PREDICTION OF THE LONG TERM GENERATION OF DEFECTS IN HDPE LINERS

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ABSTRACT: The long-term service life of HDPE geomembrane liners depends upon the rate of generation of holes in the liner and the acceptability of leachate or gas leakage at a particular site. The development of holes with time until the landfilled waste no longer poses an environmental hazard is important in assessing the long-term performance of landfills. A thorough review of physical damage, material degradation processes and the development of holes by stress cracking has been undertaken. This paper summarises the findings of the research project, which forms the basis on which guidance and assumptions on medium to long-term landfill liner performance can be formulated in the UK. A conceptual model of hole generation in six stages throughout the service life of an HDPE liner is presented. Electrical leak location surveys are seen to be effective means of identifying holes caused by physical damage during liner installation and waste disposal, and permitting their repair. Degradation of the HDPE liner is controlled by the liner exposure conditions, the activation energy of the antioxidant depletion process and the oxidative resistance of the material. Where the liner is subjected to long-term stresses, stress cracking will lead to the development to holes, and the rate of cracking will increase once oxidation of the liner commences. Methods to minimise and retard the development of holes are discussed.

1 INTRODUCTION

Legislation recently introduced in the UK, including the Groundwater Regulations 1998; Pollution Prevention and Control Regulations 2000; the Landfill Regulations 2002 and forthcoming legislation to implement the Water Framework Directive, requires that groundwater is protected from pollution and that remediation is undertaken where this is necessary. A risk-assessment and management approach is commonly adopted in the UK (DETR *et al*., 2000) in determining whether there is likely to be an unacceptable risk of pollution, and in designing mitigation measures.

Although many of the technical issues of landfill design are longstanding, the new regulatory regime is such that quantitative understanding of landfill design and leachate control has assumed a much higher priority within the Environment Agency. This is particularly true where groundwater is sensitive or landfill gas would present risks to local receptors (Environment Agency, 2003a).

Many modern landfill sites include synthetic geomembranes, typically high-density polyethylene (HDPE), as part of a basal liner system. As manufactured, HDPE is impermeable to liquid flow, and movement through intact HDPE is limited to diffusive processes, which are normally very slow. In field situations, however, a number of other factors including quality of installation, stresses caused by slope instability, contact with aggressive chemicals and the depletion of antioxidants may affect the properties of HDPE, which can give rise to defects or cause failure.

A thorough review of geomembrane (with an emphasis on HDPE) degradation processes and defect frequency has been undertaken (Environment Agency, 2003b, in prep). The results provide the basis from which guidance and assumptions on medium to long-term landfill liner performance can be formulated in the UK. The results of this study will be of direct application in undertaking an environmental risk assessment for landfills (Environment Agency, 2003a) and within a LandSim performance assessment (Environment Agency, 2003c).

Studies of landfill leachate chemistry and degradation processes suggest that landfills managed using typical current approaches will take hundreds, if not thousands, of years to stabilise (Hall *et al*., 2003). It is only after this period that they will no longer pose a pollution hazard to their surrounding environment. The durability of engineering containment and control measures is therefore critical in assessing the long-term pollution potential. The UK approach of investigating long-term geomembrane durability and including this assessment within regulatory decision-making process is not replicated in all other countries. In some jurisdictions the long timescales for waste stabilisation are essentially ignored and assessments made over a few decades. In others, geomembranes are assumed to be effective for an infinite period and evidence of degradation is ignored. The UK seeks to base its regulatory decisions on the best available scientific evidence, and the study seeks to provide data in that context.

2 GEOMEMBRANE LINER SERVICE LIFE

The service life of a geomembrane liner can be defined as the length of time the liner continues to act as an effective hydraulic barrier for the purposes of the site under consideration. Clearly, this will depend upon the circumstances at the site and, for groundwater quality, the acceptable amount of leakage of specific contaminants. Some of the factors influencing this are:

- The number and sizes of holes in a geomembrane liner overlain by leachate;
- Whether the geomembrane liner is a single liner, or part of a composite, or a form of double liner;
- In a composite liner, the quality of contact between the geomembrane and the underlying mineral liner;
- Persistence of leachate source (e.g. rate of declining source concentrations);
- Leachate head and the nature and concentrations of contaminants in the leachate;

- Site sensitivity with respect to groundwater quality (e.g. groundwater vulnerability).

A geomembrane may have a certain number of holes, with a range of sizes. At one site the resultant leakage may be deemed acceptable yet at another, more sensitive site, the leakage may be considered unacceptable. The generation of holes in geomembrane liners, whether by physical damage mechanisms, stress cracking or material degradation is only one factor in the prediction of the service life of that liner.

3 PHYSICAL DAMAGE

3.1 *Electrical Leak Location Surveys*

Most damage to geomembranes, causing holes or non-penetrative defects, has been found to occur during the installation and seaming of the liner, and as a result of the placement of the overlying drainage or cover material. The causes of geomembrane liner damage have now been extensively reported from the results of electrical leak location (ELL) surveys, (e.g. Laine (1991); Nosko *et al*. (1996); McQuade and Needham (1999); Rollin *et al*. (1999); and Nosko and Touze-Foltz (2000)). The surveys have been undertaken using mobile and fixed ELL systems. Mobile ELL surveys are carried out on completion of liner construction after placement of the cover material but are unable to detect holes once waste disposal is in progress. Surveys using fixed (or "permanent") ELL systems can be performed at any time after the system installation, continuing well into the operational and post-closure phases of the landfill.

The survey by Nosko *et al*. (1996) on the detection of defects in geomembranes indicated that:

- 24% of the holes were caused during installation of the FML;
- 73% of the holes were due to mechanical damage occurring during placement of the cover soils;
- Only 2% occurred during the post-construction phase;
- 1% were test holes.

Holes detected on completion of construction would then be uncovered, repaired and re-tested so that they do not remain throughout the service life of the geomembrane liner. Where ELL surveys are not conducted, then it must be expected that holes will be present in these liners.

Little data have been published specifically identifying holes found by fixed ELL surveys after commencement of waste disposal. As noted above, Nosko *et al*. (1996) report that only 2% of the total number of holes identified occurred in the post-construction phase during waste filling. Of these, the causes were found to be:

- 67% were accidental damage by trucks/compactors, etc.
- 31% occurred from the installation of pipes, drainage systems, sumps, haul road access, etc.
- 2% from weather damage or other unplanned calamities, such as fires.

Data have been reviewed from an ELL survey company on fixed ELL surveys conducted by them on 17 commercial sites with a total liner area of about 800,000m^2. The maximum period of monitoring for leaks after liner installation was 6 years. Of the 38 holes detected, 16 (42%) occurred during the site operation, a much higher proportion than the 2% found by Nosko *et al*. (1996). For the holes occurring during the operational phase, the causes related to physical damage and not to deterioration in the geomembrane liner material.

Results were also reviewed from a second ELL survey company from surveys using fixed ELL systems over the 7-year period 1996 – 2003. The data were obtained from 88 cells and 18 leachate lagoons at 55 landfill sites in Eastern Europe, Belgium and the UK. The total area monitored was approximately 1,022,000m^2. The number of fully penetrating defects was 1460, with 1080 (74%) located during the initial leak survey at the end of liner construction and 380 (26%) holes being located in subsequent monitoring surveys. The most common cause of damage (78% of the 380 holes) found in the later surveys was stone puncture resulting from traffic movement over empty cells, illustrating the vulnerability to damage of geomembrane liners in completed but unused cells. None of the damage was attributed to a lack of durability of the geomembrane material.

A fixed ELL system has been installed at Sandy Lane landfill, Bromsgrove, UK since 1995. The ELL system monitors the entire site throughout the construction, landfilling and post-closure stages. The system comprises a grid of electrodes installed just beneath the composite liner (HDPE geomembrane over 300mm BES) providing full coverage across the base and the extensive side slopes. Surveys have been conducted now for almost eight years on a quarterly basis.

The extensive monitoring at the Sandy Lane site has so far revealed that:

- 74 geophysical anomalies have been detected, with approximately 90 holes being associated with these anomalies over a liner area of 5.5ha. This gives a frequency of 16 holes/ha. Of these, 27% of the anomalies have been detected after completion of the liner (i.e. during the interim period before waste disposal commenced in the cell or after landfilling commenced);
- Only two holes remain unrepaired in the liner, one on the basal area and one on a side slope due to their inaccessible locations. Both holes have been estimated as being very small and no detectable leakage has been identified by the ELL system;
- The sizes of holes found after liner completion ranged from pinholes in welds to major rips caused by plant movement;
- Over the 1997 – 2002 period, holes were rarely found to develop as a result of stresses imposed by the waste alone, and those that did occurred soon after waste disposal. Almost all new holes detected after the commencement of waste disposal resulted from the early activities of landfilling (e.g. puncture by waste materials and plant movement);
- Frequent (quarterly surveys) allowed the early identification of defects and their repair. Infrequent surveys would have meant the waste was too deep to locate and repair holes;
- There has been no evidence of the gradual development of holes during the period 1995 to 2003.

3.2 *Leak Detection from Double Liners*

Double liner systems are commonly used in the USA. The leakage detection system (LDS) between the primary and secondary liners is monitored to ensure the leakage does not exceed the permitted rate. Reviews of leakage rates measured over periods of up to 10 years have been summarised by Rowe (1998) and Koerner *et al.* (2000). While the interpretation of the leakage monitoring is problematical, the studies have concluded that the leakage rate consistently decreases from the start of the landfill to well into the post-closure period. This again suggests that significant numbers of holes do not develop from degradation, stress cracking and ductile failures in the geomembrane liners for periods of at least 10 years.

3.3 *Conclusions from Study of Physical Damage*

The principal findings from the review of physical damage are:

- If no ELL survey is undertaken, holes will be present in liners at the start of their operational life from imperfect manufacture, construction and unidentified damage caused during liner installation;
- Of all holes created during the construction and operational stages of a landfill, approximately 30 - 35% may be estimated to occur during the latter period. This is equivalent to about 50% of the number of holes occurring during the installation stage;
- The installation and regular monitoring of a fixed ELL system can enable the identification of these holes and, in most cases, their repair;
- The locations experiencing the greatest frequency of defects are exposed or poorly protected liner at the margins of a cell, on bunds and benches, and on slopes;
- Once a liner is covered by several metres of waste, the agents for the future development of holes in the liner are limited. The evidence to date from ELL surveys and monitoring of leakage detection layers shows that holes are unlikely to develop for at least the first decade of the service life of the geomembrane liner, and probably much longer.

4 GEOMEMBRANE LINER DURABILITY

4.1 *Oxidative degradation*

The degradation process that has the greatest detrimental effect on buried HDPE geomembranes is thermal oxidation. Oxidation is temperature dependent with the rate of oxidation increasing rapidly as temperature rises. As oxidation continues, the physical and mechanical properties of the polymer start to change eventually leading to failure of the geomembrane as an effective hydraulic barrier.

Oxidation of polyethylene can be delayed by the addition of suitable stabilisers called antioxidants to the resin, which function by interrupting the various oxidation reactions (Hsuan and Koerner, 1995). There are various types of antioxidants and they protect the polymer in different ways and over different temperature ranges. A package of antioxidants is added to HDPE geomembranes to provide a broad spectrum of resistance both during the manufacturing process and for the service life of the material.

Hsuan and Koerner (1995) describe the oxidative degradation of polyethylenes with antioxidant stabilisers as a three stage process (Figure 1).

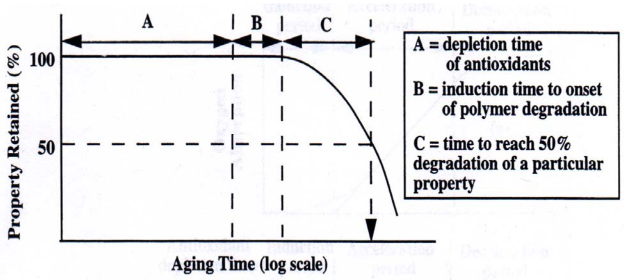

Figure 1: Three stage oxidative degradation of stabilised polyethylene (from Hsuan and Koerner, 1995)

The first stage in the oxidative degradation of HDPE geomembranes is the depletion of the antioxidants and is caused either by their consumption as a result of their chemical reactions with oxygen, free radicals and alkyl peroxides and/or to their physical loss by diffusion, extraction or volatilisation (Luston, 1986). Significant material degradation does not occur until the antioxidants have been fully depleted. The oxidation reactions generally start very slowly and there is an initial induction period during which there is minimal observable geomembrane degradation. This is followed by the final stage where oxidation causes significant loss of material properties.

Three important long-running research projects into the long-term oxidative degradation of HDPE geomembrane liners have been reported by Hsuan and Koerner (1995 and 1998), Sangam (2001) and Müller and Jakob (2003). The findings of these extensive projects form the basis of the current understanding of antioxidant depletion and, to some extent, subsequent oxidative degradation of HDPE geomembranes under laboratory conditions.

From these projects, several factors have been identified as having a key influence on the outcome of the laboratory ageing tests and, therefore, also on the estimation of the long-term durability of the HDPE geomembranes. These are:

- the characteristics of the HDPE resin and antioxidant package;
- the test duration;
- the exposure medium – air, water, leachate or soil (saturated and dry);
- the availability of oxygen;
- the ageing temperature(s); and
- the activation energy of the antioxidant depletion process.

The activation energy (E_a) reflects the necessary minimum energy of the antioxidant depletion process and will depend on the characteristics of the HDPE resin, the antioxidant package and the exposure conditions in which the antioxidant loss is occurring. As the rate of antioxidant depletion is exponentially dependent upon the activation energy, it is important to assess the appropriate value to use in the estimation of antioxidant depletion times.

4.2 *Exposure medium and ageing temperature*

Hsuan and Koerner (1995), Sangam (2001) and Müller and Jakob (2003) all investigated ageing in air. They also aged the samples in water, Müller and Jakob (2003) used de-ionised water at 80°C, Hsuan and Koerner (1995) tap water at 55°, 65°, 75°, and 85°C and Sangam (2001) tap water at 40°, 55°, 70°, and 85°C, the temperatures he had employed for the oven ageing. Hsuan and Koerner (1995) also used a "compressive stress–water saturated sand/dry sand" incubation to simulate landfill conditions while Sangam (2001) used a synthetic leachate ageing medium.

As Müller and Jakob (2003) ran their tests at only one ageing temperature, they could not construct an Arrhenius plot to obtain the activation energy and had to use estimated values obtained from tests by other researchers. However, their tests ran for up to 13 years, much longer than the tests reported by the other researchers. In these longer tests, they were able to identify not only the complete depletion of the antioxidants but also the commencement of oxidation, as seen by the marked reduction of strain of samples at break in tension tests.

The antioxidant depletion rates recorded by oxidative induction time (OIT) tests (ASTM D3895) determined by the three teams for the different geomembranes, exposure conditions and ageing temperatures are shown on Figure 2. The main conclusions are:

- Reducing the exposure temperature resulted in a very marked decline in the depletion rate;
- Immersion in the synthetic leachate resulted in a much higher depletion rate than any of the other exposure media;
- The much longer duration testing by Müller and Jakob (2003) showed a two-stage depletion process with the second being a very slow antioxidant depletion process. Therefore, the long-term durability of the HDPE geomembrane may be significantly longer than that estimated by Hsuan and Koerner (1998) and Sangam (2001), depending on the geomembrane formulation.

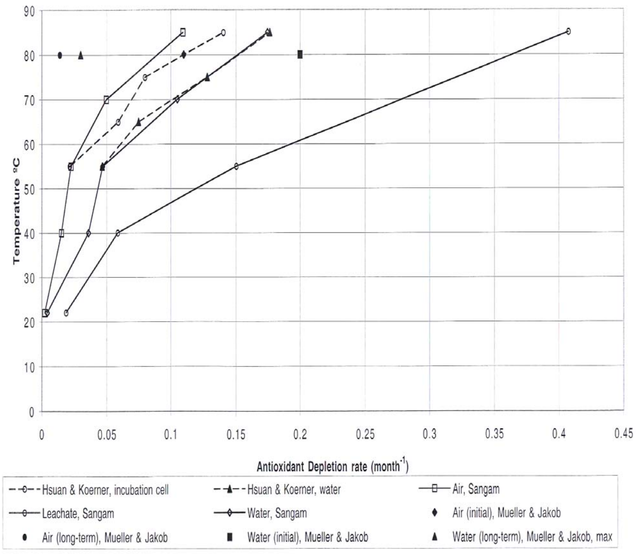

Figure 2: Comparison of antioxidant depletion rates by different researchers

High initial OIT values need not correlate with long-term oxidation stability. Certain antioxidants will markedly increase the initial OIT value but are ineffective below about 150°C and do not contribute to long-term oxidation stability at normal operating temperatures. Thus, polyethylene geomembrane specifications should stipulate not only the initial OIT value but also require a minimum retention of the OIT value following a standard oven ageing test (GRI GM13, 2003).

Müller and Jakob (2003) expected that activation energies relevant to the second, slow antioxidant depletion stage found in their long-term tests would be much higher than found by Hsuan and Koerner (1998). As the antioxidant depletion is controlled by the rate of diffusion, then the use by Müller and Jakob (2003) of relatively high activation energy values derived from studies of antioxidant diffusion appears justified. It is tentatively concluded that the lower activation energies found by Hsuan and Koerner (1995,1998) and Sangam (2001) reflect faster diffusion (or a faster consumptive process) of more easily depleted antioxidants, rather than the slower diffusion of the residual antioxidants which provide very long-term antioxidant protection.

This tentative antioxidant depletion / activation energy model for each individual geomembrane formulation depends on the actual composition of the antioxidant package used and the polyethylene resin characteristics.

4.3 *Conclusions on laboratory testing*

All three research projects provide valuable results which, when considered together, give a technical basis for the derivation of a reasonable estimate of HDPE geomembrane durability in landfill conditions. The estimate is based on:

- Slow long-term OIT depletion rates from Müller and Jakob (2003);
- The increased rate of depletion for leachate exposure found by Sangam (2001);
- The effects of a confined sample under comprehensive stress sandwiched between saturated sand and dry sand, as investigated by Hsuan and Koerner (1998);
- Measuring durability of the geomembrane in terms of the tensile test (N.B. This is not the same as the service life as a hydraulic barrier).

The slow, long-term OIT depletion rate obtained by Müller and Jakob (2003) was 0.03 minute^{-1} at 80°C for water immersion. Sangam (2001) found that OIT depletion was 2.3 times faster in synthetic leachate compared to water immersion, making the long-term depletion rate 0.069 minute^{-1}. Using an approximation procedure to relate laboratory ageing conditions to the actual exposure conditions of a composite landfill liner, the estimated antioxidant depletion time under landfill conditions (leachate above the liner and unsaturated soil (compacted clay) below) is 0.24 to 0.31 times that of leachate immersion in the laboratory within the service temperature range 13° – 33°C. The resulting OIT depletion rate for the landfill liner exposure model is derived as 0.016 to 0.021 month^{-1}. Using this depletion rate, estimates of geomembrane material durability can be derived from an Arrhenius equation on the temperature dependence of antioxidant depletion (Müller and Jacob, 2003). Typical results for different temperatures and activation energies are given in Table 1 below:

Table 1 Estimates of HDPE geomembrane liner durability in landfill conditions derived from laboratory research projects

Average landfill temperature (°C)	Activation energy (kJ/mol)	Estimated durability (years)
20	60	450 - 650
20	70	900 - 1300
35	60	140 - 200
35	70	220 - 320
35	80	370 - 530

The estimates in Table 1 rely on the results from different research projects and will benefit from confirmation by further long term laboratory investigation.

There are a number of conservative assumptions in the landfill liner exposure model:

- The durability estimates are based only on the depletion of antioxidants and neglect the oxidation induction and actual oxidation periods;
- Oxygen is absent in methanogenic landfills, so the induction period should lengthen substantially where these conditions persist;
- The low availability of oxygen within a partially, or fully, saturated compacted clay liner beneath the geomembrane would restrict antioxidant depletion, increase the oxidation induction period and defer the actual oxidation;
- The strength of the synthetic leachate remained constant in the laboratory tests whereas it will decrease with time in the landfill, resulting in a slower rate of antioxidant depletion.

The durability estimates in Table 1 refer to the complete depletion of the antioxidants and do not directly relate to the continuing ability of the geomembrane to act as an effective hydraulic barrier. The induction stage of the oxidation process will then commence followed by the onset of increasing brittleness (and reducing stress crack resistance) in the HDPE geomembrane as oxidation accelerates.

5 LINER EXPOSURE CONDITIONS

5.1 *Temperatures at the liner*

The temperature of a buried polyethylene liner will be a controlling influence on its rate of degradation.

Rowe (1998) reviewed landfill temperatures reported in the literature including Barone *et al*. (1997) who monitored temperatures at the base of a municipal solid waste (MSW) landfill in Toronto, Ontario from 1983 to 1996 using thermistors in vibrating wire piezometers. Rowe (1998) showed the data presented by Barone *et al.* (1997) plus additional data (Figure 3). A clear correlation between the temperature at the base of a landfill and the leachate head above the base is evident.

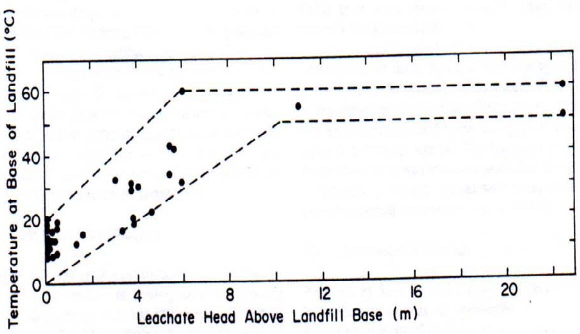

Figure 3 Variation in temperature at landfill base with leachate head for a number of landfills (from Rowe, 1998 modified from Barone *et al.,* 1997)

Koerner and Koerner (1995) report on temperature data at a "dry" cell (no additional liquids added or recirculated) at a Pennsylvania landfill, with additional data reported on the Geosynthetics Institute (GRI) website. After 9 years, an average temperature of 27°C was recorded. Temperatures measured at a "wet" cell at the same landfill operated as a bioreactor gave a liner temperature of 25°C from the start of filling (5°C higher than for the dry cell). Over a 2.5 year monitoring period, the average temperature had risen to 40°C (10°C higher than at the dry cell).

An experimental study at Beddington bioreactor landfill in the UK starting October 2000 included temperature measurements (Knox, 2003). Readings of leachate head and temperature were recorded on 19 piezometers and thermocouples. Placement of MSW began in October 2000 and the final thickness of waste exceeded 20m, attained in autumn 2001. A clay cap was installed later in 2001 and injection trenches to facilitate leachate recirculation were installed into the top of the waste.

From December 2000, temperatures increased steadily from 14 - 21°C at rates of 0.25 - 0.4°C per month. By May 2003, the temperature range had climbed to 24 - 30°C with no reduction in the rate of temperature increase evident. Recorded leachate levels were affected by intermittent extraction and by a drift in the piezometers, so that a leachate depth/basal temperature relationship could not be determined. However, the moisture content of the wastes will be elevated as a result of the leachate recirculation.

The considerable variability in temperatures recorded at the liner complicates the prediction of an average service temperature to use in estimating the long-term degradation of HDPE geomembranes. No records have been seen which show the rise and eventual fall towards ambient values of basal temperatures, so the duration of elevated temperatures is also difficult to predict. Sites that are active bioreactors, practise leachate recirculation and/or have elevated leachate levels are likely to have temperatures at the higher end of the range. A reasonable long-term average for such landfills is estimated as between 30°-35°C. This recognises that mean liner temperatures across the landfill may be about 10°C higher than this for about a decade but should subsequently reduce, bringing down the long-term average. For "dry" landfills or those with a low biodegradable content, a long-term average temperature of 15 - 20°C may be appropriate.

Reductions in biodegradable content instigated by the Landfill Directive should result in reduced temperatures at the liners.

5.2 *Availability of oxygen*

The concentration of available oxygen is an essential component of oxidation reactions but is not necessary for antioxidant depletion. If the methanogenic phase of a landfill is complete and aerobic conditions re-established before all antioxidants are removed, then oxidation should not be hindered by a lack of oxygen. However, if methanogenic conditions persist, the absence of oxygen available to the upper surface of a geomembrane would prevent oxidation of that surface, increasing the durability of the geomembrane. It is possible that oxygen may gain access to parts of the liner along the leachate collection and removal system.

On the underside of the geomembrane, oxygen availability is likely to be very small where there is good geomembrane to mineral liner contact. This will retard both the antioxidant depletion and subsequent oxidation induction stages.

5.3 *Exposure to leachate*

Many studies have examined MSW leachate effects on physical or mechanical properties of liners (e.g. Konrath and Ballod, 2001). HDPE geomembranes are recognised as having excellent chemical resistance against leachates derived from municipal, industrial and commercial wastes from landfills in the UK and elsewhere, as well as co-disposal waste sites in the UK. A significant proportion of the UK solid hazardous waste streams is currently co-disposed without prior treatment. Leachate quality from these sites has been well characterised by studies over many years (e.g. Robinson, 1995). It has been shown to be similar in most respects to the leachate quality from MSW landfills, that is, it is dominated by the biological processes responsible for the degradation of the organic compounds of MSW.

As noted by Sangam (2001), the presence of transition metals (such as Cu, Mn and Fe) in a leachate may accelerate the depletion of antioxidants.

The Landfill Directive requires member states to reduce the quantity of biodegradable MSW sent to landfill to 35% of the 1995 level, and to deposit pre-treated hazardous wastes in separate landfill areas. From research undertaken by Bone et al. (2002a and 2002b), three main factors influencing HDPE liner degradation were evident:

- The reduction in the biodegradable fraction should result in lower temperatures at the liner;

- Leachates from mechanically and biologically pre-treated (MBP) and hazardous wastes have elevated metal concentrations compared to untreated MSW or co-disposal sites. This may be instrumental in accelerating polyethylene degradation;
- The timescale before wastes complying with the Landfill Directive reach final storage quality is likely to be as long as that of current UK landfills.

6 STRESS CRACKING

Stress cracking of HDPE geomembranes has been well reported (e.g. Peggs, 1997). Normal stress rupture curves derived using the NCTL stress crack test (ASTM D5397) show ductile and quasi-brittle failure modes, with the break-in-slope (or "knee") defining the ductile/brittle transition point. Durability research in Germany (Hessel, 1990) identified a third stage (Figure 4) in which the curves at different test temperatures showed a second knee followed by an even steeper, almost vertical, slope. The second knee was defined as the stage at which all antioxidant stabiliser had been consumed, oxidation was occurring and any applied stress would cause cracking. At higher stresses close to the yield point (Stage I), the material fails in ductile mode. At intermediate stresses (Stage II), quasi-brittle break will occur before oxidation occurs, this being the stress cracking stage. In Stage III, brittle fracture is even more premature at lower stresses once the antioxidants are fully depleted and oxidation occurs.

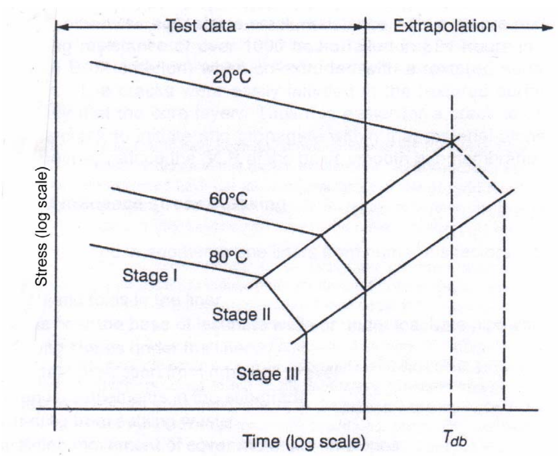

Figure 4 Three-stage stress rupture curve as a function of temperature (from Hessel, 1990)

The three-stage model illustrates that when a geomembrane is under tensile stress, or has shear stresses imposed on the surface (e.g. in textured geomembranes) at the same time as oxidation is occurring, the kinetics of degradation are more complex than the simple models used in laboratory studies where the samples are not subjected to tensile or shear stresses.

Even when the antioxidants in HDPE geomembranes have been fully depleted and oxidation commences, the geomembranes remain in place as effective hydraulic barriers unless physically damaged or they develop holes. Setting aside physical damage, holes through the liner should only develop or enlarge as a result of stress cracking unless stresses are so high as to cause ductile tensile failure. Oxidative degradation embrittles HDPE geomembranes making them much more susceptible to stress cracking so where low tensile stress persists, it is likely that stress cracks will occur. Where tensile and shear stresses in the liner can be avoided, for all practical considerations the liner may be considered to remain intact indefinitely. When the liner is under stress, cracking will eventually occur. Once oxidation commences, additional stress cracks will develop at the locations where the liner stresses had been too low previously to have triggered cracking.

The service life of the geomembrane liner will end once excessive leakage for that site occurs. If physical damage can be limited to acceptable levels, then the service life of the geomembrane liner as an effective hydraulic barrier depends on the development of stress cracks leading to excessive leakage.

7 STAGES OF HOLE GENERATION

The development of holes in HDPE geomembrane liners can be seen to occur in six stages, as proposed by the following conceptual model. The conceptual model is a simplification of a much more complex process as a geomembrane liner will be deteriorating at different rates and will be subjected to various stress levels at different locations across a cell.

Stage 1: The first stage is the number and sizes of holes remaining in the liner after construction of the liner and placement of the cover material and drainage system. Where an ELL survey has been carried out, then the detected holes can be repaired and zero or a very small number of holes may be considered to remain at the end of Stage 1.

Stage 2: This represents the holes caused before or during waste filling operations by physical damage mechanisms resulting in either new damage or the opening of latent defects. Where a fixed ELL system is in place and regularly monitored, and detected holes repaired, then only a small number of holes may remain at the end of Stage 2.

Stage 3: Present evidence shows that holes are not seen to develop for at least the next 10 years after liner completion. As there is generally no agent to cause holes, it is reasonable to assume that Stage 3 would comprise a 10 to 50 year period during which no further holes develop. The range in duration reflects different geomembrane material properties, efficacy of liner protection, design quality and standard of installation.

Stage 4: A gradual development of stress cracks within the stressed areas of the geomembrane occurs in this stage. The number of cracks depends on the estimated extent of areas under stress. The levels of stress, the stress crack resistance (SCR) of the geomembrane and the prevailing temperature at the liner control the time to the initiation and growth of stress cracks.

Stage 5: This stage occurs once oxidation of the geomembrane liner is in progress (following the loss of antioxidants and the induction period of oxidation). The geomembrane will become brittle and further stress cracking damage occurs relatively rapidly at all locations in the geomembrane remaining under tensile stress.

Stage 6: It is predicted that further generation or extension of holes in the geomembrane will be slow. The geomembrane will continue as a "leaky", degraded barrier with the HDPE geomembrane away from the cracks remaining intact and, for all practical purposes, permanent.

The length of Stage 4 may be estimated from the material durability assessment procedure outlined earlier. The duration of Stage 5 depends upon the rate of oxidation in the service environment. No data are available on which to base an estimate of this period, although Koerner and Hsuan (2003), Sangam (2001) and Rowe (1998) have made various, widely differing estimates formed without the benefit of laboratory data. From the laboratory studies presented by Müller and Jakob (2003), it is apparent that Stage 5 will be quite short relative to the length of Stage 4 and, on this basis, a period of 50 years is proposed as being a reasonable estimate.

In Stage 6, the geomembrane liner may remain as a partially effective hydraulic barrier. Depending upon the environmental sensitivity of the site and the remaining hazard of the waste, the acceptability of the leakage through the degraded geomembrane will control whether the liner has reached the end of its service life. The predicted leakage may be so large that the geomembrane can be assumed not to exist and that the barrier function (if still required by the degraded waste) has to be fulfilled by other elements of the liner system. For a composite liner, this would mean that the leakage through the composite liner would be the same as for the mineral or GCL component alone.

8 FACTORS AFFECTING LINER SERVICE LIFE

Action taken during design, landfill construction and waste filling can influence the length of the geomembrane service life by improving material durability, and reducing the extent of physical damage and the potential for stress cracking. The designer has the ability to:

- Specify a geomembrane with better stress crack resistance and OIT performance characteristics under ageing conditions. The specification should be appropriate for the site, with hazardous wastes and more sensitive sites justifying higher specification material;
- Avoid liner or landfill instability or the imposition of large scale stresses on the liner;
- Provide suitable protection for the geomembrane during landfill construction, particularly from plant movement and human activities. Long-term protection from adjacent materials is essential with the protection having a durability compatible with the desired service life of the geomembrane liner;
- As far as practicable, avoid features that may lead to stresses in the liner.

Management of the installation can ensure that the primary factors influencing the quality of the finished installation below are provided:

- Installation by well trained, experienced personnel in reasonable weather conditions;
- Independent CQA by well trained, experienced personnel;
- ELL surveys on completion of liner installation, and comprehensive repair of defects.

The presence of holes within wrinkles in the geomembrane will not only give the potential for increased leakage but can also cause local tensile stresses that may lead to future stress cracking. Placement of a wrinkle-free geomembrane is difficult and time-consuming, and relies on reasonable weather conditions and careful scheduling of procedures and resources (Averesch and Schicketanz, 2000). However, the objective of a liner with few wrinkles and in good contact with the subgrade is achievable by a high standard installation.

The quality of geomembrane seaming is another aspect of installation where improvements in techniques and equipment have reduced the incidence of defects over the years. The change from extrusion to fusion welds has been a primary reason for this improvement. Fillet extrusion welding demands a high level of skill and the reduced amount of this type of welding now undertaken means that the necessary skill and experience are more difficult to obtain. The result may be that where fillet extrusion welds are required, achieving high quality welds is becoming more difficult. While holes in welds have reduced, less obvious latent damage can be caused in forming hot wedge fusion welds by unsuitable equipment (Thomas *et al.*, 1995) and a high standard installation would avoid such damage.

It is difficult to ensure the adoption of best practice throughout the active waste disposal period to prevent physical damage to the geomembrane. The most effective means currently available for detecting penetrative damage to the liner is the provision and monitoring of a fixed electrical leak location system. This enables timely repairs to be made to identified holes.

The types of waste disposed of at the site and leachate management arrangements will have a major influence on the service temperatures at the geomembrane liner, directly influencing the rate of material degradation.

9 CONCLUSIONS

The service life of an HDPE geomembrane liner is the length of time the liner continues to act as an effective barrier for a particular site. Less sensitive sites will be able to accept a greater amount of leakage; other factors being equal, the service life at a less sensitive landfill site will be longer than at environmentally vulnerable sites. Physical damage, material degradation and stress cracking will generate holes in the liner leading to leachate or gas escape where the holes are subject to a leachate head or gas pressure.

A conceptual model of defect generation from these causes has been presented. The holes generated in each of the six stages, and the duration of each stage, can be estimated for use in environmental risk assessments of the long-term performance of landfills.

Physical damage to the liner can be readily identified by mobile or fixed electrical leak location surveys, fixed systems being able to monitor for defects during and after waste disposal, as well as at the end of liner construction. Identified holes can then usually be uncovered and repaired. High standard installation and CQA will not only reduce the number and size of holes but also the frequency of non-penetrative defects, which would eventually develop into holes.

From long-term laboratory research projects, it is seen that degradation of the HDPE material by oxidation is controlled by the liner temperature, the activation energy of the antioxidant depletion process and the OIT performance of the material under ageing conditions. Specifying a geomembrane with superior stress crack resistance will increase the delay before the initiation and development of stress cracks, improving the service life of the geomembrane liner.

10 ACKNOWLEDGEMENTS

This work has been funded by the Environment Agency under R&D project P1-500. The views expressed herein are those of the authors and are not necessarily those of the Agency or EDGE Consultants UK Limited.

The following companies and organisations also participated in the project:

I-Corp International, USA; Nottingham Trent University, UK; and Rapra Technology, UK.

The authors thank the following companies and organisations for assisting in or providing data used in this paper: BHF Environmental; Cleanaway; Federal Institute for Materials Research and Testing (BAM), Berlin; Geologger Systems; Geosynthetics Research Institute; Knox Associates; and SENSOR International.

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