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Prof. Dr.-Ing. Georg Heerten,

RWTH Aachen, Germany

Prof. Robert M. Koerner,

Ph.D., P.E., NAE, Geosynthetic Institute (GSI),
Folsom, PA, USA

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Georg Heerten and Robert M. Koerner

Abstract

Some 25 to 30 years after Western nations, the emerging economies in Asia and South America, as well as the countries of the former Soviet Union now have to address the environmental problems of waste management, and to establish long-term safe landfills as a first step towards a waste management regime governed by recycling and waste-stream reduction. A cover system as part of the landfill design should permanently prevent the uncontrolled release of landfill gas (primarily methane gas (CH_4)) and pollutants, as well as the infiltration of precipitation water into the body of the landfill. Active degassing of municipal landfills takes on particular significance in the light of current climate-protection objectives, and can also provide energy by utilizing the captured gases. This paper describes current problems with classic compacted clay liners (CCLs) and their still unquestioned use in landfill legislation and landfill construction around the world. This paper focuses on dehydration/desiccation and deformation cracking when CCLs are used in landfill-capping applications. As alternative solutions, it is shown that modern capping design using geosynthetics such as certified geomembranes and certified geosynthetic clay liners (GCLs) are more than 'equivalent', and have proven to give better long-term, reliable solutions. The authors recommend the replacement of CCLs by certified geosynthetic components such as geomembranes and GCLs.

Key words: clay cracking, compacted clay liners, durability, field performance, final covers, landfills

1. INTRODUCTION

High population densities and a high degree of industrialization, in combination with lifestyles that have detrimental effects on the environment, for example in the US and in Germany, led comparatively early (about 30 years ago) to organized waste disposal at landfills designed with base and surface seals. Prior to this, of course, garbage was collected but mostly deposited unsorted in old sand or gravel pits, in stone quarries or on soil having minimal permeability – frequently in the vicinity of residential areas – without a base seal.

Modern landfills, both during their active operation and after closure, should be isolated by a combination of sealing systems and contamination barriers to restrict their adverse effects on the environment to an acceptable level. Surface sealing systems should permanently prevent the uncontrolled release of landfill gas (primarily methane gas (CH_4)) and pollutants, as well as the infiltration of precipitation water into the body of the landfill. Active degassing of municipal landfills takes on particular significance in the light of current climate-protection objectives. This is because the combustion of collected methane gas in internal combustion engines or simply by flaring it (i.e. open flame burn-off) contribute significantly to climate protection, as methane gas is about 20 times as detrimental as carbon dioxide (CO_2).

Currently, many societies and countries around the world are forced to pay the price of population explosion and industrialization, in the form of rapidly rising environmental stress. They too must now define comparable disposal paths for their industrial waste, household garbage and inert waste materials. With a delay of about 25 to 30 years, emerging economies in Asia and South America, as well as the countries of the former Soviet Union (which have comparable environmental problems) are going through this development without utilizing or conforming to the body of expertise that has

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Authors
Prof. Dr.-Ing. Georg Heerten, RWTH Aachen, Germany
Prof. Robert M. Koerner, Ph.D., P.E., NAE, Geosynthetic Institute (GSI), Folsom, PA, USA

Figure 1. Large landfill in a residential area of a large Asian city in 2006

been gathered over the past 30 years in countries such as the US or Germany.

An example of this, in 2006, was the large landfill in a residential area of a major Asian city shown in Figure 1. This is an example of the serious detrimental effects on groundwater and the atmosphere that are produced by the absence of a base seal. Severe damage and contamination to air, land and water as a consequence of population growth and ongoing industrialization are the compelling reasons for developing and implementing appropriate environmental practices with correspondingly large economic overheads. The mind-set and general acceptance of active garbage collection and safe disposal is still to be cultivated in these societies. Even though, for example, the European Union has adopted environmental goals to prevent waste and recycle waste in tightly closed material streams so that landfilling can be made an obsolete concept, economic development politics should not forget that societies must make their way through all stages of development along the path from uncontrolled dumping to closed material streams. Thus, support in many of these emerging markets for waste logistics and orderly, secure landfill practices must have top priority as a first step toward more sophisticated, and much more expensive, environmentally prudent goals. In this phase, the objective is to bolster development in waste-disposal and landfill engineering by making available the expertise gained over decades in countries like the US and Germany. Even the now-recognized potential hazards associated with the long-term effectiveness of landfill sealing systems must be made transparent in order to make the case for economically and ecologically superior solutions, thereby avoiding a repetition of negative experiences. As will be presented in more detail, this is particularly true of the unquestioned use of classic compacted clay liners (CCLs) as the sealing element in surface sealing systems.

2. A GLOBAL COMPARISON OF COVER SYSTEMS

2.1 Cover systems in current national legislation

About 25 years ago, the first national guidelines, ordinances and regulations were introduced in the US and Germany for controlled (well-regulated) waste disposal in landfills. These introduced binding requirements for landfill base sealing and cover systems. The core elements of the sealing systems were mineral components, clay as the classic sealing layer, and gravel or sand as the seepage water and gas drainage layers. When, in 1999, the Geosynthetic Research Institute (GRI) carried out the first worldwide survey of landfill liner and cover systems,[13] 37 countries or federal states had already established regulations for landfill sealing systems. The requirements were often different for hazardous waste landfills, municipal landfills and construction material dumps. All of these guidelines and regulations were basically ‘carbon copies’ of then-progressive pioneering efforts, and concentrated on mineral solutions for their sealing systems, employing clay, gravel or sand layers for the aforementioned tasks, sometimes with variations in permeability requirements or layer thicknesses.

Almost ten years later, in 2007, in a second worldwide survey of landfill base and surface sealing systems,[16] the number of nations with landfill regulations covered by the study had grown to 52 countries – an increase of about 40%. The USEPA, followed by most countries, had three unrestricted components which were found to be predominant as sealing system elements:

- the CCL;
- the geomembrane; and
- the sand drainage layer.

Thus, the initial guidelines gained wider acceptance. Combination seals of CCLs and geomembranes (HDPE) were required, particularly at the landfill base for hazardous waste and municipal waste landfills, but also as landfill covers for hazardous-waste landfills. In 23% of the regulations reviewed there was no prescribed method of sealing a landfill's surface; in 65% of the regulations, a classic compacted clay liner was perceived as sufficient; and in only 8% of the regulations was a composite liner system required to be made from CCL and HDPE geomembranes. Thus, 73% of the regulations state that a classic clay liner for the landfill surface should be provided, i.e. three out of four landfills should have a classic clay liner. Even in separate reviews of individual US states, which must at least conform to EPA requirements for sealing systems, the current situation is that they all more-or-less exclusively rely on the long-term effectiveness of a classic clay or fine-grained sealing layer for the final surface seal on municipal landfills. From the standpoint of the authors and many expert colleagues, this is a surprising situation – particularly in view of the further points made below. This situation calls for global, rigorous corrective action.

2.2 Surface seals in practical implementation

Due to the uncritical transfer of mineral capping solutions from the regulations in one country to those in others, as well as in the super-ordinate stipulations of the USEPA, alternative system components or sealing systems are not even mentioned or, at best, only implied by statements that 'equivalent' systems or system components, may also be used. This is not the case for the landfill regulations of individual US states, which must first comply with the super-ordinate regulations of the USEPA but go beyond these basic rules by expressly specifying geomembranes and geosynthetic clay liners (GCL), as well as geodrains or other geosynthetic drain structures for the design of landfill base and cover systems. This situation in US states, seemingly decoupled from the rest of the world, is justified by virtue of documented economic, ecological and functional advantages. For example, it has been explicitly documented for seepage water control systems implemented in the US, that a composite liner system of geomembrane and geosynthetic clay liner exhibits far less seepage water volume than do other system structures under otherwise comparable conditions. Beyond this situation in the US, international practice for landfill construction is to plan and execute such 'equivalent' solutions, for the most part as standard solutions prescribed by governmental agencies. Aside from the standard practice of using a geomembrane over composite liner systems (almost exclusively HDPE – currently about 150 million m^2/year), there are currently about 40 million m^2 of geosynthetic clay liners and about 75 million m^2 of geodrain systems being incorporated into landfill sealing systems around the world each year. Thus, practical execution differs quite markedly from governmental minimum requirements, with the result that geosynthetics now very clearly characterize actual engineering practices for the sealing systems of hundreds of landfills around the globe.

Whereas these standard systems and their mineral components, as envisioned by governmental agencies, are simply presupposed and expected to have long-term effectiveness without any further evidence; the so-called 'equivalent' geosynthetic system components are typically subjected to comprehensive testing to prove their long-term effectiveness – from today's perspective a totally inequitable treatment of alternative sealing systems. After over 30 years of unjustified faith in the long-term effectiveness of classic clay sealing systems, there is still no proof concept for this material, as there has long been in the case of geosynthetics.

3. COMMENTARY ON THE LONG-TERM EFFECTIVENESS OF CCLS IN SURFACE SEALING SYSTEMS

3.1 General

CCLs have long been used as hydraulic barriers or seals in canals, dams, retaining basins and other structures in direct contact with water. Extensive geoengineering and geological literature is available on classic clay liners. Therefore it is only natural that one would consider using a CCL as a seal beneath a body of waste where seepage water is to be trapped. In the opinion of the authors, this is entirely justifiable for landfill sealings when a fine-grained soil is economically available; when the clay layer can maintain the stability of its water content over the long term without problems; and when it is installed on a solid foundation of subsoil where settlement is minimal or non-existent. However, the use of a classic clay liner over a body of waste (i.e. in the cover or surface seal of a landfill) is a major challenge in view of the long-term sealing effect for critical water-content parameters of the clay liner, and the uneven settlement and subsidence associated with the body of waste.

Thus, the text which follows will deal with questions arising from current realities in Germany and the US with respect to whether or not a classic clay liner used as a landfill surface seal is at all able to fulfil its assigned function over the long term.

3.2 Increased permeability due to dehydration

3.2.1 Experience in Germany

Investigations of sealing systems with lysimeters, test fields and excavations have reported repeatedly on the danger to, or loss of, the sealing effect of mineral sealings[6,7,8,9] which renders questionable the original concept for standard sealings, designed as a composite liner system. The standard system is based on the assumption that, as a convection barrier, the geomembrane is characterized by limited long-term effectiveness, and that, subsequently, the 50-cm-thick clay liner will take over the sealing effect on a permanent basis. This technical solution has been discarded, since it has become known that the clay liner can lose its sealing effect within only a few years of dehydration, and thus is not a truly long-term solution.

A sealing system in which a geomembrane is necessary to protect another sealing element (e.g. as a barrier to roots and as a safeguard against dehydration of the mineral clay sealing layer) cannot be perceived as a composite liner system because, in this case, the two sealing components are not independent of one another, but rather complement one another in order to accomplish the sealing effect.[11]

Since the standard system has long been a 'legally fixed constant', there are no specific investigative techniques available to evaluate the long-term effectiveness of composite liner systems in surface sealing systems. With the information currently available, it therefore follows that the standard sealing (as it stands in current administrative regulations) should be eliminated when formulating new integrated landfill regulations, as is currently the case in Germany. Existing proof concepts have been demonstrated at Georgswerder in Germany and Sigmundskron/Bozen in Austria;[4] for example, an accompanying long-term test-field/lysimeter investigation of the mineral components in a composite liner system without the protective effect of an overlying geomembrane, in order to provide the multi-year monitoring data that would produce firm conclusions about the long-term effectiveness of the mineral sealing components. Although carried out at comparatively high temperatures in the waste body of a mono-landfill, five years of monitoring the test-fields of moderately plastic clay at the Sigmundskron/Bozen landfill, both with and without a protective geomembrane, revealed dehydration damage, with crack formation in the moderately plastic clay layer. Cracks in the test-fields without a geomembrane had reached a semi-permanent state, with the shrinkage cracks within the layer having widths of up to 4.5 mm.[4] Concomitant to this there was a seven-year monitoring programme of mixed-grain mineral sealings that revealed no comparable degradation. However, extrapolation options for the corresponding results in mineral-system components still need to be developed in order to draw conclusions about the long-term effectiveness of these methods.

On the subject of 'Anforderungen an Deponie-Oberflächenabdichtungssysteme' [demands made on landfill surface sealing systems], participants in a status workshop arranged by Working Group 6.1. 'Geotechnik der Deponiebauwerke' [geotechnics in landfill structures] of the Deutsche Gesellschaft für Geotechnik (DGGT) [German Geotechnical Society] and the Höxter department for waste management and landfill engineering at the Lippe and Höxter Polytechnic University, came to the following conclusions in December 2006.[21]

The standard sealing system for Class I landfills in Germany (building-rubble landfills) is a surface sealing system with only a classic, mineral clay sealing component. Scientific investigations and experience over recent decades have shown that the effectiveness of this clay-mineral sealing layer can be endangered by the following:

- Rising capillary water, convective water vapour transport and root penetration can lead to dehydration of the mineral sealing, with the potential for the formation of irreversible desiccation cracking, which would make the sealing ineffective over the long term.

It should be noted that, to date, no design rules for surface sealing systems exist that are proven to eliminate desiccation cracking in a clay-mineral sealing, or which describe how a respective system structure for sealing systems could be conceptualized to prevent the occurrence of unacceptable water-content fluctuations.

According to the original concept underlying German landfill regulations for composite liner systems, the mineral sealing component's initial function in the composite is to limit water penetration of any small imperfections in the geomembrane. Over the long term (a period >> 100 years), the mineral sealing component should provide the permanent sealing function. However, along with the failure of the geomembrane, the root barrier function is also lost, thus the mineral component might then be exposed to the same influences as a single mineral sealing layer in the standard system for Class I landfills.[11]

While the mineral sealing components are shielded against water intrusion by a functional geomembrane, there is also a risk of water extraction as a result of temperature-induced water migration. For primarily downward-oriented temperature gradients (i.e. where sealing components at the landfill's surface are warmer than the landfill's body) medium- to long-term dry-cracks can occur.

Henken-Mellies[11] come to the conclusion that composite liner systems, as they have been specified in Germany's standard sealing system, are not suitable for preventing water from seeping into the landfill's body over the long term, i.e. not significantly longer than the functional lifespan of the geomembrane. This is because the mineral components, in the form of a mineral clay sealing layer with a high percentage of fine-grained material, become susceptible to shrinkage cracks and dehydration.

This critical evaluation of the 'standard sealing system' for landfills of Class II and III (municipal waste and hazardous waste landfills) was thoroughly endorsed by the participants of the status workshop.

Thus, the geomembrane becomes the decisive element for long-term effectiveness. A composite liner system made of geomembrane and classic clay sealing renders the classic clay sealing superfluous.

3.2.2 Experience in the US

There are also reports from the US of clay seal failure scenarios as a result of changes in water content. It has been determined that, even in regions with a cool/humid climate, critical dehydration of CCLs can take place in the summer months, and that frost can also have a damaging effect.

Over the past 15 to 20 years, there have been various studies to research the performance of CCLs in landfill surface sealings. These studies employed various sizes of lysimeter beneath the CCLs, in order to collect and measure the seepage water penetrating the CCL. It should be noted that the generally accepted maximum permeability coefficient of the CCL is $k < 1 \times 10^{-7}$ cm/s, and that the corresponding conversion to 32 mm/year of seepage is important for the use and evaluation of field lysimeters. Albright *et al.*[1] provide a good overview of the investigations performed in three different climatic environments in the United States: cold/humid, warm/humid and semi-arid. It has been reported that the CCL only functions acceptably in the two semi-arid locations, with a seepage rate of less than 32 mm/year. This may be due to the initially minimal precipitation rates of only 140 to 300 mm at the semi-arid locations. In all other regions the seepage rate for the CCL was greater than 32 mm/year, and in some cases it was substantially greater. In some cases, samples were taken and the actual permeability coefficient was assessed in the laboratory, revealing increases as high as four orders of magnitude. A separate study carried out by the Maine Department of Environmental Protection found similar values when using an on-site test method for measuring the actual permeability of the CCL in the field.

In the same study, Albright *et al*.[1] evaluated the performance of three CCLs in landfill surface sealings. This study concentrated entirely on changes to the permeability coefficient, by means of laboratory permeability tests, made on samples taken that had been buried for four years. Here too, the permeability coefficients had increased substantially, with values of $k = 3.6 \times 10^{-5}$ cm/s, 1.3×10^{-5} cm/s and 3.9×10^{-6} cm/s, whereas the required value is $k < 1.0 \times 10^{-7}$ cm/s.

The most recent example is reported by Albright *et al*.[2] in the case of a CCL in a final surface sealing in southern Georgia. Following a four-year service period, the permeability coefficient had risen from about 1×10^{-7} to 1×10^{-4} cm/s.

There are a number of reports from the United States, with many examples, in which a clay sealing layer initially met requirements ($k < 1 \times 10^{-7}$ cm/s), but after only a few years of service exhibited significantly increased water permeability rates as a result of dehydration processes and accompanying crack formation – with measured permeability coefficients reaching 10^{-4} to 10^{-5} cm/s (10^{-6} to 10^{-7} m/s).

This establishes that, independently of differences in the overall design of sealing systems, surface sealing systems with classic clay liners and superimposed drainage layer and re-cultivation layers of up to 1.5 m thickness are insufficient to prevent substantial increases in the clay liner's permeability to k values of $10^{-4}/10^{-5}$ cm/s or $10^{-6}/10^{-7}$ m/s.

A geomembrane integrated as a second sealing element and component of a composite liner system can delay this development, above all by providing long-term active protection from root penetration. However, the long-term effectiveness of the composite liner system is only ensured by the geomembrane. Thus, a classic clay liner according to current concepts of landfill surface sealing systems as described here, is entirely superfluous, because it only provides permanent effectiveness in conjunction with a geomembrane which already provides this protection. The selection and installation of the geomembrane is therefore of decisive significance for the permanent effectiveness of the sealing system.

Should the regulatory authorities and landfill operators wish to continue to employ classic clay liners in surface sealing systems, there is an urgent need to develop a proof strategy from which suitable system structures and material choices can be derived for permanently effective clay liners. A requirement calling for lysimeter fields (that would be operated for a minimum period of ten years) as a mandatory constituent of surface sealings that contain classic clay liner components, could provide the basis for rapid dissemination of data about clay-liner dehydration security or endangerment. Despite this measure, however, the second major potential for endangering the permanent effectiveness of classic clay liners, namely forced deformation caused by irregular settlement and subsidence of the body of the landfill, would still have to be monitored separately.

4. RISKS TO SEALING EFFECTIVENESS CAUSED BY IRREGULAR SETTLEMENT AND SUBSIDENCE

4.1 General

Mineral sealing layers are particularly sensitive to various types of settlement and subsidence in the body of a landfill. The forced deformation in the surface sealing system, combined with surface seal crack-formation and dehydration, can lead to increased system permeability beyond tolerable limits.

Even while the landfill is still in operation, the regular measurement of landfill body settlement can provide a basis for the prognosis of residual deformation, which can be anticipated when temporary or final surface sealings are applied. This permits an estimate of the stress magnitudes, which are to be borne by the projected sealing elements. A proof is recommended as the criterion for clay liner compatibility, such as that proposed by GDA Recommendation E2-13,[5] which evaluates the anticipated deformation of the mineral sealing system's surfaces (top or bottom of layer) against its elongation at break value for the sealing material to be used. Witt[23] has proposed that in the future the sealing material's water permeability should be determined directly on laboratory samples with an axial elongation of $\varepsilon = 2‰$. This proposal not only confirms an existing deficiency in the assessment strategy for the permanent sealing effectiveness of classic clay liners as a component in landfill surface sealing systems, but is also an important indication of the very strict limitation on clay liner deformation at $\varepsilon = 2‰$ (0.2%). This value must be

Table 1. Data on tensile strain at failure for compacted clay[17]

Type or source of soil	*w* * (%)	P.I. ** (%)	ε_f*** (%)
Clayey soil	19.9	7	0.80
Illite	31.4	34	0.84
Kaolinite	37.6	38	0.16
Anonymous Dam	16.3	8	0.14
Rector Creek Dam	19.8	16	0.10
Woodcrest Dam	10.2	n/n	0.18
Wheel Oil Dam	11.2	n/p	0.07
Willard Embankment	16.4	11	0.20
			Ave. = 0.31%

* Water content
** Plasticity index
*** Tensile elongation at failure

observed, particularly for all landfill surface sealings over municipal waste and the long periods of large-scale settlement and the resulting surface deformation.

4.2 The compatibility of landfill deformation with tolerable elongation of classic clay liners

Even though settlement in a waste body comprising municipal waste may be as great as 30% of its initial depth (depending on the waste's composition, the manner in which the waste is deposited, the fill depth, the water situation and the age of the deposits), several examples are available in the literature which establish the critical deformation limits of classic clay liners with respect to their permanent sealing effectiveness. The problem is less associated with the overall even settlement of the waste body than it is with local, closely limited differences in settlement and subsidence.

In the US, there are many documented, proven cases of critical differential settlement and subsidence of landfills that exhibit acceptable limits – among others, landfills in New Jersey, Pennsylvania, Florida and Ohio (Koerner 2003). Current measurements at the landfill in New Jersey have revealed that there is differential settlement and subsidence at the surface. The 25-hectare (61.78-acre) landfill was in operation from 1966 to 1981. It was filled with municipal waste, plant waste, commercial waste and small amounts of dry, treated sewage-sludge. Probably this material was used to fill an old quarry with an unknown depth of waste – a typical old landfill without a base seal, like many others of its kind that can be found around the world and which, in some cases, unfortunately, are still in operation today.

A surface sealing system with the following components was completed in 1990:

- 150 mm of topsoil;
- 450 mm cover soil;
- 300 mm sand drainage layer;
- 300 mm compacted clay liner;
- 300 mm cover soil;
- about 450 mm levelling layer;
- waste body.

Seven years after installing the surface sealing, and 16 years after dumping ceased, the landfill's surface appearance was characterized by seven different settlements and subsidence areas. The valleys and craters were measured individually. The approximation equations specified by Koerner[15] were used to calculate the deformation relevant to the clay sealing layer. The deformation profiles and maximum elongation values for the surface seal are illustrated in Figure 2. The calculated deformation in the sealing system varies from 1.8 to 27.4%, and thus lies magnitudes beyond the permissible elongation, at break values published in the literature for individual soils and clays and for dam construction[17] (Table 1).

In the vicinity of the measured and calculated deformation, it can certainly be assumed that the installed 300-mm-thick compacted clay liner has widely lost its sealing effectiveness due to the deformation cracks, perhaps aggravated further by dehydration. Frequently a seal failure is also indicated by visible disturbances in plant growth (Figure 3).

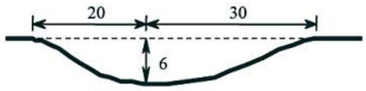
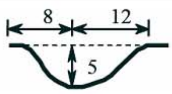
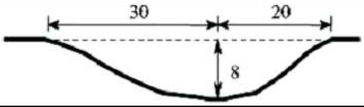
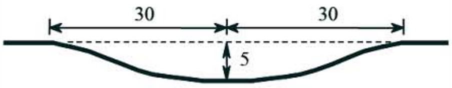
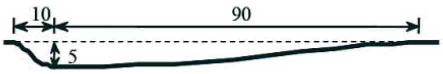
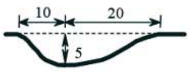
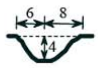
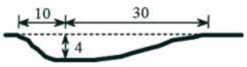
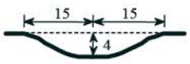
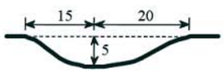
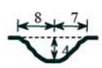
Location	Description	Approx. Dimensions (ft)	Max. Strain (%)
1	Road subsidence		5.8
2	Major crater		24.2
3	100-ft-long valley		10.3
4	Large crater		1.8
5	350-ft-long valley		15.9
6	Three craters		15.9
			27.4
			10.3
7	Four craters		4.6
			22.5
			7.3
			20.5

Figure 2. Contours of local settlement and subsidence in a New Jersey landfill, with the calculated maximum elongations in the surface seal system

The situation described here is unfortunately typical of many old landfills predominantly filled with untreated residential waste: i.e. with no base seal at all, and only a classic compacted clay liner or just a soil cover over the landfill's surface. These practices are still current in the emerging economies.

Lehners[18] describes the necessary long-term strategy to derive prognosis values for residual settling from settlement measurements taken during a landfill's utilization. These values can then be used to design an intermediate cover layer and/or final surface sealing for a landfill.

Figure 3. Visible disturbances in plant growth indicate a seal failure

At the Damsdorf landfill in northern Germany, it was possible to wait for landfill body deformation and settlement to take place or to control it in such a manner that the permissible elongation of the stiff boulder clay (ε = 2.5‰ (0.25%)) employed there would not be exceeded, and furthermore that anticipated vertical deformations, of the order of 3 to 5% of waste depth, would not lead to deformation-related damage to the sealing.

Lehners[18] recommends:

- the measurement of the deformation already occurring during landfill operation, in order to obtain initial values for the design of a surface seal;
- the control of deformation by waste selection or sorting, and the managed deposition of waste at the site;
- the repositioning of waste deposits if this is necessary to help reduce future deformation;
- the monitoring and evaluation of surface deformation with line profiles in order to monitor the stress on the surface seal.

An appropriate strategy can at least prevent deformation-related damage to classic clay liners in surface sealing systems. However, the potential damage that can be caused by changes in water content or dehydration remains unrestricted.

5. ALTERNATIVE SOLUTIONS WITH GEOSYNTHETICS

5.1 General

Whereas the mineral components of a landfill's sealing system for sealing or drainage as defined in regulations (e.g. layer thickness, permeability, grain sizes, calcium content) and which are in compliance with installation criteria (e.g. density, water content) are built and constructed to a high standard, their actual long-term effectiveness and stability after installation is simply presupposed and accepted without any proof – frequently based on the grain material's long-term stability.

However, long-term stability is not equivalent to long-term effectiveness. A component that is effective in the long term is, however, necessarily also stable for this period of time. A myriad of interactive effects and influences can make a long-term stable component ineffective for its planned task in a landfill sealing system. There are various so-called 'mineralogical analogies', which may allow judgements to be made about the long-term stability of mineral substances (e.g. quartz grains), but these are certainly not valid for judgements about the long-term effectiveness of geotechnical structures made of materials such as gravel, sand, clays or their mixtures, with and without additives to improve certain characteristics.

Evidential proof of long-term effectiveness in sealing systems will be dealt with in the text that follows.

This treatment will draw on alternative geosynthetic components as a measure for comparison, because the experience of recent years has shown that there are no other system components whose suitability has been internationally compared, intensively discussed, researched, reviewed and proven. The minimal knowledge about the long-term effectiveness of mineral layers has led, paradoxically, to their greater acceptance, rather than geosynthetic components, despite the greater body of knowledge that exists about them.

5.2 Proof of the long-term effectiveness of geosynthetics

5.2.1 Geomembranes (GM)

HDPE geomembranes have been preferred as sealing elements in landfill construction for about the past 35 years, due to their superior chemical stability. They are almost exclusively a constituent of composite liner systems, as specified in national regulations. The approval procedure for HDPE geomembranes was introduced by the Berlin-based Bundesanstalt für Materialforschung und -prüfung (BAM) [Federal Institute for Materials Research and Testing] at the end of 1989. This procedure has now been used in Germany for almost 20 years to evaluate the permanent functionality of geomembranes as a landfill sealing component. In the US, the regulatory requirements are defined by the GRI (Geosynthetic Research Institute) Test Method GM13 – 'Test Methods, Properties and Testing Frequency for High-Density Polyethylene (HDPE) Smooth and Textured Geomembranes'.

The following supplementary factors should be noted when using BAM or GRI-Standard approved or tested geomembranes in a surface sealing system:

- the superimposed layers (drainage and cover) offer perfect long-term protection against UV radiation;
- the geomembrane is able to withstand a large range of forced deformation without damage;
- the geomembrane remains impervious to the effects of frost, fluctuations in water content or water tension in the overlying layers (e.g. cover soil and topsoil layers);
- the geomembrane is a stable barrier against roots and rodents;
- the geomembrane remains permanently water- and gas-tight.

Supplementary proof of the stability of landfill embankments must be documented separately. This should be done with state-of-the-art techniques for assessed friction coefficients between the geomembrane and adjacent friction parameters, with sufficient safety factors for the structural and operational conditions of the specific product.

The inspection of surface seals (as reported by Rödel[22]) which employ BAM-approved geomembranes is carried out in Germany using electrical leak detection systems. These inspections are to establish that there is less than one damaged location per 50 000 m^2 of GM liner material. The causes of the defects found were about equally divided between construction activity associated with the installation of overlying mineral layers and with faults in the welding of the geomembrane. Thus, more than 100 000 m^2 of this material are properly welded, and more than 100 000 m^2 are properly installed and covered (earthworks) without any defects – impressive evidence for the high quality that can be achieved with a sealing made of HDPE geomembranes. It can be assumed that under these documented boundary conditions, the sealing objectives, i.e. the prevention of uncontrolled release of landfill gas and hazardous materials into the environment, as well as prevention of precipitation water from intruding into the landfill body, are optimally achieved on a long-term basis. Therefore BAM-approved or GM13-tested geomembranes can now serve as the standard against which all other sealing components are measured (even though BAM approval demands markedly stricter requirements). This assessment is supported by investigations and conclusions in the international literature.

There is currently an extensive literature base regarding the long-term effectiveness of HDPE geomembranes[20] which is based on time-temperature superposition followed by Arrhenius modelling (Koerner and Hsuan[14] and Müller[20]) (Table 2).

The material's definitive mechanical characteristics will be degraded over the specified timeframe. These are conclusions derived from aggressive laboratory immersion tests conducted at 80°C, in order to accelerate the ageing processes at a constant temperature. According to Table 2, at a given constant ambient temperature for the geomembrane, for example 30°C, the mechanical characteristics will have degraded over a

Table 2. Long-term effectiveness of HDPE geomembranes in conjunction with ambient temperature

Temperature (°C)	Long-term effectiveness (years)
20	400–1000
25	250–600
30	150–400
35	100–250
40	60–180

period of 150 to 400 years, to the point at which only a brittle synthetic plate remains, which, however, does still fulfil its sealing function. This timeframe is denoted in the literature[20] as the ‘service life’, and is therefore the sought-after long-term effectiveness of the by-then brittle HDPE plate that still has its sealing effect intact. At the end of this period it will be lying on a stable landfill body that has long since ceased to require ‘post-operative’ care, but which continues to fulfil its sealing function. Even with somewhat different proof techniques, this fundamental claim for BAM-approved or GM13-tested HDPE geomembranes can be made. Corresponding quality assurance systems can guarantee the long-term effectiveness of sealing systems anywhere in the world.

5.2.2 Geosynthetic clay liners (GCL)

Developed 20 years ago, shear-force-transferring bentonite mats or geosynthetic clay liners have already found widespread application as replacements for, or improvements to, classic compacted clay liners around the world. The largest single market for these liners is North America, followed by Europe. Market conditions in North America led to bentonite mats employing bentonite granulate bound in needle-punched or glued textile–bentonite–composite products. In Europe, the needle-punched bentonite mat with bentonite powder as the fibre-reinforced sealing element is dominant in landfill construction. Whereas glued bentonite mats are barely able to transfer the shear force (due to the necessary water-solubility of the glue that produces the sealing effect in its swollen state), needle-punched, fibre-reinforced bentonite mats must be capable of transferring shear forces over the long term, particularly on steep embankments.

In Germany, two products (Bentofix B 4000 and Bentofix BZ 6000) were recently forwarded from the LAGA-Adhoc-Gruppe ‘Deponietechnische Vollzugsfragen’ [LAGA *ad hoc* group for landfill engineering implementation questions] to the Ausschuss für abfalltechnische Fragen (ATA) [committee for waste engineering questions] of the Länderarbeitsgemeinschaft Abfall (LAGA) [states’ working group for waste] with a recommendation for approval of their use as mineral sealing components in landfill surface sealing systems (DK I) [landfill class I] and indicated that their use could be expanded to DK II [landfill class II] providing that two additional proofs are successfully completed.

German government representatives in the LAGA-Adhoc-Gruppe have thus accepted the proofs of permanent stability and permanent sealing effects for these products. This followed a multi-year proof procedure that was able to build on the foundation of test results and appraisals in an earlier approval issued by the Deutsches Institut für Bautechnik (DIBt) [German institute for construction engineering].

BAM was able to prove a permanent shear-force transfer after developing and performing appropriate long-term shear/creep tests.[19] In 2004, it was possible to present a BAM test report on the long-term shear strength of a bentonite mat, documenting the extrapolated functional longevity at a 15°C ambient temperature for a period of over 400 years.

Several samples from this long-term series were subsequently examined for residual internal shear strength in short-term experiments. The samples used in these BAM experiments had been artificially aged for the equivalent of hundreds of years, yet still exhibited substantial load-carrying reserves.[12] In summary, the results show that, when used in landfill surface seals, the internal shear strength of the geosynthetic components alone, in the bentonite mats investigated, is sufficient to ensure the structural stability of the sealing system over at least centuries (>>100 years), whereby these current testing methods are unable to establish a definitive limit on the functional lifespan.

The proof of a permanent sealing effect with great system effectiveness was established through experiments in the field and in the laboratory. In the evaluation of test-field excavations and lysimeter measurements, it was proved that the shear-force-transferring, needle-punched, single-layer bentonite mats with powder-form sodium bentonite possess a self-healing capability under typical system boundary conditions. Among landfill design experts it was erroneously supposed that the thick compacted clay liners, were able, after dehydration and desiccation cracking, to (self)-heal the polyhedral aggregate structure and to restore adequate sealing effectiveness in the long term.

The measurements taken by a special lysimeter system since 1998 have provided proof of the long-term sealing effect through changing moisture conditions. To date, this system, consisting of six individual lysimeters, is still in continuous operation, involving scientists, engineers and other personnel from the University of Hanover's department for Foundation Engineering, Soil Mechanics and Hydropower. The set-up and initial measurement results are described in detail.[3] The results clearly show the differences between dry periods in the summer months and wet periods in the winter. As an example, Figure 4 shows, for one lysimeter, the corresponding degree of efficiency of a standard Bentofix® bentonite mat, as well as the system efficiency of the overall set-up with regard to the presence of a sealing effect.

Whereas the degree of efficiency of the bentonite mat was calculated as a quotient of permeation based on the volume of drainage, i.e. the amount of water from precipitation which seeps down as far as the bentonite mat, the system efficiency, in contrast, results from the permeation based on overall precipitation, and describes not only the barrier effect of the bentonite mat, but also the evaporation arising from the recultivation layer and vegetation. It is obvious that, each summer, the efficiency of the bentonite mat is reduced through desiccation processes, but that these are also compensated for by evapotranspiration from the recultivation layer/vegetation, such that a high degree of system efficiency, approximately 98 to 99%, is maintained. Equally obvious is the level of improvement in the efficiency of the Bentofix® GCL each winter, which repeatedly reaches the level of the previous year. Since an ion exchange took place (an exchange of

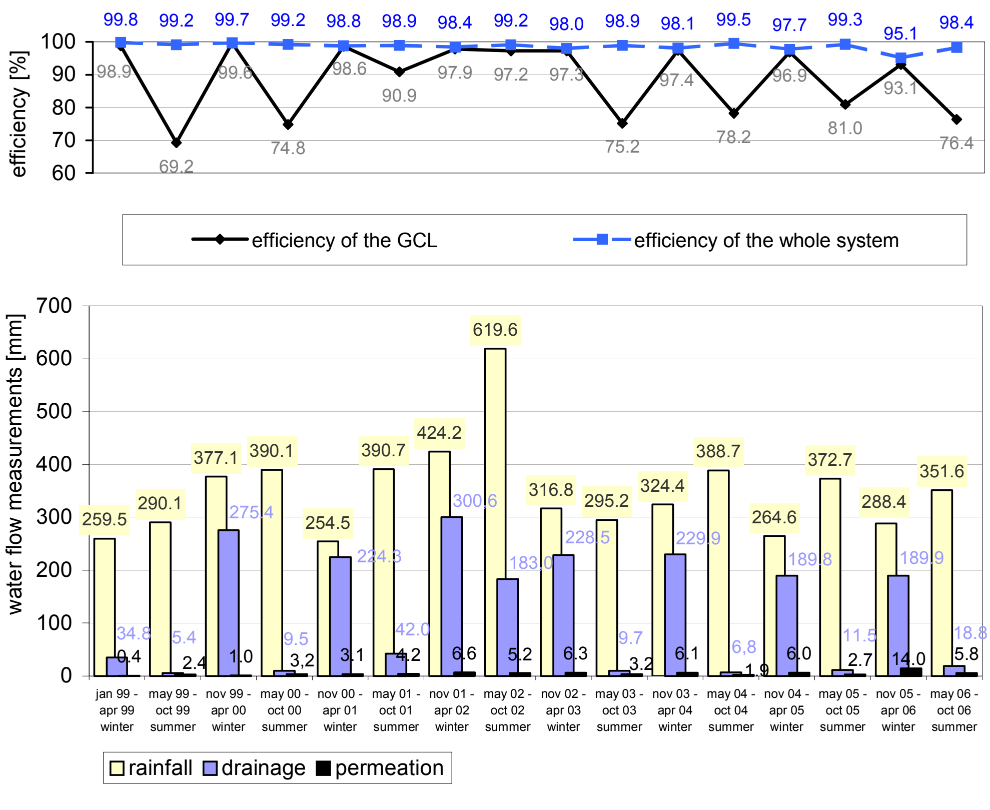


Figure 4. Lysimeter 3 – effects of summer and winter cycles on the sealing efficiency of a single-layer, standard Bentofix® bentonite mat with a 1-m recultivation layer

sodium ions against calcium ions in sodium bentonite) in the bentonite layer of the bentonite mats installed in the lysimeter two to three years after installation, the results establish that there is no reason to fear a reduction in the quality or sealing efficiency of Bentofix® or in the efficiency of the system following ion exchange in surface sealing systems of comparable design, even after many alternating dry and wet cycles.

These results show that geosynthetic clay liners have reached the long-term effectiveness level of HDPE geomembranes.

If the quality of geosynthetic products; the quality of installation for HDPE synthetic sealing liners; and that of needle-punched geosynthetic clay sealing liners succeed in becoming appropriately established around the world, permanently effective surface sealing systems can be built anywhere in the world.

6. SUMMARY AND FUTURE PROSPECTS

Because the standard sealing systems prescribed by many countries and states specify a compacted clay liner as the sealing element in administrative regulations, a paradoxical situation has developed in which these standard systems are presumed to have permanent long-term effectiveness, along with the assumption that alternative systems must first undergo extensive approval or suitability procedures to verify their 'equivalency' and long-term effectiveness – a lack of knowledge about the long-term effectiveness of standard mineral components has led to their extensive acceptance rather than the extensive knowledge of geosynthetics, as provided by specific proofs. In the light of current awareness about the failure of compacted clay liners in standard systems for surface seals – as a result of desiccation and forced deformation – along with the existence of approvals and suitability proofs for alternative components, it is only logical and absolutely welcome to see that geosynthetic products are finding increasing application in landfill sealing systems around the world.

The standard sealing, with its singular focus on a natural mineral clay sealing as the 'permanently' effective sealing element is still waiting for new design and execution concepts – which are likely to incur distinctly higher overheads for verification, testing and execution. Assessment of clay minerals using mineralogical analogies does not lead to results that suggest longer-term stability, or equally, the long-term efficiency of clay as a sealing layer. This has been demonstrated by findings from field studies, for example by Albright *et al.*[1,2]

Unconditional faith in the stability and effectiveness of the mineral compacted clay (standard) sealing often creates insurmountable hurdles for technically superior alternative solutions that have proven long service lives amounting to centuries, and prevents these better solutions from making a contribution to the super-ordinate goal of environmental protection. In the sense of a call for more truthfulness in dealing with landfill surface seals, the limits of material and engineering prognoses for all systems and components should be openly admitted.

BAM-approved or GM13-tested HDPE geomembranes, produced in compliance with approval conditions and carefully installed by qualified personnel, ensure a period of utilization far beyond that forecast by all realistic engineering timeframes. Corresponding faith in the long-term effectiveness of bentonite mats that have been subjected to a German governmental (LAGA) suitability assessment, can also be anticipated.

Landfill engineering in the 1990s was aimed at ensuring that the landfills of our time do not become hazardous waste sites for future generations. The installation of suitability-tested, quality-monitored geosynthetics provides help around the world to achieve this lofty goal – with permanently effective surface sealing systems.

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