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Limits of stress and strain: Design criteria for protective layers for geomembranes in landfill liner systems

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ABSTRACT: Environmental stress cracking can damage the HDPE-geomembranes in a landfill over a long period of time. A conservative estimate of the acceptable limits of stress and strain for geomembranes is derived with respect to service-time reduction by stress cracking. Protective layer design as well as installation procedures have to consider these limits in order to ensure lasting landfill liner systems with long service time, necessary for save waste disposal.

1 INTRODUCTION

Protection of geomembranes in landfill lining systems comprises a long-term and a short term aspect. Very often only the short term aspect is allowed for by prevention of severe damage like deep scratches, short term elongation beyond the yield point or perforation during manufacture, transport and installation. This is essentially a problem of quality control and installation conditions and procedures. On the other hand, geomembranes, especially those made of polyethylene, are susceptible to environmental stress cracking (ESC). Over a long period of time ESC may cause severe damage in the lining system. However, there are two solutions to this problem: geomembrane resins with high resistance to stress cracking and, secondly, reduction of stresses and strains during the entire service life of the lining system. The latter is essentially a task of lining design and long term protection.

Under normal conditions in a landfill the stress in the geomembrane is a result of slow deformation. Deformation may predominantly occur due to indentations from grains or crushed aggregates, i.e. from the roughness of adjacent layers or due to subsidence in the subgrade. A protective layer must strongly prevent local deformation and unacceptable stress levels in the geomembrane. Therefore, well designed protective systems contribute substantially to the long term performance of the entire lining system.

What is the upper long term limit for stresses and strains in the geomembrane? This is of crucial importance for the design of protective layers. In the following we address this question for HDPE-geomembranes. (Although HDPE is the common term, it is somehow misleading. Normally, medium density butane, hexane or octane copolymers are used for geomembranes, which should be described as medium density (MDPE) or linear low density (LLDPE) polyethylene). In the following we reconsider the estimation according to Koch et al. [1] for the service life of geomembranes. The testing procedure for protective systems is discussed and finally we give some examples of novel protective layer systems which are nowadays frequently applied in German landfills.

2 ACCEPTABLE LEVEL OF STRAIN AND LONG TERM BEHAVIOUR

Figure 1 shows data from long term internal pressure creep tests on pipes. Pipes are manufactured with HDPE-resins used for geomembranes. (These pipe tests are an important part of the BAM-certification (BAM, Federal Institute of Materials Research and Testing, Berlin) procedure. According to the German technical guidelines for lining systems [2] only BAM-approved geomembranes may be used for landfill applications).

For a typical material the hoop stress is plotted versus the geometric mean value of the failure times at different temperatures. The stress cracking failure curves in the brittle region at 20° and 40°C are extrapolated from measured data at 60°C and 80°C, respectively, according to the extrapolation procedure described in the German standard DIN 16887 'Testing of thermoplastics pipes; Determination of the behaviour to long term internal pressure'. From these curves we learn about the service life of geomembranes exposed to a permanent stress level at a

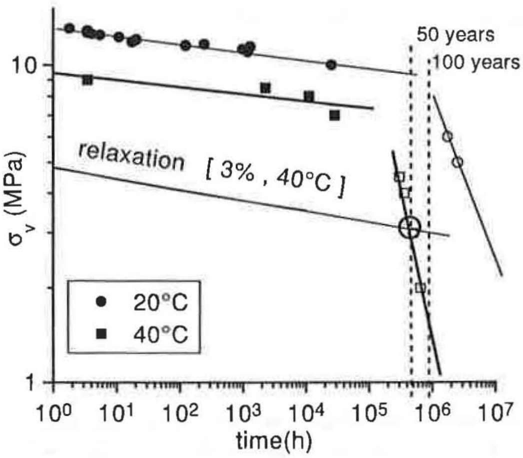


Figure 1: Long-term internal pressure creep test on pipes and relaxation of HDPE at 40°C and 3 % strain.

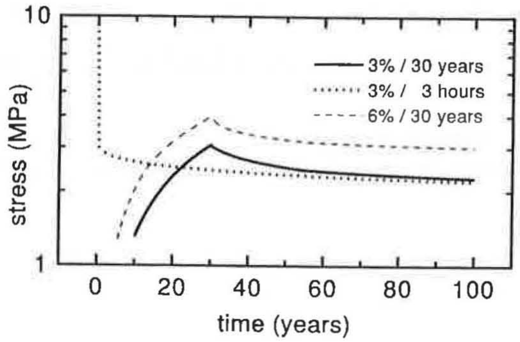


Figure 2: Stress relaxation curves for HDPE with different deformation histories.

given temperature. At 40°C, a mean service time of at least 50 years is reasonable, provided the hoop stress level does not exceed 3 to 4 N/m^2.

Figure 2 shows stress relaxation curves resulting from different deformation histories. For all curves the deformation is assumed to increase linear in time (constant deformation velocities) until a certain deformation level is reached and then kept constant. The time dependent stresses assigned with that deformation are then calculated with the help of a fully visco-elastic numeric materials model for uniaxial deformation [3]. The resulting curves show the stress relaxation typical for HDPE. From these "field stress curves" we learn that within the expected entire lifetime of a geomembrane there still remains a considerable long term stress level, even when deformations are slow.

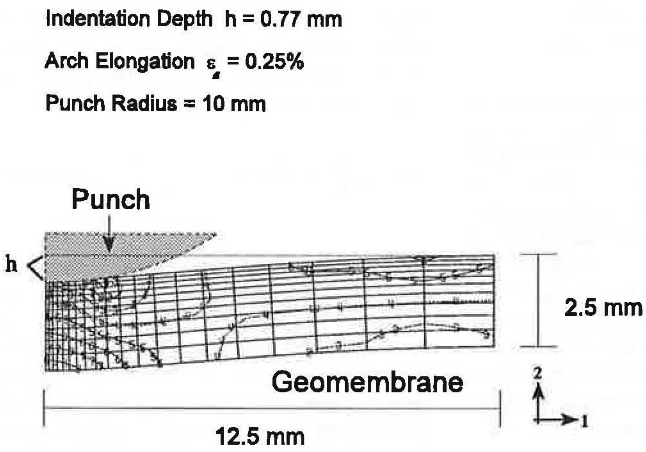
The following two important assumptions may now serve to estimate an appropriate limit for the acceptable local strain ϵ_L in the geomembrane.

1- An internal long-term stress level due to deformation causes stress cracking just as stress due to constant load. We assume that the failure time in a constant strain relaxation test with a certain mean long-term stress level is practically equal to the failure time in a constant load creep test, performed with the same stress level. To put it more formally, we assume that the stress curve is approximated by discrete time-steps. While σ_n, (n = 1,2,3...) is associated with the stress level in every step, t_n is the step width. From the constant load creep tests (figure 1) we may obtain the failure times $t_F(\sigma_n)$ assigned with the above stress levels σ_n. Then the failure time under the strain controlled conditions in a landfill (field stress curve) may be estimated according to the rule of linear damage accumulation by

$$\sum (t_n / t_F(\sigma_n)) = 1 \qquad (1)$$

From this assumption we may derive an acceptable strain level comparing relaxation curves and the constant stress curves from the pipe tests. There is no rigorous proof of this assumption for geomembrane materials. However, there is experimental evidence from pipe testing and research which supports this assumption [1], [8].

2- The second assumption simply states that the strain limit determined on the basis of the above assumption is also valid for local deformations in an indentation caused by bending. Figure 3 illustrates this assumption. It shows a vertical cross-section of a typical indentation in the geomembrane. The total deformation is the sum of two contributions. Firstly, there is an area increase as the deformed area exceeds the original one. The corresponding arch elongation is calculated, describing the outline of the indentation by a segment of a circle. Secondly, the geomembrane also suffers bending. Boundary fibres at the convex outer side of the indentation are additionally elongated, compared to neutral fibres in the middle of the geomembrane. This local deformation is determined by the local radius of curvature. It holds true, that for small size indentations



In-Plane-Strain	ε_1 (%)
1	-2.55
2	-1.67
3	-0.80
4	+0.08
5	+0.95
6	+1.82
7	+2.70
8	+3.58
ε_1 (max)	+ 4

Figure 3: FEM-simulation result of a deformation state in a geomembrane after typical indentation characteristic of loaded 16-32 mm coarse gravel grains. The indentation depth corresponds with an arch elongation of 0.25% in the membrane. Numbered lines indicate constant local deformation, i.e. radial component of in-plane strain, ε_1 , according to values in the table (negative signs correspond to pressure, positive signs to elongation).

due to grains the local strain is by far larger than the overall arch elongation. Although this assumption of the damaging potential of local deformations lacks experimental verification, it is a reasonable, physical approach, leading on the side of safety.

A detailed calculation of strain limits for given service times under various conditions is not possible. The relevant pipe pressure test curves may only serve as crude extrapolations. There are no accurate data for biaxial relaxation of the materials available. In addition, one should take into account that stress-strain states of pipes in internal pressure tests do not precisely match those states in biaxial deformations of geomembranes (indentations with rotational symmetry).

However, for a worst-case analysis we estimated failure times according to (1) from the relaxation curves of fig. 2 with low and high deformation velocities and a long-term strain level of 3 %. The failure time is predominantly determined by the long-term stress level and may only significantly be shortened by high and extended stress peaks. Therefore, for a lifetime assessment it is not necessary to know the deformation history in detail. It is then convenient to relay on relaxation data as typically published for most plastic materials. For comparison a biaxial relaxation curve of the HDPE material at 40°C and strain of 3% is also shown in fig. 1. If the service time of the geomembranes should at least come up to 50 years at 40°C a maximum value of $\epsilon_L = 3\%$ is a reasonable guess.

One should keep in mind that this is a quite conservative estimate. For example, a slow decrease in temperature will drastically increase the failure time, as can be seen by (1). Therefore the service time of HDPE-geomembranes under normal landfill conditions will probably exceed 100 years.

We like to emphasize that the stress relaxation behaviour - i.e. the long-term stress due to deformation - is as important as the stress crack resistance under constant load for a proper assessment of the acceptable stress level and, finally, for the long term performance of the geomembrane. Therefore the notched constant load test (ASTM D 5397), which proves the short term stress crack resistance under constant load, may not be used as the only and decisive test for the selection and further improvement of materials. One has to be careful in assessing long term behaviour on the basis of short term test results. For medium density polyethylene-copolymers with high stress crack resistance there is no evidence of a simple correlation between short term failure times in the notched constant load test and long term failure in pipe tests (at least from the data available to us). The above mentioned BAM-certification relies upon long term pipe pressure testing accompanied by testing of the relaxation behaviour (DIN 53 441, stress relaxation test).

Our above stipulation of 3 % maximum local strain also limits the acceptable radius of curvature r_L. With d = 2.5 mm geomembrane thickness according to the German technical guidelines and $\epsilon_L = d/(2r_L + d)$ we obtain $r_L \approx 4$ cm. On the other hand, using the elongation at break from a short term biaxial tensile test or burst test ($\epsilon \approx 20$ % to 30%) we estimate $0.3 < r_L < 0.5$ cm. The different long term and short term approaches to the assessment of protection requirements for geomembranes obviously have drastic consequences for the design of protective systems. This should be kept in mind comparing design practice especially between the US and Germany.

3 EVALUATION OF PROTECTIVE LAYER EFFICACY TESTS

The mechanical protective efficacy test device used in Germany is well known and fully described elswere [4]. Therefore we only give a short description here and focus on the evaluation of the test results. A geomembrane sample and a soft metal plate are laid upon an elastomer body inside a cylindrical container. A test sample of the protective layer system is mounted on top and then covered with the drainage gravel. In order to translate load conditions in landfills into experimental parameters, a test load, one and a half times the maximum expected surcharge will be applied. The test temperature of 40°C compares to the assumed service temperature in the waste body of landfills. The soft metal plate serves as a permanent plastic deformation memory for indentations suffered by the geomembrane. After 1000 hours the stored indentations are evaluated. As proven by many experiments, the design is on the side of safety, compared to load conditions in landfills.

With the foregoing consideration in mind we propose three evaluation criteria. At first, there is a very simple but practical one: A protective system passes the obligatory efficacy test provided no indentations are visible in the geomembrane sample after removing and keeping under standard climate for 24 hours. This criterion is used as general guide to the efficacy of a protective system. But it is also necessary to evaluate indentations evoked by joints, overlapps, or by the surface structure of the protective layer and to compare the efficacy of different protective systems. For these purposes the following advanced evaluation methods may serve: the quick and easy measurement of the arch elongation. This quantity can be estimated by describing the outline of an indentation by a segment of a circle with the smallest dimension of the indentation as a chord a, the greatest depth as height h of the segment and the angle α. The arch elongation ϵ_a is then determined as:

$$\epsilon_a = \frac{\mathrm{arc}\alpha}{\sin\alpha} - 1, \textit{ where } \sin\alpha = \frac{a\,h}{(a/2)^2 + h^2} \textit{ and } \mathrm{arc}\alpha = \frac{2\pi\alpha}{360}$$

We learned by experience that even when indentations seem to be negligible, the geomembrane may already have reached the 3 % limit of local elongation. Therefore a suitable protective system must keep the arch elongation below 0.25 % in order to safely prevent geomembranes from unacceptable large local deformation due to bending. The third criterion - the evaluation of the local deformation - is somewhat expensive and therefore only recommended if detailed data are needed. Values should remain below 3%. Both quantitative criteria may serve to improve the designs of protective systems - for instance, of lap joints, seams or overlaps. They also enable the comparison of different test designs or test parameters.

4 PROTECTIVE LAYER SYSTEMS

In Germany geomembranes (HDPE-liners from 2.5 to 3 mm thickness) are an essential component of composite basal landfill liner systems to prevent the contamination of soil and groundwater from leachate seepage. As it was shown above geomembranes are only able to perform this function, when reliably protected against damaging by grains of the drainage layer during installation and landfill operation. In Germany the standard structure for the area drainage over the geomembrane is very coarse gravel (e.g. round grain or double-crushed aggregate), graded from 16 to 32 mm, according to the technical guidelines "Technische Anleitung Abfall", and "Technische Anleitung Siedlungsabfall". The waste load of landfills in Germany may reach to ~ 900 kN/m^2, corresponding to a waste height of ~ 60 m.

The coarse drainage gravel, the high waste load and the deformation limit $\epsilon_L = 3\%$ for the geomembrane are the relevant parameters for the assesment of the load distributing efficacy of protective systems to reliably prevent the geomembrane from intolerable strains. Today, in Germany three main types of protective layers between geomembrane and coarse gravel drainage layer (grain size 16-32 mm) exits [5]. All of them meet the above requirements.

1- Nonwoven geotextiles (HDPE or PP) of $\geq$1200 g/m^2 mass per unit area, covered with a layer of coarse grains (0-8 mm) of ≥15 cm thickness. Mainly the mineral layer and to a lower degree the nonwoven contributes to the protective effect. The geotextile also serves as a substrate to make installation of the grain layer easier. This system is frequently used and meets all requirements.

2- Sandfilled systems, comprising mineral filler like river sand (or comparable material) and geosynthetics like woven mattresses, double-layer spacer fabrics or nonwoven sandwich liners. Geotextiles may be filled in-plant or in-place. Only the mineral filler contributes to the protective effect, a minimum layer thickness of 20 mm was found to be necessary. The geotextile ensures the erosion stability at the interface of sand and coarse gravel at least during the period of landfill operation and post-closure care (>30 years), and serves as packing up for the filler during installation. Due to easier handling, installation and reduced costs these systems more and more substitute the above mentioned system.

3- Geotextiles, e.g. nonwoven with very large mass per unit area (>2000 g/m^2) or nonwoven with geogrids. These systems meet the requirements for mechanical protective efficacy and durability only in some cases such as reduced waste load along with drainage material of reduced granulation, e.g. embankments, flat landfills.

A lot of research on protective layers was carried out during the last years in Germany, especially within the framework of a five year research program on landfill liner technology which involved state research and testing institutes as well as universities and industry. It was supervised by the German Environmental Protection Agency and managed by the Federal Institute for Materials Research and Testing (BAM), see [6] for latest reports. The results enabled BAM to release guidelines for protective systems which now provide the standards of testing and application of protective layers in the base of landfills [7]. There was a desired spin-off effect. Some firms developed novel protective layer systems of type 2 during the past years. Today, several protective systems, each with different pros and cons, are available in Germany and the most apropriate system can always be chosen for every specific landfill project.

REFERENCES

[1] Koch, R., Gaube, E., Hessel, J., Gondro, Ch., Heil, H. (1988), Langzeitfestigkeit von Deponieabdichtungsbahnen aus Polyethylen, *Müll & Abfall 8*, pp. 348-361.

[2] Guidelines for the Certification of Geomembranes as a Component of Composite Liners for Municipal and Hazardous Waste Landfills and for Lining Contaminated Land, *BAM, Berlin*, Febr. 1994.

[3] Menges, G., Schmachtenberg, E. (1987), Das Deformationsmodell, *Kunststoffe 77*, pp. 289-292, and

Michaeli, W., Fölster, Th., Lewen, B. (1989), Beschreibung des nichtlinear-viskoelastischen Verhaltens mit dem Deformationsmodell, *Kunststoffe 79*, pp.1356-1358, and references therein.

[4] Brummermann, K., Blümel, W. Stoewahse, C. (1994), Protection Layers for Geomembranes: Effectiveness and Testing Procedures, in: *Proceedings of the 5th International Conference on Geotextiles, Geomembranes and Related Products*, Singapore, September 1994, pp. 1003-1006, and

Müller-Rochholz, J. Asser, J. D. (1994), Sandfilled Geosynthetics for the Protection of Landfill Liners, in: *Proceedings of the 5th International Conference on Geotextiles, Geomembranes and Related Products, Singapore*, September 1994, pp. 1011-1014.

[5] Seeger, S., Müller, W., Jakob, I., Tatzky-Gerth, R. & August, H. (1995), Anforderungen an die Schutzschicht für die Dichtungsbahn in der Kombinationsdichtung, Teil 1, in: *Müll & Abfall 8*, pp. 544-560.

[6] Landfill Liner Systems, A State of the Art Report, Ed.: Holzlöhner, U., August, H., Meggyes, T., Brune, M., *BAM & SHWRU*, 1995, Penshaw Press, UK, pp. C1-C34, and

Meggyes, T., Holzlöhner, U., August, H. (1995), Improving the Technical Barrier for Landfills in: *Proc. Sardinia 95, Fifth International Landfill Symposium*, S. Margherita di Pula, Sardinia, Italy, pp. II.89 - II.102.

[7] Anforderungen an die Schutzschicht für die Dichtungsbahnen in der Kombinationsdichtung, Zulassungsrichtlinie für Schutzschichten, *BAM*, Berlin, 08/95.

[8] Akiyama, S., Takagi, N., Nagatani, F., Ishimaru, N. (1991), A Method For Life Prediction Of PE Under The Constant Strain Condition, *Proceedings of the Twelfth Plastic Fuel Gas Pipe Symposium*, September 24-26, Boston, Mass., USA.