Figure 6. Stress relaxation curves at 1, 2, 4 and 6% strain (Koch et al. 1988)

Figure 7 shows simply the stress at which the stress relaxation history of a specimen initially rapidly strained to 3% strain and maintained at 40°C intersects the steep (SC) segment of the 40°C stress rupture curve for a service lifetime time of 50 years. It intersects the 20°C stress rupture curve at well over 100 yr. This was felt conservatively to be adequate performance, so 3 % was selected as the MAS in the geomembrane as being that strain that would generate a maximum allowable stress for adequate long term performance. However, note that this stress relaxation test was most likely performed by quickly ramping up the pressure/load to achieve the 3% strain, with no allowance for stress relaxation had the pressure/load been applied slowly.

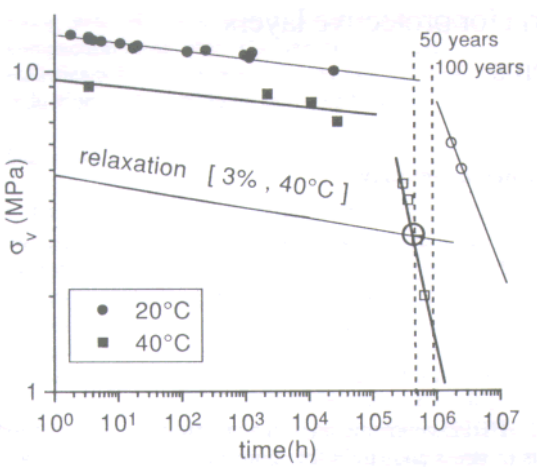

Figure 7. Pipe creep rupture and stress relaxation data (Seeger and Müller 1988)

In Germany 16 to 32 mm drainage stone is used over the geomembrane. It was recognized that individual stones could cause a local puncturing deformation in the top surface of the geomembrane and this would result in bending strains on the lower surface. While this might not result in immediate puncturing there was concern that the stress cracking susceptibility of HDPE might result in premature failure during service from the imposed stresses. In essence, with the minimum specified HDPE thickness of 2.5 mm, a 3% bending strain on the underside of the geomembrane is generated by an indentation that imposes an arch strain in the top surface (due to the indenting stone) of about 0.25%. Hence protection systems were required that would limit the localized multiaxial strain due to a stone indentation to 0.25%.

Thus, a very local strain of 0.25% is not to be exceeded while a global strain of 3% is also not to be exceeded. However, there are a few ameliorating factors that must be taken into account to properly assess the practical performance of a separation geomembrane used in vertical expansions. The two most significant factors are the stress relaxation performance of the geomembrane and the major improvements in the SCR of HDPE geomembranes that have been made since these allowable strains were developed in the mid 1980s. And it is also important to recognize the wide range of SCR values that exist in the different commercially available HDPEs.

As previously described the GRI.GM13 SCR specification for HDPE geomembranes is now a minimum of 300 hr. Until recently many of the European resins on which the 0.25% and 3% allowable strains were based could not meet this specification (as experienced by Peggs, Thomas (TRI/USA), and Jones (Golder/UK in proprietary research and CQA projects), so the US resins have been basically more mechanically durable than the European resins, therefore being able to tolerate higher strains and the consequent stresses. Therefore, Sehrbrock's (2002) statement that 3% general strain is too conservative, particularly for US HDPE resins, is justified.

Stress Relaxation

While the benefits of stress relaxation are apparent it is not a topic that has been thoroughly studied for geomembranes. Soong et al. (1994) investigated stress relaxation in a 1.5 mm thick HDPE geomembrane with initial stresses of 40, 50, and 60% of yield stress (at test temperature) and initial strains of 1, 3, and 5%, at temperatures between –10 and 70^{o}C. These were quasi-biaxial tensile tests using 4 in. (100 mm) wide by 2 in. (50 mm) gage length "wide width" tensile specimens. Initial loading was done quickly to minimize stress relaxation on loading. Whatever the starting conditions, there was a trend to a very narrow range of final, but still significant stresses, after about 100 days. The relaxation modulus curves (stress/strain as a function of time) for a given starting condition could be superimposed into a master curve for a given relaxation temperature, as shown in Figure 8.

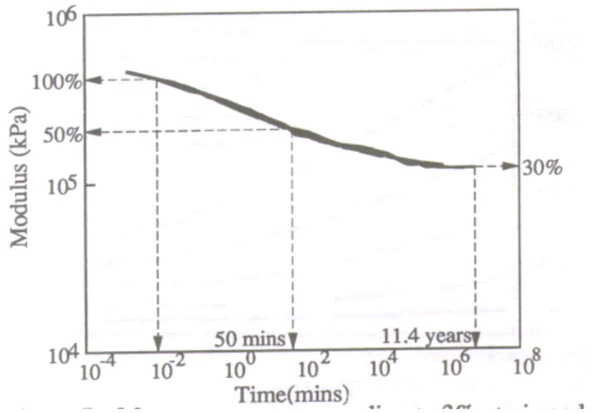

Figure 8. Master stress relaxation curve for 3% strain at 10^{o}C (Soong et al. 1994)

In this case 50% of the applied stress is removed by relaxation after 50 minutes with final equilibrium being achieved at about 30% of applied stress after 11.4 years. At higher temperatures the stress would relax more quickly. The equilibrium residual stress is between 2500 and 4000 kPa, or between about 13 and 21% of the room temperature yield stress. Note that the strain was applied far more quickly than will occur during subgrade settlement, so in a landfill significant stress relaxation will occur during deformation. Soong et al. (1994) stated:

"Trial tests were performed initially to determine the suitable loading rate. The results suggested a rate of 12.7 mm/min as being appropriate…….. At slower rates a very significant amount of stress relaxation occurred during the loading process…."

Also, note that Soong et al. (1994) concluded:

"…… *other HDPE geomembranes will undoubtedly respond differently than the HDPE studied……."*

Thus all HDPE geomembranes are not the same, just as their SCR performances are not the same.

These stress relaxation rates compare well with those generated by Soong and Koerner (1997) for stress relaxation in waves in HDPE geomembranes under a uniform vertical loading. After 1000 hr at temperatures of 23, 42, and 55^{o}C they found stresses relaxed between 60 and 78% leaving residual stresses of between 1% and 22% of the yield stress. However, these tests were done under semi-confined conditions (waves raised off a flat support surface) while the Soong et al (1994) tests were done under unconfined conditions. Under semi-confined conditions the residual stresses were lower than for unconfined specimens, possibly a result of the stress relaxation occurring during loading.

Creep/Stress Rupture

Duvall (1993) performed multiaxial creep/stress rupture tests on HDPE geomembranes by clamping a 1.5 mm (60 mil) thick round specimen (density 0.95 g/cm^3) in a flanged pipe joint and pressurizing the specimen from one side at up to 60% of the break stress, at temperatures of 23, 40 and 60^{o}C for over 15,000 hr. Stresses and strains in the specimens were determined from the measured deflection of the center of the specimen. After 15,000 hr multiaxial strains of about 20% had been reached without any signs of yielding. Duvall (1993) references work performed by Crissman (1991) who found that at low strain rates yield strains between 20 and 70% occurred in creep tests on "similar" (no explanation) resins at 24^{o}C.

At the higher temperatures both ductile and brittle breaks occurred as shown in Figure 9. Thus these specimens show the same ductile to brittle transition " knee" as the uniaxial specimens in Figure 3. Ductile break strains were in the region of 30% and brittle break strains were around 20%.

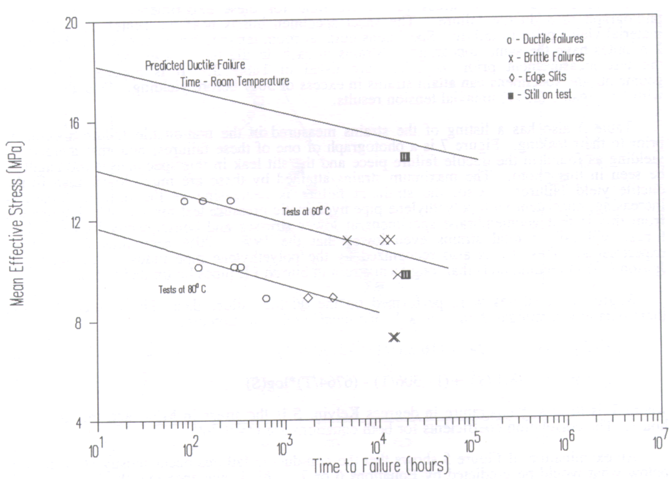

Figure 9. Multiaxial creep curves (Duvall 1993)

Duvall (1993) repeated Soong et al.'s (1994) warning that his data only applied to the test-specific HDPE geomembrane product and that other materials, even those with similar Melt Index and Density, could behave quite differently.

Thus, it is not reasonable to define a single MAS for HDPE geomembranes without unjustifiably penalizing the more mechanically durable higher SCR products.

DISCUSSION

The data presented show that, because of its prominent yield point and its susceptibility to SCR, HDPE is unique when compared to LLDPE, PP, and other geomembrane materials in its requirement for a MAS. Not only that, but because of their wide range of SCR values, different HDPEs will also require different MAS values.

In 1997 Smolkin and Chevrier determined a maximum allowable local strain for HDPE geomembrane lining systems after consideration of both the US and German approaches. They felt that the maximum 0.25% strain at stone indentations was far too conservative. They performed laboratory compression tests using two different protection geotextiles (550 g/m^2 and 1200 g/m^2) between their drainage stone (19 mm) and the proposed 2.0 mm thick HDPE geomembrane. After 240 hr the maximum indentation arch strains in the geomembrane under the two geotextiles were 1.50% and 0.92% respectively. After 1000 hr they projected that maximum arch strains would be about 2% and 1 to 2% respectively. They then calculated an allowable long term stress that would "prevent rupture" using the approach of Berg and Bonaparte (1993):

$$\sigma_s = (\sigma_r \text{ x } FCxFWxFI)/FS$$

where:

- σ_s is the allowable tensile stress
- σ_r is the rupture stress at service temperature (23^{o}C) and specified design life (100 yr)
- FC is factor of safety for chemical degradation (assumed 1.0)
- FW is factor of safety for seam strength (assumed 0.8)
- FI is factor of safety for installation damage (assumed 1.0)
- FS is the overall factor of safety (assumed 2 to 3)

This generated an allowable tensile stress of 2 to 3 MPa. The data generated by Duvall (1993) were then used to define a 50-year isochronous stress/strain curve which identified MAS values of 1% and 2% for stresses of 2 and 3 MPa respectively. Based on this they chose to use the heavier protection geotextile that would limit local indentation (arch) strains to between 1 and 2 %.

The decision by Smolkin and Chevrier (1997) to seek a higher allowable arch strain complements the thoughts of Saathof and Sehrbrock (1994) when discussing geotextile protection:

> *" It has to be reflected whether the protection effect required in the guidelines with a permissible deformation of the geomembrane of 0.25% is fixed by considering the material properties and whether an increase to 0.5 to 1.0% might be permissible"*

Note that Smolkin and Chevrier (1997) made no allowance for stress relaxation and made no consideration of the fact that in 1997 they were probably working with a more durable HDPE resin than did Duvall in 1993. Saathof and Sehrbrock also made no allowance for the actual performance properties of the geomembrane, but clearly did recognize that it could have some beneficial effect. Also recollect that Duvall specifically mentions that his test results may not be applicable to geomembranes made with other HDPE resins. And in their paper Berg and Bonaparte (1993) also specifically state:

> *" This simple comparison highlights the importance of identifying the potential for a particular geomembrane to undergo brittle rupture when loaded, and the benefit to be gained by using a geomembrane resin not susceptible to this failure mode during the specified design life. Finally, it is noted that if the geomembrane was able to relax, a larger initial allowable stress would be acceptable."*

This last point is again driven home by Berg and Bonaparte (1993):

> *" The procedure described in this section of the paper is applicable only to stress-controlled boundary conditions; it is not directly applicable to situations where the geomembrane will substantially relax."*

Thus, these ameliorating factors are all recognized but not yet incorporated in design protocols and regulations.

In a typical vertical expansion the geomembrane will not be required to tolerate permanent tensile stress to maintain stability. Tensile stresses will only be generated by uniform and differential settlement of the subgrade waste. Such settlement strains, and the resulting stresses, will occur "extremely slowly" perhaps 5 to 15 years for the initial 60% of the total strain, and 50 to 80 years for the remaining 40%. Therefore stress relaxation will have a significant impact on the actual geomembrane stresses. Recollect that Soong et al (1994) found that significant stress relaxation would occur at strain rates less than 12.7 mm/min in 100 mm gage length specimens.

Typically a geomembrane will be placed on compacted clay or a GCL and will be overlain by a geotextile/geonet composite drain and sand, a cushion geotextile and sand, or simply a drainage sand layer. Sand will typically pass a 0.5 in. sieve and will be sub-angular. Thus there will be no large drainage rock indenting the geomembrane, a more optimum situation than that faced by Smolkin and Chevrier (1997). Thus, there is justification for a more tolerant position on allowable indentation strain.

Separation geomembrane may also be at a service temperature between 20 and 40^{o}C. Measurements reported by Carey et al. (1993) on separation liners while in service have shown temperatures of about 30^{o}C. However, there is a possibility that sometime in its life the geomembrane might experience temperatures as high as 60^{o}C. As the temperature increases, so the stress relaxation will increase. In addition, as the HDPE tries unsuccessfully to expand within the confining soils a compressive stress will be generated within its plane, further reducing the residual tensile stress resulting from any settlement. However, at the same time the SCR resistance of the HDPE will decrease somewhat, thus there will be a balancing of effects. Even so, note that whatever the SCR of the geomembrane, if there is no stress there will be no break. Thus, the change in performance of the geomembrane under elevated temperatures is purely a function of the performance of the confining materials, the increased stress relaxation rate, and the reduction in SCR which is a function of the SCR of the basic material.

HDPE geomembranes have operated for many years without failure when exposed to tropical sunshine in applications such as leachate and evaporation pond liners. In such applications they regularly reach temperatures of over 80ºC. Fortunately there are no microstructural changes in ultimate break characteristics until the HDPE reaches over 90ºC, therefore laboratory tests at elevated temperatures are confidently used to accelerate in-service kinetic processes.

A simplistic assessment of mechanical changes as temperature increases from 20 to 60ºC indicates that the SCR might decrease by about two orders of magnitude. However, this change in temperature will occur slowly such that stress relaxation will occur at a faster rate than it would have occurred at 20^{o}C. At the same time, any tensile stress in the geomembrane will be reduced by about 6% of the yield stress (using an expansion coefficient of $1.7x10^{-4}$/ºC for HDPE), as compressive stresses increase due to constrained thermal expansion. A balancing increase of two orders of magnitude in SCR occurs if the tensile stress in the geomembrane is decreased by about 20% of the yield stress, or is reduced to about 35% of the stress at 20ºC. Since Figure 8 shows that approximately 50% stress relaxation occurs in 50 minutes – it appears that practical increases in in-situ geomembrane temperatures will not significantly affect the durability of the primary liner.

In summary, for a confined separation liner, we know:

- HDPE must be treated differently to other materials due to its susceptibility to stress cracking.
- HDPE's susceptibility to stress cracking is one of the major reasons for the concern about a limiting strain.
- Available HDPE geomembranes have a wide range of SCRs that can be used to advantage.
- Stress relaxation must be taken into account.
- Confinement is beneficial.
- Biaxial stress states rather than uniaxial stress states must be considered.
- There is a general feeling among design engineers that 3% general strain and 0.25% local strain limitations are too conservative. The practical performance of lining systems in the USA, where heavy puncture protection geotextiles are not used, appears to support this position.
- An increase in geomembrane temperature has no adverse effect on its durability.

For the definition of a meaningful MAS it is necessary to know the SCR of the HDPE geomembrane proposed for use when measured according to ASTM D5397 (single point). Materials with an SCR above 1500 hr will be treated differently to those below 1500 hr. This is admittedly an arbitrary specification but is felt to be quite practical in relation to available HDPE geomembranes. A minimum SCR of 400 hr is recommended. While this exceeds the GRI.GM13 specification, it has already been proposed by some as being an appropriate upgrade, and it was used by one HDPE geomembrane manufacturer in the 2001 Geotechnical Fabrics Report Specifier's Guide.

Clearly, the most appropriate experimental data for multiaxial creep testing of HDPE geomembranes has been generated by Duvall (1993). Both Smolkin and Chevrier (1997) and Berg and Bonaparte (1993) used Duvall's data to generate a maximum allowable long term stress at 23^{o}C for design lives of 50 and 100 years, respectively. Both identified a rupture stress of about 7 MPa. From this Smolkin and Chevrier (1997) identified a maximum allowable liner strain and therefore were able to define the required geotextile to use for puncture protection. However, as previously stated, we should not be seeking a safe operating stress and deducing an allowable strain. Since deformation is a consequence of settlement we need to identify the MAS that will not result in damaging stresses – the strain comes first, the stress second.

Nevertheless, Smolkin and Chevrier (1997)identified a maximum allowable indentation arch strain of 1 to 2% associated with a long term rupture strength after appropriate factors of safety had been applied. Following the BAM model that defined a bending strain of 3% on the underside of an arch strain of 0.25% in a 2.5 mm thick geomembrane, the bending strain developed by a top surface arch strain of 1.5% on the underside of a 2mm thick geomembrane is approximately 10%. This is approximately 40% of the biaxial stress at which local yield failures occur in HDPE.

In recent correspondence Müller states:

> *" ..... A strain limit of about 3% is an extremely conservative estimate from pipe pressure data for environmental conditions (base lining) with temperatures up to 40^{o}C. At room temperature (cap lining) a limit of up to 6% seems to be acceptable."*

Hence, the German BAM Institute now allows a maximum general strain of 6% in cap HDPE geomembranes.

The allowable general strain figure of 3% was generated from pipe tests in which the stress was maintained constant (stress relaxation does not occur) and Janson's (1981) recommendation of a maximum 5% strain is in a service situation where applied stresses (internal gas pressure) are active and constant. And in none of these situations is the material intimately confined between two masses holding the material "together" – and controlling its strain history. For instance, the confining soil will prevent the local ballooning of a thin spot that would otherwise occur if the geomembrane were pressurized on one side and unsupported on the other side. Under equilibrium settlement conditions the confining soils will not allow a geomembrane to further deform to allow a crack to open up. Therefore, if an active strain of 3% is felt sufficient to induce a potential critical stress in an HDPE geomembrane, but loading is very slow so that stress relaxation (by a factor of 2) can occur, the critical stress will actually be achieved at a strain of 6% or more, by the time stress relaxation has accumulated.

Therefore, on consideration of the various test data, the opinions expressed by those involved with the regulations and specifications, the contributions of confining pressure, the occurrence of stress relaxation, and the nature of the soils on each side of the liner, it is our calculated opinion that maximum allowable biaxial strains be conservatively set at 6% and 8% for HDPE geomembranes with 400 hr<SCR<1500 hr and SCR>1500 hr, respectively.

FRICTION ENHANCED GEOMEMBRANES

The influence of surface profiles on the MAS requires some interpolation from basic HDPE data since no meaningful creep, stress relaxation, or stress cracking tests have been performed on textured geomembranes. The significant factor is the influence that the profiling has on the SCR of the basic sheet. Therefore one cannot test a notched specimen that transfers the measurement point into the center of the geomembrane – simply another test on the equivalent smooth geomembrane. Tests should be performed on unnotched specimens (Thomas 1993), which in Germany are required to survive beyond 700 hr.

No special consideration will probably be necessary for the structured profiles generated by calendering since these profiles are built on top of a uniform thickness of geomembrane and the structures undergo the same thermal history as the bulk of the geomembrane. In the early days of such products there were significant stress concentrations at the base of conical profiles, but profiles are now smaller and profiling techniques have been improved.

While the post-extrusion thermally-bonded particulate textures are also added to the surface of the basic geomembrane and have little effect on the uniaxial tensile properties of the geomembrane, the point welding process has been seen to initiate microcracks in the weld around the base of the particle. Hence, the compromise that has to be made with bond strength: an increase in bond strength causes a decrease in SCR. For this reason it is necessary to be more conservative in the MAS values for the randomly textured products.

The textures generated by the nitrogen-injection round-die process in three layer co-extruded geomembranes reduce the uniaxial tensile break strength and elongation of the geomembrane but may have very little effect on the SCR of the geomembrane since the texture is subjected to essentially the same thermal history as the core of the geomembrane.   The outer layers are often made using lower density resins (even LLDPE is possible) than the core, resulting in lower comparative SCR values.

The multi-axial stress/strain curve of one nitrogen-injection randomly textured geomembrane is shown in Figure 10.   It shows a somewhat lower break strain than for the two smooth materials – approximately 22% compared to 29% and 48%. However, this may also be a function of the higher density of the textured geomembrane – note that break strain increases as density decreases, as would be expected.   On the other hand, the strain at ultimate (maximum) strength of both smooth materials is about 26%, still somewhat, but not much, higher than that for the textured product.

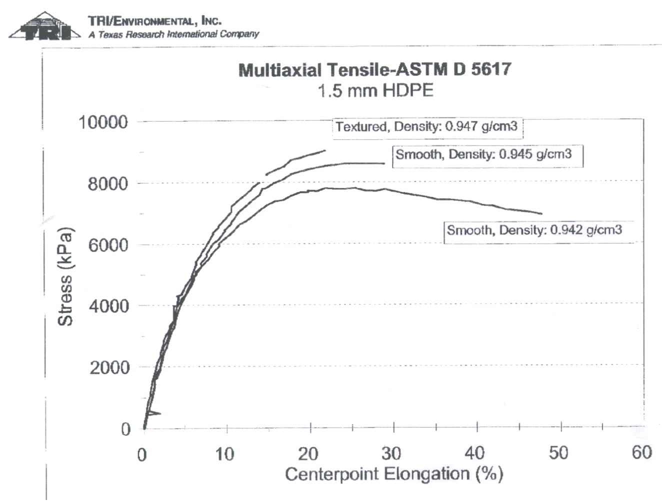

Figure 10. Multiaxial tensile stress/strain curves for textured and smooth 1.5 mm HDPE geomembranes (TRI 2002).

From these curves the relative positions of the yield points cannot be determined, but past experience has shown that yield points are relatively unaffected by surface profiles.   This is confirmed by the GRI.GM13 specification for smooth and textured HDPE in which there is no difference in yield parameters but where the break parameters for textured materials are considerably lower than those for smooth materials.   Thus ultimate and break strengths are the more appropriate indicators of the relative long term performance of the material.   Thus, there is some indication that the textured geomembrane should have a more conservative MAS.

As a consequence of the changes and potential changes in mechanical performance characteristics of structured and textured materials it is proposed that MAS for calendered structures be set at 6% and at 4% for the randomly textured products, both regardless of geomembrane/resin SCR values.   As an added safety factor it is assumed that all profiled HDPE geomembranes are made from the lower SCR commodity type of resin.   These are again considered to be conservative MAS values.

LLDPE AND PP GEOMEMBRANES

As previously described it is possible and desirable to treat LLDPE and PP quite differently to HDPE because of their microstructures and resulting different mechanical performance characteristics. A recognition of these differences should be incorporated in designs. Since these materials are in the same polyolefin polymer family as HDPE, and since they are less crystalline than HDPE, they will have higher stress relaxation rates than HDPE. It is also well-established that they are not susceptible to stress cracking in the as-manufactured condition – the GRI.GM17 specification for LLDPE does not include SCR, nor did the GRI.GM18 specification for PP prior to its provisional withdrawal.

Multiaxial stress/strain curves for PP and LLDPEs of different densities are shown in Figure 11. They all show "break" strains above 50%, all much higher than HDPE. They show ultimate strength strains of about 23%, not much different to those shown for HDPE. However, these materials do not have yielding-type failures as does HDPE – they uniformly deform up to final break. Therefore, the break strain is a valid measure of their relative long-term performance.

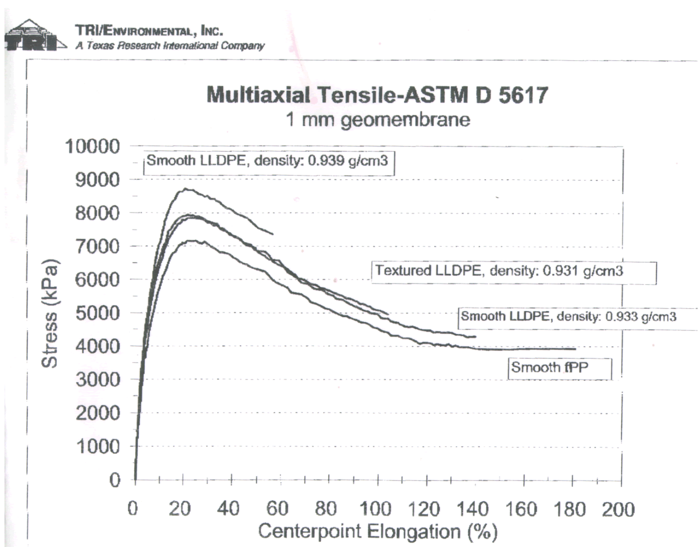

Figure 11. Multiaxial tensile stress/strain curves for 1 mm LLDPE and PP geomembranes (TRI 2002).

Since all available information leads us to recommend 6 and 8% allowable strain for HDPE with a yield/ultimate strain in the multiaxial stress/strain curve at about 22%, it is reasonable to recommend an allowable strain of about 12% (a factor of only 1.5 to 2 higher) in these similar materials that do not yield, that have break strains higher than the ultimate strength strains in HDPE by a factor of 2 to 8 (50 – 180% strain), that are not susceptible to stress cracking, and that have a higher stress relaxation rate.

Note that the curves for smooth LLDPE, as for HDPE, show a significant dependence of break strain on density – as density decreases from 0.939 g/cm^3 to 0.933 g/cm^3 the multiaxial break strain increases from about 50% to 140%. Hence the lower density products, 0.935 g/cm^3 and below, could have a higher MAS than the higher density products. We propose 12% compared to 10% for the higher density products. Such a difference between LLDPE products was apparent when GRI was developing the GRI. GM17 specification – there were considerable discussions on whether there should have been different specifications for two classes of LLDPE product – the higher modulus lower ductility type and the lower modulus higher ductility type.

It is noted that the textured LLDPE shown in Figure 11 has a lower break strain than a smooth product of slightly higher density – the opposite of the expected density effect. Thus, the textured surface appears to cause a reduction in break strain. This may simply be a result of the reduced cross-sectional area at deep valleys on the surface. Since LLDPE is not susceptible to stress cracking there is not the need for such a significant reduction in MAS as for HDPE, therefore it is proposed that structured profiles be limited to 10%, independent of density, and randomly textured profiles be limited to 8% also independent of density.

Since PP has a larger elongation at break (~180%) than does LLDPE (< 140%) its maximum allowable strain will be set at 15%. There is very little variation in the conventional short term mechanical performance of PP geomembranes since all in North America are made from one resin made by one manufacturer.

CONCLUSIONS

The maximum allowable multiaxial strains proposed for candidate geomembranes for separation liners in vertical landfill expansions are:

- Smooth HDPE (SCR <1500 hr) 6%
- Smooth HDPE (SCR >1500 hr) 8%
- Structured HDPE 6%
- Textured HDPE 4%
- LLDPE (Density >0.935 g/cm^3) 10%
  (Density <0.935 g/cm^3) 12%
- Structured LLDPE 10%
- Textured LLDPE 8%
- PP 15%

These are proposed as conservative MAS values.

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CAVEAT

It is essential to understand that these MAS values are only applicable to geomembrane strained slowly between confining layers. They do not apply to free geomembrane with a constant active load applied.

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