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Müller and Wöhlecke

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Zero leakage? Landfill liner and capping systems in Germany

1 **Werner W. Müller** PhD
Physicist, Leader research team geosynthetics, Division of Contaminant Transfer and Environmental Technologies, Federal Institute for Materials Research and Testing, Berlin, Germany (corresponding author: werner.mueller@bam.de)

2 **Andreas Wöhlecke** MIng
Plastics Engineer, Division of Contaminant Transfer and Environmental Technologies, Federal Institute for Materials Research and Testing, Berlin, Germany


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An approach to achieve 'zero leakage' is discussed with respect to experience in Germany, where strict regulations for landfill lining and capping systems have been developed and issued because of large environmental problems related to landfills that accumulated in the 1970s and 1980s. Using a thick, high-quality high-density polyethylene (HDPE) geomembrane (GM) that is installed free of residual waves and wrinkles in intimate contact with a compacted clay liner or geosynthetic clay liner of very low permeability, by a qualified, experienced, well-equipped and properly third-party-controlled installer, and which is protected by heavy protection layers designed with respect to the long-term performance of the GM may result in a liner or capping system of practically no leakage. This is demonstrated by analysing results of measurements obtained from permanently installed leak-detection systems in combination with HDPE GMs. The survey was based on 32 German landfills with 1 276 500 m^2 of installed GMs.

Notation

l_{after}	edge length of a quadratic GM test specimen after heat treatment
l_{before}	edge length of a quadratic GM test specimen before heat treatment
δl	relative change in edge length in percentage, the so-called dimensional stability of the GM

Introduction

There is much debate and ongoing research (Rowe, 2015) about the issue of leakage through landfill-sealing systems with a geomembrane (GM). The assumption that 'all liners leak' (Peggs and Giroud, 2014) is readily accepted by many geotechnical engineers (Peggs, 2015). The authors wish to show that it is possible to avoid leakage by engineering methods to an extent that leakage may be considered as zero with respect to any practically relevant concerns. In Germany, the regulations focus on such a 'zero-leakage' approach. This stems from the environmental concerns of many citizens' initiatives. It transpired that it was actually impossible to agree on an acceptable amount for waste water leakage, even though it would have been impossible to determine and control it reliably. The approach is nowadays enforced by very restrictive German regulations (Water Resources Act, BMJV (2009a)) concerning groundwater protection.

This paper discusses this approach, which is based on the following requirements: (*a*) the use of a certified, thick and robust GM; (*b*) the establishment of detailed requirements and quality control (QC) measures with respect to installation and welding procedures; (*c*) the realisation of a composite liner system of a GM in intimate contact with a mineral layer of very low permeability; (*d*) special requirements on the protection layer (PL) above the GM (Holzlöhner *et al.*, 1999; Müller, 2007). Avoiding faults in the first place and realising an intimate contact – free of waves and wrinkles – of the GM and a subgrade with low permeability are the two essential aspects of the zero-leakage approach. A small number of small holes will become critical only if the subgrade has a high permeability and if there is a large network of covered waves in the GM, which form channels where intruding water can flow freely.

Permanently installed leak-detection systems (LDSs) are part of capping systems in various cases. Using the results of leak-detection surveys, the authors will show that due to (*a*), (*b*) and (*d*) the occurrence of holes in a GM is extremely rare. Then, it is discussed that, according to (*c*), leakage may be neglected if the number and areas of holes is actually very small. Finally, the authors wish to highlight the importance of an appropriately designed PL – that is, requirement (*d*) – to prevent the future occurrence of holes after the completed installation of an intact sealing system.

German regulations

In Germany, the requirements for landfills are regulated by the Landfill Ordinance (BMJV, 2009b). There are four classes of landfills: for inert waste (0), low contaminated waste (I), significantly contaminated waste (II) and hazardous industrial waste (III). Certain wastes have to be deposited in underground storage sites (IV). Municipal waste has to be incinerated or treated by mechanical–biological techniques. Only the residues may be deposited, depending on the contamination. The techniques for determining the contamination and the criteria for the assignment of waste to the different landfill classes are described in the appendices of the Landfill Ordinance. The requirements for the basis liner system and the capping system are given in Table 1. All geosynthetics and the LDSs used in landfill-sealing systems must be certified for this application. The certifications are issued by the Federal Institute for Materials Research and Testing (BAM, 2017), an agency of the Federal Ministry for Economic Affairs and Energy. Founded in 1871, BAM is working in various fields related to safety in technology and chemistry with a budget of €151 million and about 1600 staff members. The certification is based on various guidelines. English translations of these can be obtained from BAM (2015).

Requirements on high-density polyethylene GMs

Only high-density polyethylene (HDPE) GMs have been certified so far, which have high stress crack resistance and are properly stabilised by antioxidants against oxidative degradation. In this respect, the certification guidelines (BAM, 2015) are comparable to the Geosynthetic Institute's GM13 standard (GRI, 2015). However, there are differences with respect to other properties.

In geotechnical engineering, HDPE GMs with different thicknesses are used and there is ongoing discussion about the minimum thickness necessary. One has to choose the optimum between mechanical robustness, stress crack resistance and oxidative resistance, performance during installation and, above all, welding on the one hand and financial expenditure on the other hand. Mechanical robustness, stress crack resistance and even oxidative resistance significantly increase with thickness. Welding, in particular extrusion welding, can be much easier and more reliably performed with thicker GMs. There is consensus that under no circumstances should HDPE GMs be thinner than 1·5 mm. However, there are many reports about regular problems with extrusion welding of 1·5 mm thick HDPE GMs (Hein *et al.*, 2003). Usually, a minimum 2·0 mm thickness is recommended. In the Landfill Ordinance, the thickness is specified to be at least 2·5 mm to ensure high mechanical robustness, reliable welding properties and low permeability of organic pollutants. Robustness and welding properties are of relevance to the occurrence of leaks.

The section titled 'Evaluation of measurements with LDSs in landfill cappings' discusses the importance of an installation free of waves and wrinkles for zero leakage. To achieve this goal, one has to take into account the dimensional stability or shrinkage behaviour of the GM as an important property. During production (extrusion and calendering), orientation and related stresses are imposed on the product and locked in during the cooling procedure. Later on, the orientation and stresses relax to a degree during transport and installation, particularly when exposed to higher temperature on the installation site. The relaxation leads to an 'intrinsic' waviness of the GM. Therefore, inferior dimensional stability can cause serious problems for welding and wrinkle-free installation.

The following method of measuring the dimensional stability may be used to characterise this effect. Quadratic specimens (plates) with 100 mm edge lengths are cut from the GM. The edges must

Table 1. Components of sealing system from bottom to top according to the Landfill Ordinance (BMJV, 2009b), bold signifies geosynthetics

Component	Class 0	Class I	Class II	Class III
Base liner system				
Geological barrier[a]	≥1 m $\leq 1 \times 10^{-7}$ m/s	≥1 m $\leq 1 \times 10^{-9}$ m/s	≥1 m $\leq 1 \times 10^{-9}$ m/s	≥5 m $\leq 1 \times 10^{-9}$ m/s
First sealing layer	No	**2·5 mm GM** or CCL	CCL ≥ 0·5 m, 1×10^{-10} m/s	CCL ≥ 0·5 m, 1×10^{-10} m/s
Second sealing layer	No	No	**2·5 mm GM**	**2·5 mm GM**
PL in case of GM[b]	No	**Sand mat or combined PL**	**Sand mat or combined PL**	**Sand mat or combined PL**
Drainage layer[c]	Coarse gravel 0·3 m	Coarse gravel 0·5 m	Coarse gravel 0·5 m	Coarse gravel 0·5 m
Capping system				
Gas drainage layer	No	No	Where necessary	Where necessary
First sealing layer	No	2·5 mm GM or CCL	CCL, **GCL**[f], CB, **LDS**	CCL, **GCL**, CB
Second sealing layer	No	No	**2·5 mm GM**	**2·5 mm GM and LDS**
PL in case of GM[d]	No	**Sand mat or GTnw** (≥800 g/m^2)	**Sand mat or GTnw** (≥800 g/m^2)	**Sand mat or GTnw** (≥800 g/m^2)
Drainage layer[e]	No	Gravel or **GCD**	Gravel or **GCD**	Gravel or **GCD**
Restoration layer or functional layer	Yes	Yes	Yes	Yes

[a] Laboratory permeability measured at hydraulic gradient 30
[b] Combined PL: combination of 1200 g/m^2 GTnw and fine gravel
[c] Thickness of the base drainage layer may be reduced according to landfill conditions (no accumulation of water)
[d] No PL in the case of a GCD
[e] GCD: filter GTnw ≥ 300 g/m^2 and carrier GTnw ≥ 200 g/m^2
[f] GCL, geosynthetic clay liner
CB, capillary barrier; GTnw, non-woven geotextile

be right-angled and the lateral faces must be even. The specimens are kept in an oven at 120°C for 1 h. The edge lengths (l_{before} and l_{after}) of the plates before and after heating in the oven are measured in the extrusion direction and cross-wise, and the percentage of change in length with respect to the initial length

$$\delta l = \left(\frac{l_{\text{before}} - l_{\text{after}}}{l_{\text{before}}}\right) \times 100 \tag{1}$$

is calculated for each direction and rounded to ‰ values. The BAM guidelines require that the absolute value of the dimensional change in extrusion as well as in the cross-extrusion direction must be ≤1·0% for smooth GMs and ≤1·5% for GMs with an embossed surface pattern. However, the absolute value of the difference in the dimensional changes along the width has to be significantly lower than 0·4% for a smooth GM and 0·6% for an embossed GM. Figure 1 shows the results of dimensional stability in the extrusion direction of a GM, which appeared reasonably flat after production. (The BAM guidelines set, in addition, a limit on the waviness, which is checked at the beginning and end of a production run. The maximum clearance between the GM and the level of the supporting surface is assessed over a length of 10 m when rolled out over 12 m. The measured value must be 5 cm at most.) Figure 2 shows the appearance of the same GM after installation. Since shrinkage in the extrusion direction was large at the edges but small in the middle, a typical 'bulginess' occurred. A wrinkle-free installation would be impossible, even with elaborate installation techniques. Therefore, not only mechanical robustness but also low intrinsic waviness is an important prerequisite for an installation that avoids holes.

There is some confusion in the European standardisation about the determination of the mechanical properties of a HDPE GM. In the USA, ASTM D 6693 (ASTM, 2010) describes a well-defined procedure. In Europe, the test has in principle, to be performed according to EN ISO 527-3:2003 (CEN, 2003). There, it is required to measure the elongation at yield with high accuracy using optical or mechanical extensometers and to determine the elongation at break by using the measurement of the separation of the specimen grips and using the initial grip separation of 80 mm as the reference length. This gives values much lower than the ASTM standard. Therefore, manufacturers often take 50 mm as the reference length and the certification guidelines sanction this practice. The confusion arises because in various European standards, use of an extensometer is even required for the determination of elongation at break. However, most of the yielding above the yield point takes place outside of the mechanical tongs or optical marks of the extensometer, which stand still during a significant part of the testing time. Nevertheless, a high elongation might be formally obtained because a very small reference length of only 25 mm is used. Yet, this 'artificial' elongation has no relation to the actual yielding and elongation at break of the specimen.

Installation

The state-of-the-art in GM installation as used in German landfill construction is now discussed. Clearly, there is a large variety in the extents to which the requirements are actually fulfilled. Yet, as is shown in the next section, a sealing system free of holes is realised in many cases.

Before installation can start, the subgrade (or supporting layer), on which the GM will be deployed and welded has to be produced and its surface prepared. The particle shape, size and size distribution of the subgrade material must be selected in order that the loads, which occur during construction and use, do not result in inadmissible deformations by indentations and imprints in the GM (see the section headed 'Protection layers'). Therefore, the BAM guidelines contain material technical and geometrical criteria for the surface of the subgrade. These also apply to the surface of the compacted clay liner (CCL) in the

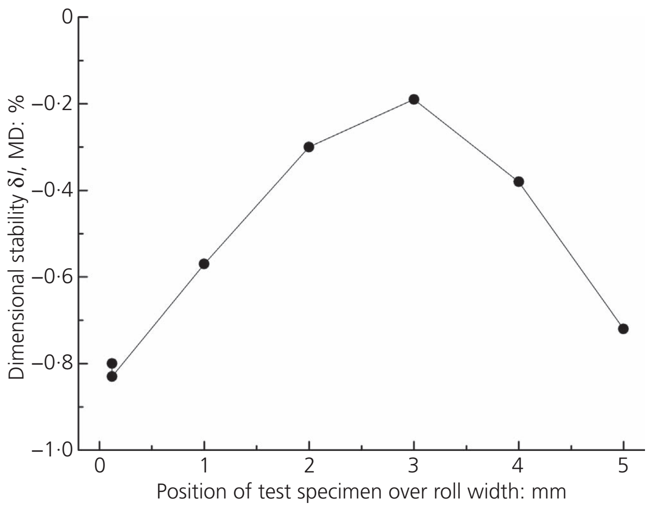

Figure 1. Dimensional stability (MD, machine (extrusion) direction) along the width of GM

Figure 2. Intrinsic waviness of a GM

composite liner. The surface must be stable bearing, homogeneous, fine-grained and free of holes. Gravel particles with a diameter >10 mm and foreign particles have to be removed. All finer gravel components must be embedded in such a way that they are surrounded on all sides by cohesive material. Gravel particles and foreign particles must not lie on the surface. Generally, abrupt changes in height should be smoothed to a large extent. As a reference point, a permissible height of 0·5 cm is considered for steps (impression differences). Unevenness, when measured beneath a 4 m long lath (straight edge) resting on the surface, may not exceed 2 cm. The production of such a surface requires a substantial constructional engineering input (Averesch and Schicketanz, 1998).

As a rule, the GM has to be installed in such a way that as few welding seams as possible are necessary and that dual hot wedge seams with machines, which realise electronic control of the welding parameter, a control desk and a data logger, can be used to the largest possible extent. A process model that relates welding parameters to the geometrical parameters of the seam and the long-term behaviour of the seams in long-term peel tests is described elsewhere (Lüders, 2000, 2002; Müller, 2007). Further requirements for welding are described in the technical recommendation DVS 2225-4 (DVS, 2016a). The new draft (in German) is available at DVS (2016b).

An installation method, which uses the temperature gradient over the day, can guarantee intimate contact of the GM with its subgrade to a large extent. A change in temperature of 10°C between night and day can alter a 100 m long HDPE GM section due to thermal elongation and contraction by an amount equal to 2 m. Therefore, if a GM that is acclimatised to the temperatures of the warmer time of day is aligned, installed with minimum undulation and welded, it will pull itself smooth as it cools during the night. Installing a geotextile and fine gravel or a heavy sand mat as a PL and backfilling with the coarse gravel drainage material (basis liner) or installing a geotextile PL (or a geocomposite drain (GCD)) and backfilling with a layer of reclamation earth (capping) will fix the GM and realise intimate contact. It is very important to ballast the GM at the appropriate time. The waviness of an uncovered GM area will increase significantly over time and, after a certain period, it will be impossible to achieve intimate contact. The guidelines require that a sufficient load must generally be applied on the same or the following day and at the latest on the second working day after installation of the GM.

A special installation technique is used in liner systems to realise perfectly flat GMs (Averesch and Schicketanz, 1998). After welding and testing are finished, so-called anchoring bars are constructed. At both ends of the GM section, a roll of sand mat protection or geotextile PL is unreeled and then loaded by additional heaps of gravel of the drainage layer. The dead weight of these bars fixes the GM. Normally, the mineral foundation for pipes is installed in the trenches above the GM and thus an anchoring bar is established there. With the gradually increasing evening coolness, the GM will increasingly contract and become taut. Therefore, an anchoring bar has to be arranged along the toe of the slope. Otherwise, due to the contraction of the GM, it would lift and bridge over the trench and transition zone between the base and the slope (trampoline effect). Mostly by late evening, but early next morning at the latest, the clamped GMs reach complete flatness. They can then be covered with the PL and backfilled with the drainage gravel.

Installation companies have to have highly qualified and experienced staff. They should have a wide range of experience and suitable state-of-the-art equipment. Industrial associations of GM manufacturers and installers have established a QC system based on the recommendations of BAM, offering supervision and installer certification. Certification emblems are issued if the installer belongs to the association, fulfils the requirements and proves this in regular audits by a BAM auditor each year, alternately in the company and on an installation site (Agas, 2015; AK GWS, 2015). However, it is not only the installation of the GM that includes special procedures and QC. Other plastic components such as pipes, shafts and construction elements such as pipe penetration through a GM are positioned at the most critical locations in a landfill. For this reason, it is obligatory that only certified installation companies are allowed to weld these components in the shop fabrication and on site (SKZ/TÜV-LGA, 2013).

It is well known that third-party control is of great importance for flawless GM installation (Cadwallader and Barker, 1986). Tables of requirements for the type and numbers of on-site tests are included in the certification guidelines. The requirements of these tables are obligatory for installation of the products. Accreditation according to ISO/IEC 17020:2012 (ISO, 2012) for the inspection body and ISO/IEC 17025:2005 (ISO, 2005) for its laboratory is required. The requirements for the accreditation of third-party controllers are available on the internet, together with examples of relevant inspection instructions, QC plans and reports (BAM (2015), available only in German).

Evaluation of measurements with LDSs in landfill cappings

Permanently installed LDSs are applied in German landfill cover systems in combination with HDPE GMs (Wöhlecke and Müller, 2014). Such a combination can be equivalently used as a substitute for a composite liner system. LDSs can detect and localise cracks and holes in a GM with respect to their size and occurrence. LDSs used in German landfill constructions are based on electroresistive measuring techniques and sensors (Darilek and Laine, 1999), making use of the insulating behaviour of the HDPE GM and the change in electrical potentials in the area of a defect. Instead of the flow of water, the flow of electric current is measured. Therefore, an external voltage must be introduced into the barrier system during a measurement. If the conditions are not particularly unfavourable, a hole can be detected electrically much earlier and with higher accuracy than by any monitoring of any hydraulic effect. LDSs are certified by the BAM for this application (BAM, 2015).

The efficiency of an LDS is defined in terms of what minimum leak size can be detected and with what spatial resolution. The LDS detection limit is the minimum size of a hole in the GM, assumed to be circular, that can be detected with certainty under normal conditions. For certification, the LDS must be able to detect a circular hole of at least 5 mm dia. with 100% probability. However, more than 20 years of experience has shown that LDSs are able to detect even smaller holes. Data from the examination of a capping system after the construction process and during use were provided to the authors by Sensor Dichtungs-Kontroll-Systeme GmbH. The operation of an LDS usually starts with an assessment of the performance of the LDS itself. For this, a third-party controller 'secretly' drills small holes into the installed GM component, which have to be localised by the LDS. Then, there is an approval measurement after the end of the construction of the capping system. After that, there are regular measurements at some time intervals of the performance of the capping system during operation and after-care of the landfill. The certified LDS contains a 'self-control' procedure: before each measurement, it is checked whether the cables, sensors and electronic equipment are functioning correctly. Therefore, the data provided by the sensor may be considered reliable.

Figure 3 shows the results of 14 years of controlling capping systems with permanently installed LDSs in German landfills. The data include the results of the approval measurement and the regular interval measurements. Data from 32 landfills with an overall capping area of 1 276 500 m^2 became available. The 32 landfill capping systems were built with certified HDPE GMs, and the requirements for installation, installers and third-party control were mandatory. There were only six failures found, which means a failure density of only one defect every 21·3 ha. This is, in fact, negligible. In 26 of the 32 construction sites, no defects were determined at all. On the remaining six construction sites, only one defect per capping system could be found. No details were given for one of these defects. All other defects were located outside the seams in the panel area of the GMs and were caused by physical impact. Failure due to poor craftsmanship or stress cracking was not relevant. One of the defects was deliberately and secretly introduced during the construction process with the perspective of a second validation of the construction later on. Two defects were due to puncturing by sharp objects (for example, see Figure 4). A quite large 1 cm dia. defect was created by an excavator shovel. For one 1 cm dia. hole, no further information about the origin was available. Taking all landfills, there were on average 0·05 small holes per hectare. Zero leakage therefore seems to be actually achievable. In comparison, a literature survey gave the following construction defect frequencies for geosynthetic barriers: 0·5 defects per hectare (dph) for strict QC, 2·5–10 dph for good QC and up to 60 dph and even more for poor QC (Kavazanjian *et al.*, 2006). It is difficult to relate these frequencies to leakage rates. Leakage rate depends on the hole size, the permeability and

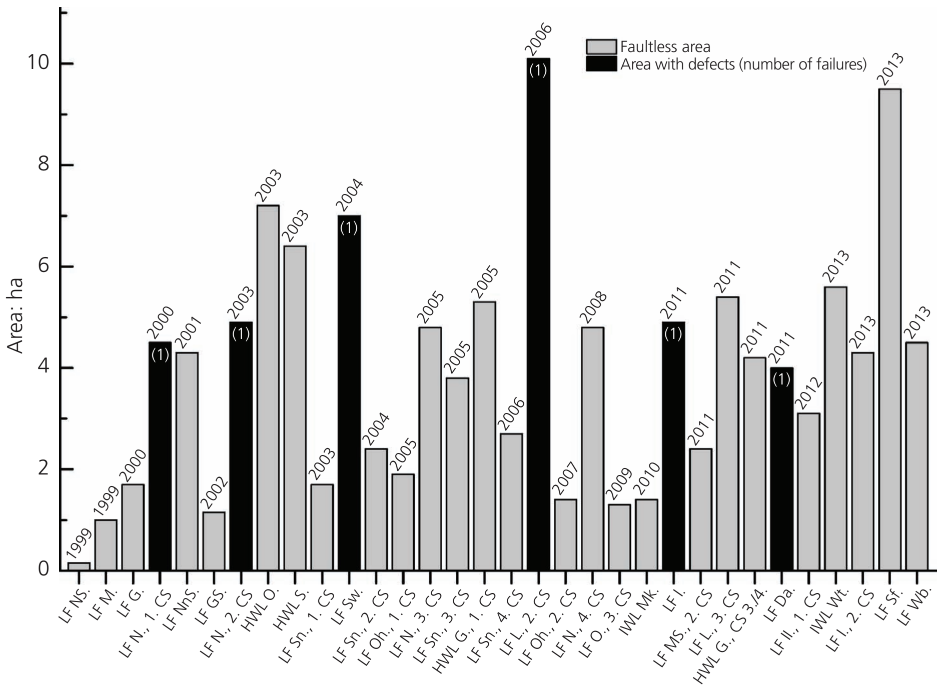

Figure 3. Monitored areas of capping systems with LDSs of anonymised landfills in Germany. The year of construction is indicated above and the number of failures within the bars. LF, landfill; HWL, hazardous waste landfill; IWL, industrial waste landfill; CS, construction section

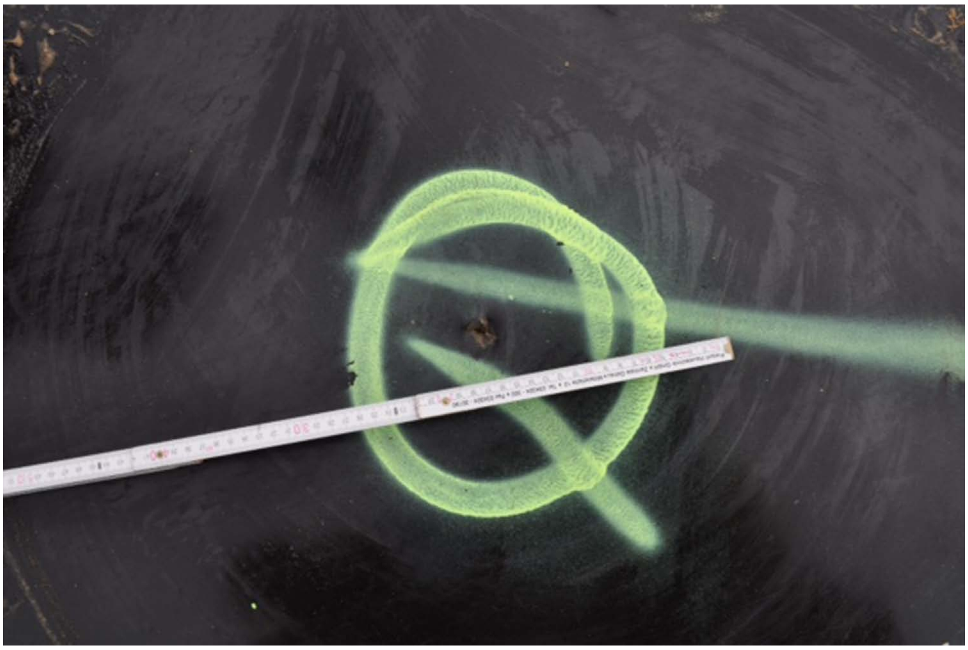

Figure 4. Defect caused by a pointed object found in the HDPE GM of landfill 'Da'

thickness of the subgrade layer, the water accumulation height and on whether the contact of the GM and subgrade is intimate or loose (Müller, 2007).

Leakage through composite liner systems

The leakage – that is, the volume of water flowing through a hole divided by the time duration of the flow – strongly depends on the contact with and the properties of the GM subgrade (Bannour *et al.*, 2016; Müller, 2007; Rowe, 2014). Quite often, formulae are used for quantitative estimates of the severity of a hole, where it is assumed that water can flow freely within a gap between the subgrade and the GM (Giroud and Bonaparte, 1989a, 1989b; Jayawickrama *et al.*, 1988). This assumption is based on the following arguments. The subgrade would usually be a soil or sand–gravel layer without being specifically rolled or scraped, or prepared in any other way. Pores, wheel marks, cracks, impressions, outstanding gravels, overlying gravels and foreign particles would shape the surface. No great importance would be attached to the surface contact of the GM. Due to temperature differences during the course of a day, the GM would develop a large number of waves, which would be covered during ballasting. Obviously, the formulae apply only to an installation practice, which allows bad subgrades, waves and wrinkles and insufficient covering. On the other hand, it was shown that, with a reasonably flat surface of the subgrade and a GM free of waves, intimate contact is easily obtained by a relatively small overburden. Under this condition, flow is located near the hole and the flow rate is essentially determined by the permeability of the subgrade (Walton and Sagar, 1990; Walton *et al.*, 1997). Therefore, a subgrade of low-permeability in intimate contact with the GM will strongly reduce the flow rate and the leakage through a hole.

In particular, the waviness of the GM is very important with respect to leakage through a GM (Müller, 2007; Rowe, 2012). Since HDPE material is incompressible, waves cannot be smoothed out by ballasting the GM. A small residual wave will remain. Larger waves or a number of waves are pushed together and standing folds, lying flat folds or mushroom-shaped waves are produced by ballasting (Koerner *et al.*, 1999). These types of waves and wrinkles typically emerge when GMs are installed over large areas, remain uncovered over long periods of time and are finally backfilled (Rowe *et al.*, 2012; Take *et al.*, 2007). The various types of residual waves and wrinkles will form a network of channels in which water can freely flow. In the flat areas in between and bounded by the network of waves, a quite intimate contact between the GM and subgrade is usually found. The effect of such a network on the flow through holes in a GM is discussed by Müller (2007) and Rowe (2012).

It follows that leakage through a hole will be extremely low if the subgrade has a flat surface and a very low permeability and if installation takes care to avoid waves and wrinkles to a large extent. Therefore, the liner and capping systems of German landfill class II (residues of thermally or biologically treated municipal waste) and landfill class III (industrial and hazardous waste) have to be realised as composite liners with a GM subgrade component of very low permeability. The regulations also include strict requirements with respect to surface properties of the subgrade and wrinkle-free installation, as described in the section titled 'Installation'.

Protection layers

More than two-thirds of GM faults that have been found in various kinds of LDS measurements in other countries and/or in other fields of application were caused during the installation of subsequent layers – that is, during construction but after the GM installation (Nosko and Touze-Foltz, 2000). Therefore, it is very helpful to cover the GM as soon as possible with a heavy, highly effective PL, which protects the GM from perforation by sharp-edged or pointed objects during construction work following the installation. However, PLs are relevant to the occurrence of holes in the long run, too. The formation of holes long after installation will be triggered by the formation of stress cracks at points of large deformation and related local stress concentration. Oxidative degradation will accelerate this process since it strongly reduces the resistance of a GM against environmental stress cracking.

An inappropriate GM subgrade and, mainly, the gravel drainage layer (base liner) or the earthen reclamation layers (capping) above GMs will contain gravel, stones or even foreign bodies of various sizes. Under dynamic and static loadings during the construction phase or in use, these objects may cause unacceptably large indentations and imprints with high local deformations. Therefore, a PL properly designed with respect to these impacts has to be placed over the GM as part of the installation to avoid the formation of holes in the long run by stress cracking. The type and design of the PLs depends on the characteristics of the neighbouring layers and the loading conditions. However, in all cases, one has to ensure that deformations imposed by indentations and imprints do not exceed the permissible local limiting strain values for the service life of the structure. A detailed description of the respective test methods for PLs and the resulting types of PLs are given elsewhere (Müller, 2007; Seeger and Müller, 2003).

Stress cracking related to deformations was studied by Abdelaal *et al*. (2014). They pre-aged HDPE GM samples in a synthetic leachate, constructed an experimental set-up of (subgrade–GM–PL–gravel), put the systems under representative loads in a 'liner longevity simulator', accelerated stress crack formation by elevated temperatures and synthetic leachate, and described and analysed the performance of the GM for the chosen PL. Stress cracks were actually initiated at the points of the largest local elongation near the edge of the indentations (Figure 5). The range of local strain, where rupture occurred during the test, was determined as a function of temperature (Figure 6). Extrapolation to low temperatures gave values not too far away from the limiting values used for PL design in Germany (3% biaxial strain for GMs in base liners and 6% for GMs in capping systems). Müller and Seeger (2003) estimated that the time to rupture at 40°C of an HDPE GM with high resistance to stress cracking and oxidation should be significantly larger than 100 years, if local strain above this limiting value is prevented by a PL.

The requirements for PLs for HDPE GMs in the base liner can be easily achieved even under very high loads with geotextile containers filled with fine sand, which form rolls about 2 cm thick. Very thick non-woven geotextiles have to be used to achieve comparable protection efficiency. Besides the perfect protection performance, the sand rolls are heavy enough to realise a quick ballasting of the GM, which is so important for avoiding waves and wrinkles.

Conclusions

Not all landfill-sealing systems necessarily leak. This was shown by an evaluation of leak-detection measurements on the latest technology for GM capping and liner systems. It is possible to describe the relevant factors for leakage accurately. They are related to the properties of the GM, the properties of the surface and permeability of the subgrade, welding and installation, the intensity of QC, the design of PLs, the procedures of the

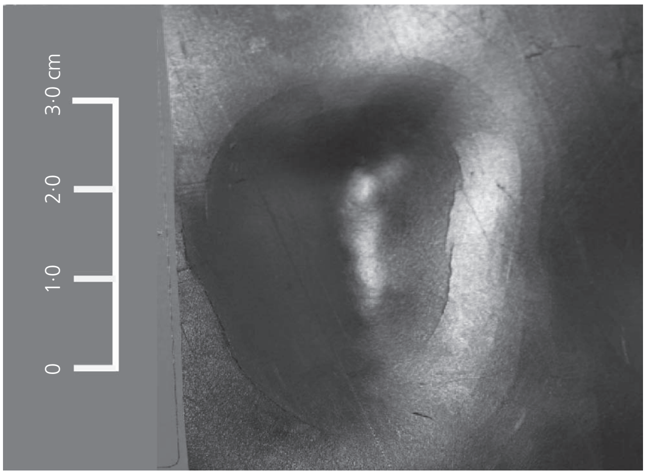

Figure 5. Stress crack formation at the edge of indentation as formed during a long-term load test at 75°C with a pre-aged 1·5 mm thick HDPE GM protected by a 560 g/m^2 non-woven geotextile PL against coarse gravel (D_{10} = 32 mm, D_{85} = 55 mm, particle diameters at which 10% and 85% by weight of the particles are finer). The picture is from Abdelaal *et al*. (2014) reproduced with permission of the publisher

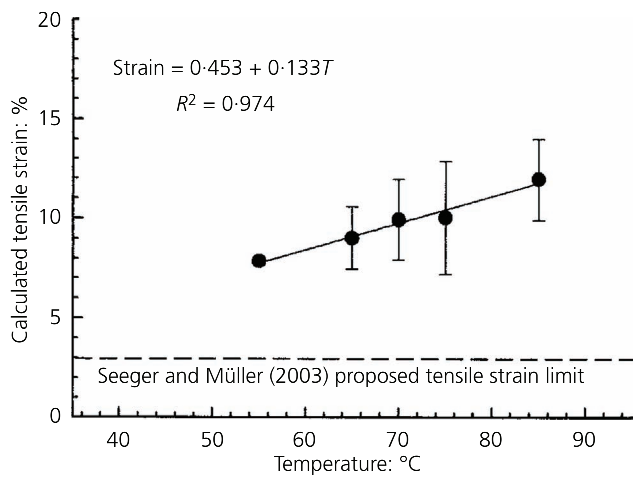

Figure 6. Maximum strain in the outer fibre of the GM, at which stress crack formation was observed, as a function of test temperature. The data were taken from Abdelaal *et al*. (2014)

backfilling and the careful planning of penetrations and constructions. It is possible to avoid the problems of leakage by engineering methods. Clearly, the procedures and requirements described in this paper are cost intensive. The installation speed is small, on average about 1000 m^2 per day of installation and crew. However, a fair cost–benefit comparison would have to take into account various externalities, which are difficult to estimate realistically and are often omitted. These are, for example, the costs of groundwater pollution as well as remediation and follow-up care of contaminated sites in the long run.

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