GEOMEMBRANES IN LANDFILL ENGINEERING

GEOMEMBRANELE IN CONSTRUCȚIA DEPOZITELOR DE DEŞEURI

Prof. Dr.-Ing. H. Düllmann
Facultatea de Inginerie a Materialelor şi Resurselor Minerale RWTH, Universitatea Aachen, Germania

ABSTRACT. Further on in waste management the basic principle is valid: waste avoidance before waste recycling before waste disposal. This demand includes that in spite of modern avoidance and recycling strategies waste has to be deposited. Thus landfills are essential components of each waste disposal concept. Design, construction and operation of landfills have to take place in a way that unexpected incidents which may lead to serious damages are practically impossible, if they occur however they must be corrigible with low effort. Landfills produce at long sight always hazardous sites. For all landfill concepts it is therefore essential that the long-term safety can be provided reliably. This paper will give a report of the geomembrane role in landfill engineering today.

REZUMAT. Principiul de bază in managementul deşeurilor rămâne in continuare valabil: cu cat mai puține deşeuri produse, cu atât mai puține deşeuri de reciclat, ceea ce înseamnă cu atât mai puține deşeuri de depozitat. Această cerință înseamnă că, in ciuda strategiilor moderne de evitare pe cat posibil a producerii deşeurilor, cat şi a strategiilor de reciclare, tot mai rămân deşeuri ce trebuie depozitate. Din acest motiv, depozitele de deşeuri reprezintă o componentă esențială a fiecărui concept de eliminare a deşeurilor. Proiectarea, construcția şi operarea depozitelor de deşeuri trebuie să se desfăşoare astfel încât incidentele care ar putea duce la deteriorări majore să fie practic imposibile, iar dacă totuşi acestea apar, să poată fi corectate cu efort minim. Pe termen lung, toate depozitele de deşeuri devin nişte construcții imprevizibile. Din acest motiv, pentru toate conceptele de depozite de deşeuri este esențială asigurarea in condiții optime a siguranței pe termen lung. Lucrarea de față prezintă rolul geomembranelor in construcția depozitelor de deşeuri.

1. Safety considerations – Multi-Barrier-Concept

To avoid the mistakes of the past already at the end of the eighties and the beginning of the nineties intensified safety considerations started, which lead in Germany e.g. to the Technical Instructions on Waste (TA Abfall, 1991) and Technical Instructions on Municipal Waste (TASi, 1993). In these technical instructions for the first time aims of proctection and levels of protection have been defined clearly. Taking into account the principles of TASi landfills have to be designed that several widely independent effective barriers exist and the release and migration of pollutants can be avoided with respect to the state of the art. This aim will be achieved by:

- qualified geological and hydrogeological locations (**geological barrier**),
- adequate liner systems (**technical barrier**),
- adequate waste pre-treatment and disposal techniques (**waste barrier**) and
- compliance with chemical and mechanical **assignment criteria**.

Considering the assignment criteria particularly the following protection goals should be achieved:

- practically no development of landfill gas,
- low organic contamination of leachate and
- negligible settlements by biodegradation.

The level of protection in the technical instructions are expressed by the assignment criteria and by some verbal requirements and from these derived the necessary protection level of common welfare.

The subjects of protection are predominantly: health of people, animals, flora and fauna as well as the environmental media water, soil and air.

Besides the protection goals listed in fig. 1 TASi declares as a superior protection goal the prevention of pollutants emission.

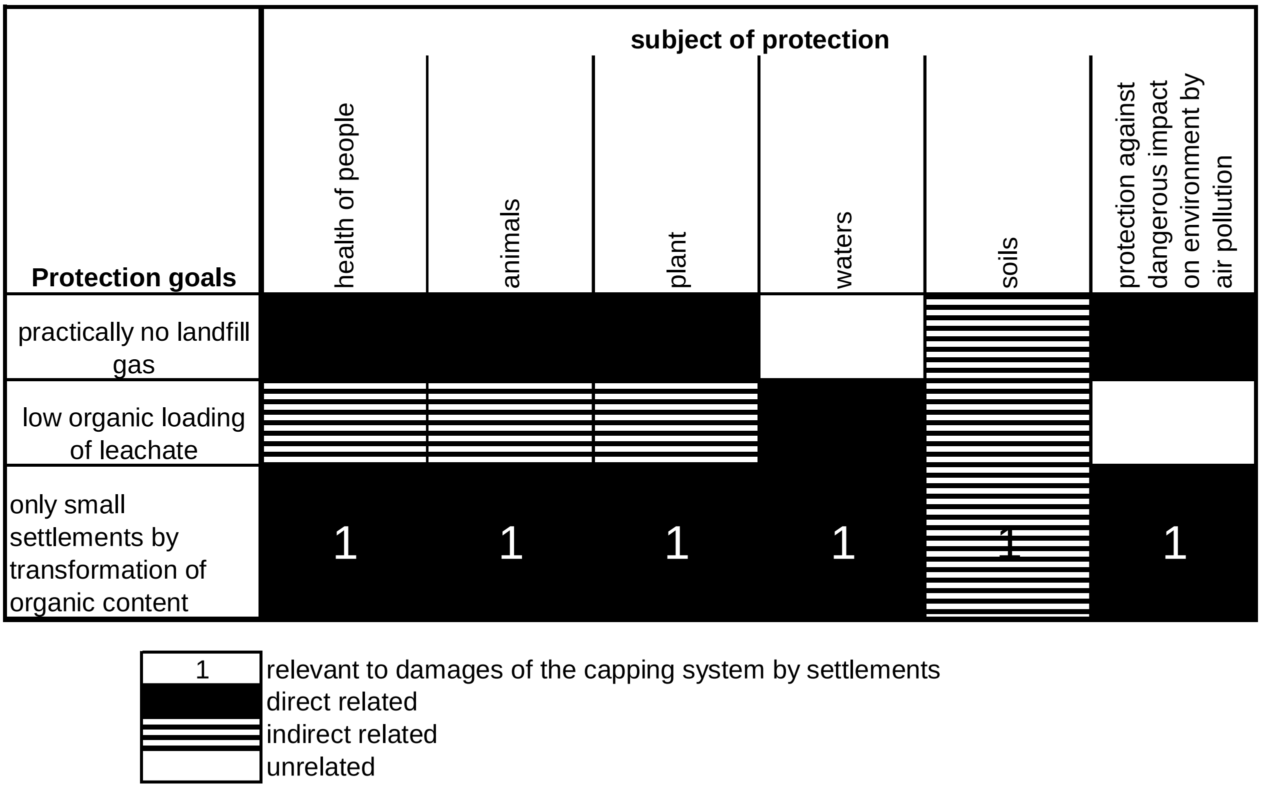


Figure 1. Relations between protection goals and subjects of protection (DÜLLMANN, 1999)

With regard to the level of protection this means zero emission of gaseous and liquid pollutants as far as this can be achieved with respect to the state of the art. This aim should be assured by different independent barriers (waste deposit, liner systems and landfill environment), that means by a system of barriers, the so called “Multi-Barrier-Concept” (fig. 2).

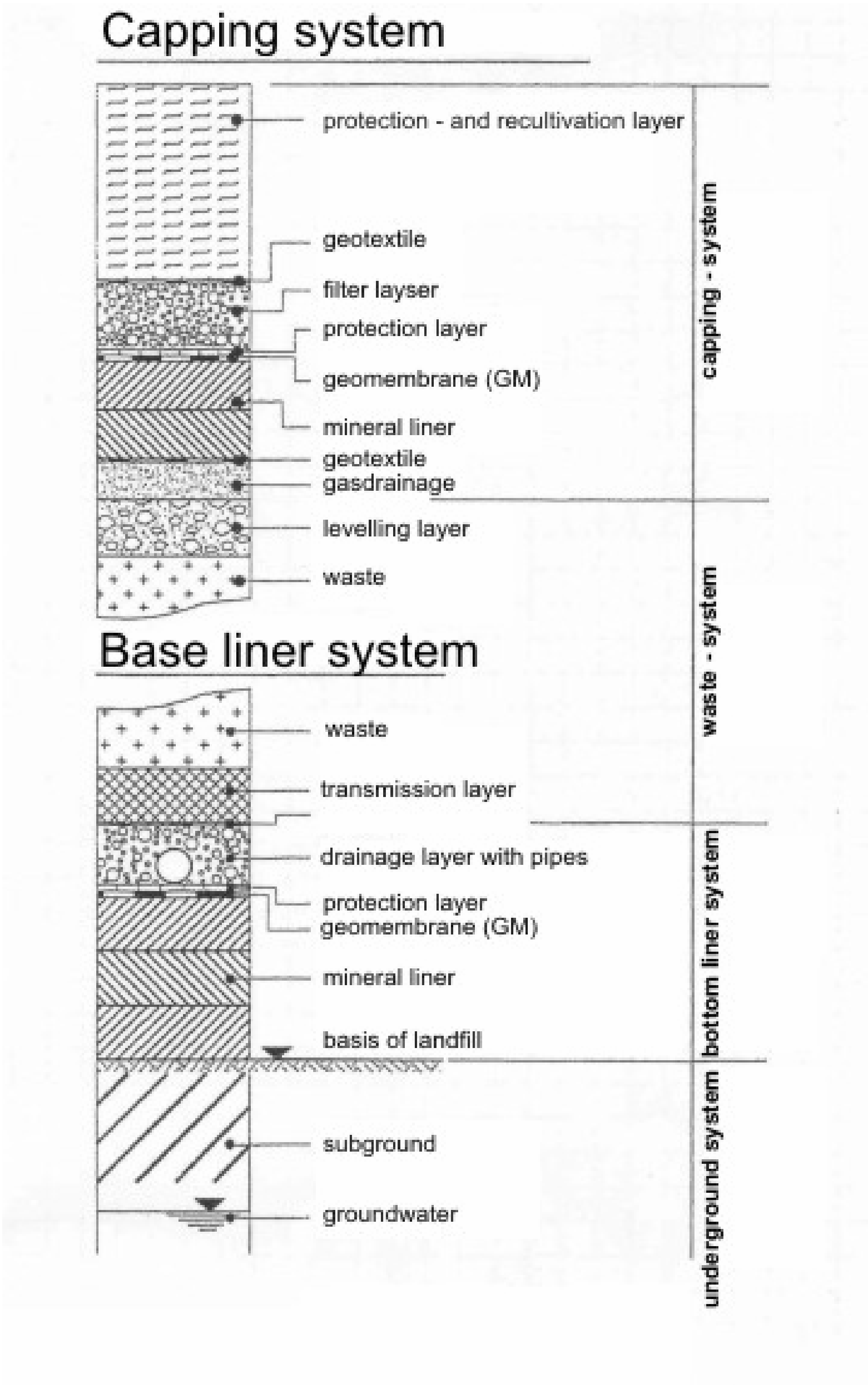


Figure 2. Components of the "Multi-Barrier-Concept"

The realization of the “Multi-Barrier-Concept” takes place in the technical design by:

- choice of qualified materials,
- dimensioning of retaining elements with regard to the required function,
- technical instructions for establishing the different protection elements.

The demand for safety and reliability of the single elements and the complete system is very high and can be achieved only by defined quality requirements, usually defined by minimum values. Till this day there is a lack of useable approaches for a checkable quantification of the standards and the methods of calculation and evaluation, by which the compliance with the requirements can be checked. Furthermore there is a lack of numerical evaluation of failure probabilities of single components and of the complete system which are necessary for an analysis of sensitivity and critical points. A first approach can be found in RODIĆ (2000).

Essential elements of long-term safety are the durability of materials and the effectiveness of the complete system. It has to be assured that the long-time impact has no negative influence on the liner systems and the liner systems remains completely in function.

Another aspect of great importance is the quality management when installing the liner systems. This is valid for the mineral components as well as for the geosynthetic components as geomembranes (GM), geotextiles for protection, separation, reinforcement and stabilization. Only quality mangement guarantees that the quality standards according the state of the art will be maintained for the complete construction of a landfill as well as for the single component. Quality management refers to the applied materials and to the quality of construction (see also chapter 5).

Considering the guidelines of the Technical Instructions concerning the Multi-Barrier- Concept, the geometrical and qualitative specifications for retaining elements, the installation of a quality management system and the aftercare the formulated protection goals can be maintained.

2. Composite liner systems

The composite liner system plays an important role in the Multi-Barrier-Concept. It has to be noted, that the concept has been developed in a time, when bottom liner systems of landsides were predominantly object of scientific and technical considerations and developments. The requirements and findings for the bottom liner system have been transferred approximatively to liner systems for the top of a landfill. Thereby has been expected that a composite liner system being composed of a mineral liner and a geomembrane will be effective unlimited in time.

However in the last years questions and doubts appeared whether the concept of the composite liner in accordance to the Technical Instructions is further on valid on the base of new scientific and practical findings and expert knowledge especially for liner systems on top of a landfill. Furthermore different and controversial opinions have developed about the long- time behavior of mineral components in comparison with geosynthetics, especially geomembranes.

2.1 Mode of operation of the composite liner

The effectiveness of the composite liner system consists in the sequenz of polar and nonpolar sealing materials. Important is the inner compound of the single components (pressure compound). The mineral liner causes additionally the effect of redundancy. Provided the pressure compound exists a leakage in the geomembrane is only of local consequence. Local imperfections in the geomembrane are however compensated by the mineral liner. When covering the mineral liner by an impervious geomembrane convective migration of water or leachate will be prevented completely.

The geomembrane has a certain, relatively low permeability against nonpolar organic ingredients. These substances are hardly soluble in the porewater of the strong polar mineral liner material and will be rarely reabsorbed. Inside the geomembrane will take place a concentration and from this follows a reduction of the gradient of concentration and of the rate of diffusion and permeation (fig. 3).

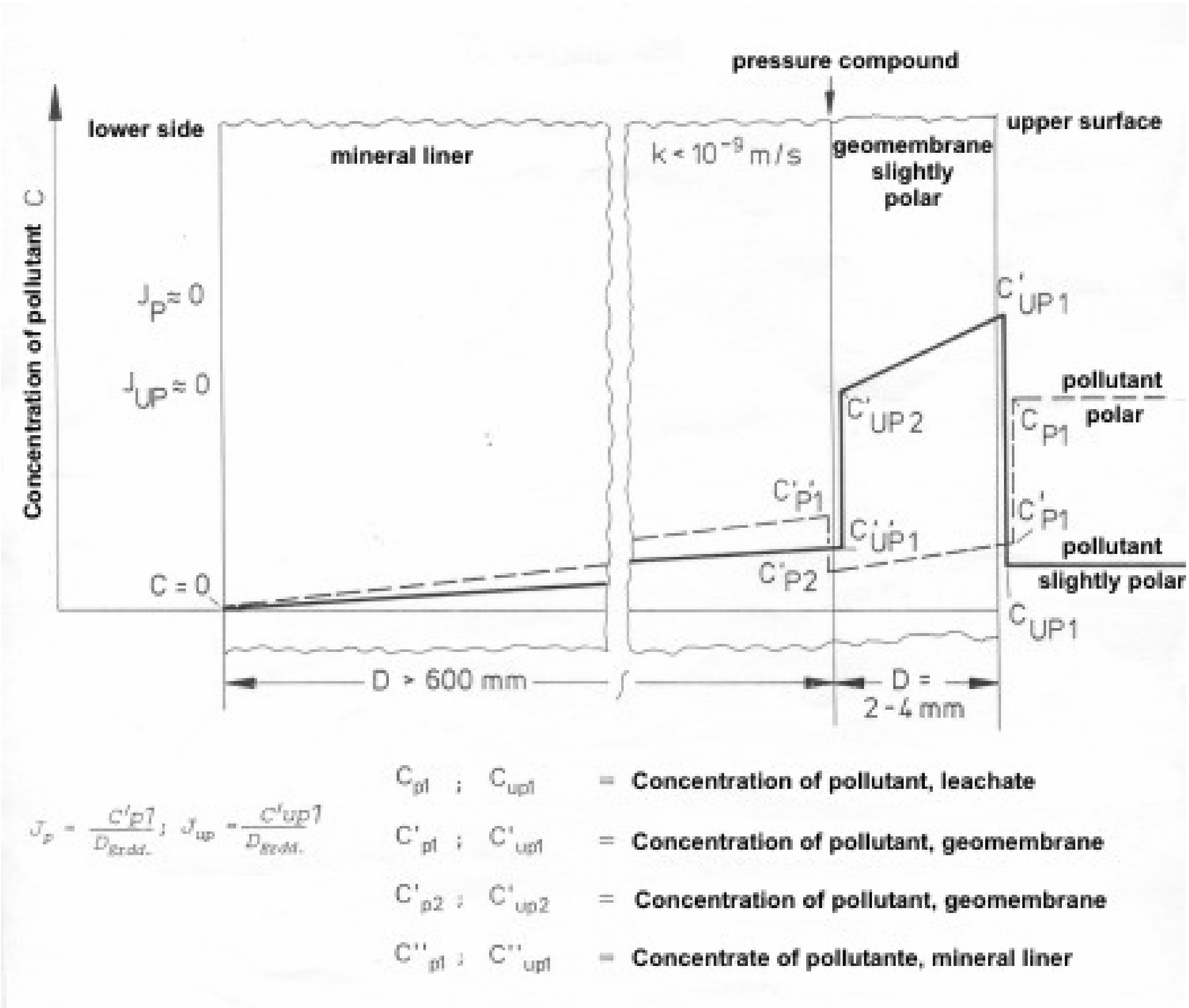


Fig. 3: Development of concentration (quantitative) of polar and nonpolar pollutants in a composite liner (AUGUST et al., 1992)

The further transport in the mineral liner depends on the difference of concentration between the upper and lower side of the mineral liner, the gradient of concentration is very small.

Polar pollutants will be better transported in the pore water of the mineral liner because of their good solubility, but because of their different chemical behaviour they will be adsorbed on a significantly lower level. All together can be estimated, that the permeability of polar components in the leachate will reach negligible values provided that the geomembrane has a sufficient thickness. When estimating the discharge of pollutants through a composite liner system MÜLLER (1994) comes to comparable results. The time of induction for many inorganic pollutants, especially metals, will be much longer than the operation duration of a landfill. The geomembrane protects the mineral liner in a phase with a high amount of organic loaded leachate and reduces the transport of leachate to pure diffusion. These rates are negligible.

2.2. Effectiveness of the mineral component

Today are preferred in accordance with the Technical Instructions (TASi, 1993) fine grained materials with a high clay content and a classification as TM or TA ($w_L > 35$ %) in the Casagrande diagram. The compaction is suggested on the wet side of the Proctor diagram ($w_{Pr} < w < w_{0,95}$) with a minimum compaction of 95 % Proctor-density. As a consequence from this follows, water is a not negligible component of the liner material. Water influences not only the compaction- and permeability-behavior but also the deformability and volume changes by reducing the water content. According to newer cognitions the emplacement of a clay with a distinct plastic behaviour and a relatively high water content when compacted can no longer be recommended. Favourable are soils with a low to medium plasticity (UL, TL, TM) and compaction in the range of the optimal water content or some what lower combined with a higher compaction energy. When the compaction can not be applied another concepts for the liner material have to be chosen.

In accordance to own experiences in the future importance has to be attached much more to long term effectiveness of the mineral liner instaed of low permeabilities in the phase of construction. The long term resistance of fine grained soils against leachate can certainly be expected because of the genesis of these materials, but not the long term effectiveness as a result of possible structural changes, e.g. due to crack formations as a result of changes in water content and/or mechanical stresses and strains in the desiccated state. Long term effectiveness of the mineral component can only be ensured, when a balanced relationship between the parameters permeability, tensile strength, shrinkage capacity and installation (WITT, 2006) is given.

2.3. Effectiveness of geomembranes

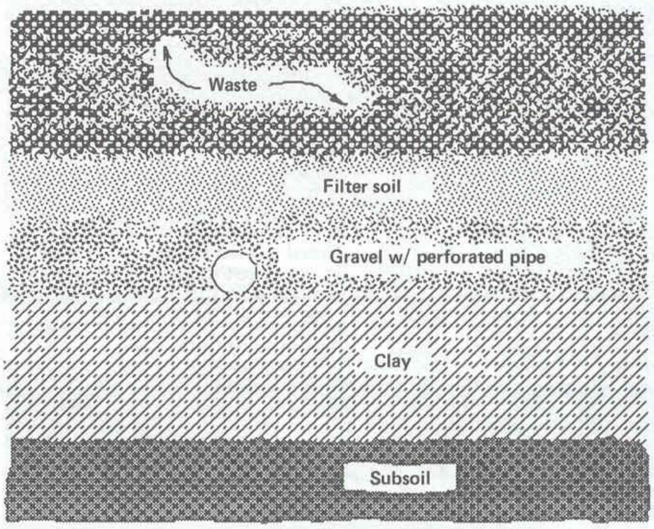
Geomembranes, manufactured with high quality from special Polyethylen-moulding materials and with adequate thickness, show a very high long time effectiveness, which has been tested in the past in extensive and independent test procedures (MÜLLER, 2007). The high efficiency depends to a high degree on the quality of installation. The knowledge about material behaviour and experiences with geomembranes is better than for most other, especially mineral liner materials, nevertheless these mineral materials are expected to have a better long term effectiveness. The durability of PEHD geomembranes which follow the BAM certification guidelines (s. chapter 5) reach more than 100 years for base liners with leachate contact, geomembranes in capping systems >> 100 to 200 years.

2.4. Evaluation of composite liners for different application areas

2.4.1 Preliminary remarks

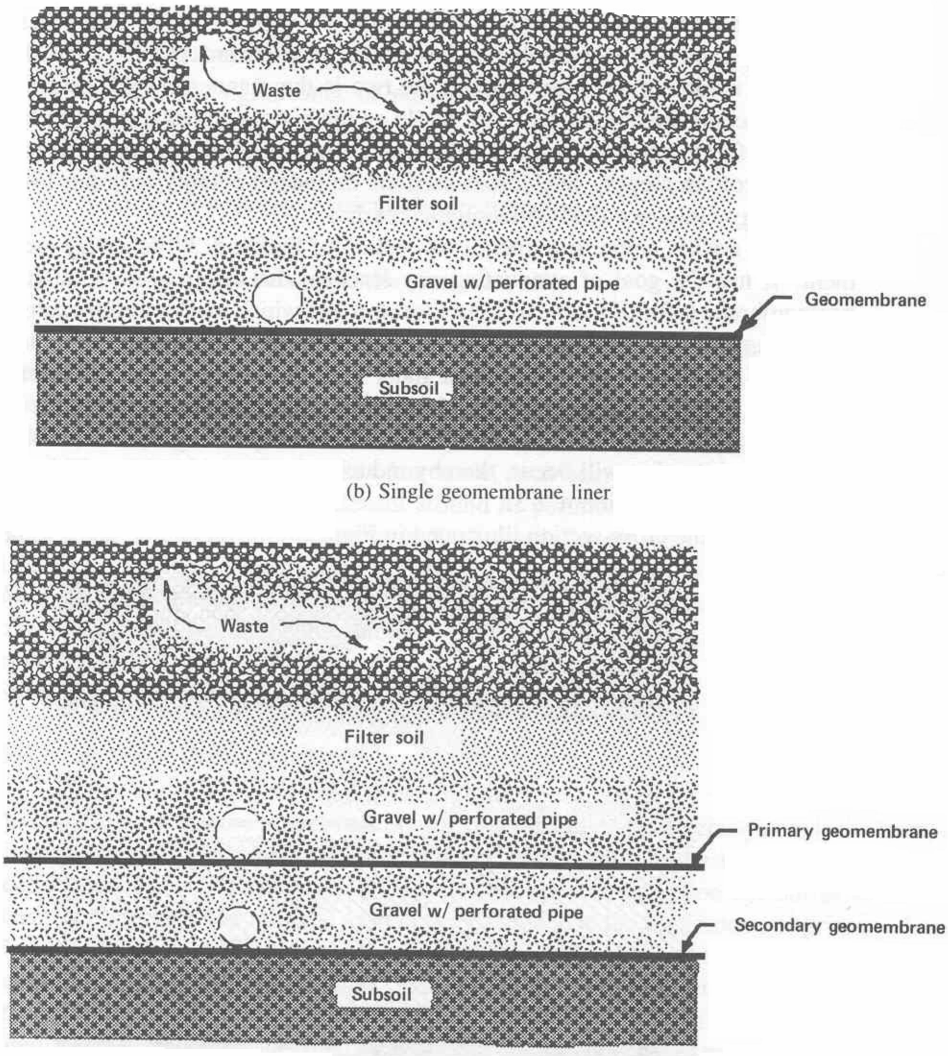
In Germany the Technical Instructions from 1991 (TA Abfall) and 1993 (TA Siedlungsabfall) describe in detail the design of the basal liner and capping system for four landfill classes. Class 0 is for inert waste materials, classes I and II are for low-contaminated mineral waste and treated municipal waste and class III is for wastes with high amounts of hazardous substances. Along with an increasing hazardous potential of the waste disposed in the various types of landfill the requirements on the basal liner and capping systems are increasing (MÜLLER, 2007). The standard basal liner and capping system for landfill classes II and III is the composite liner made of a plastic geomembrane in intimate contact with a compacted clay liner.

A very interesting insight into the development of geomembrane liner systems in the U.S. offers KOERNER (1990) in fig. 4. The figure shows that the systems become in the course of time a very complex composition and show further that geosynthetic materials (geotextiles, geocomposites, geonets, geomembranes) are essential elements in all liner systems.



(a) Single clay liner

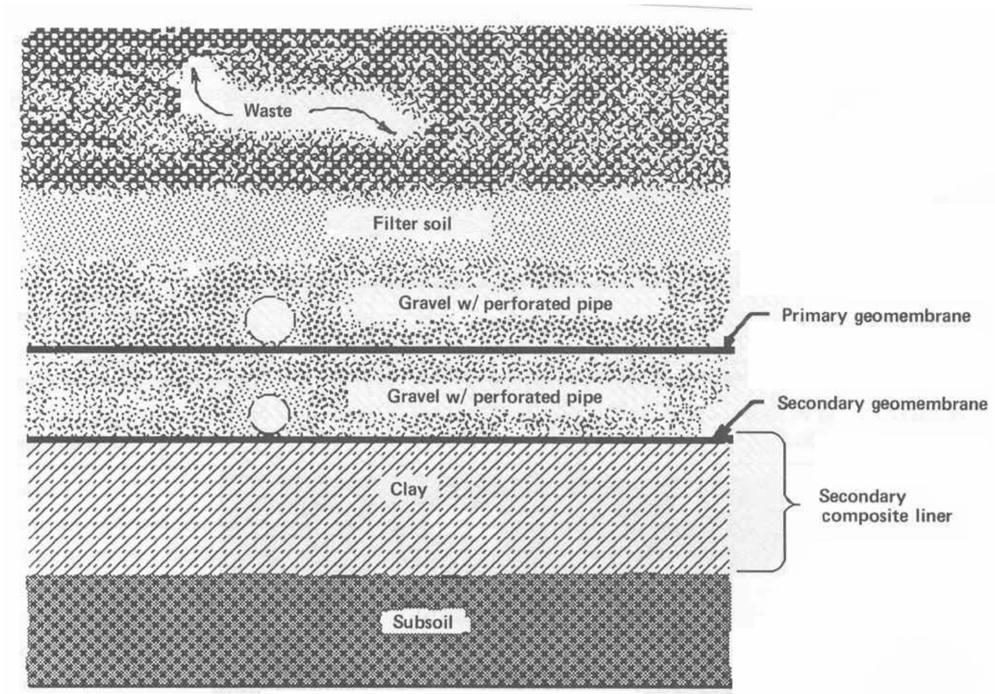
Figure 4. Genesis of liner cross-sections used to contain solid waste in the U.S. since 1982 (KOERNER, 1990)



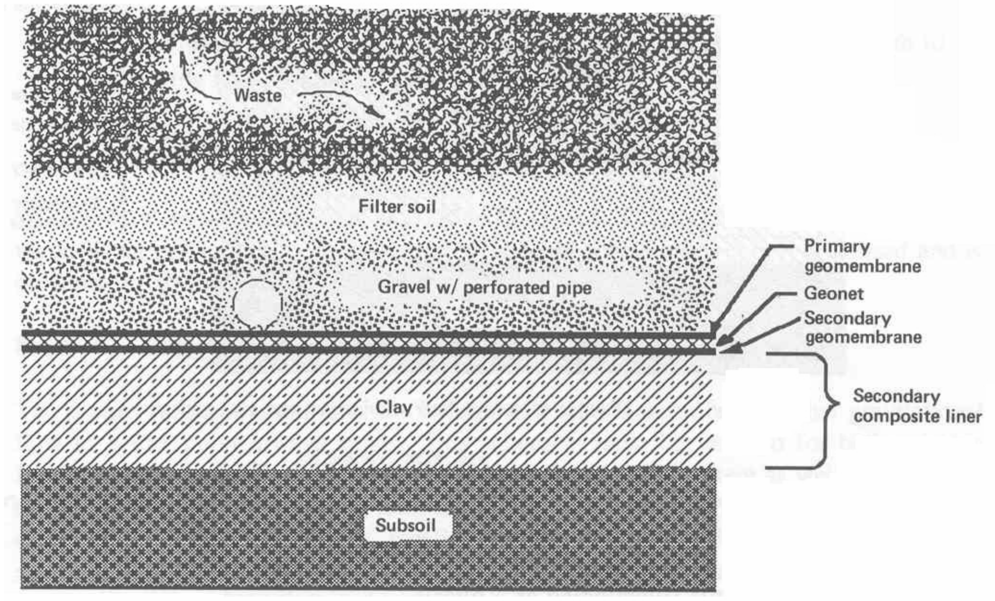
(b) Single geomembrane liner

(c) Double geomembrane liner

Figure 4. (Continued)

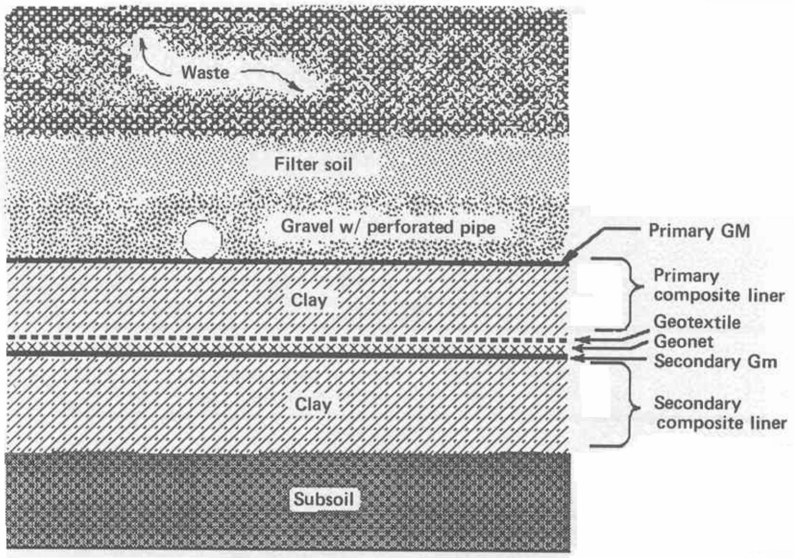


(d) Single geomembrane, single composite liner

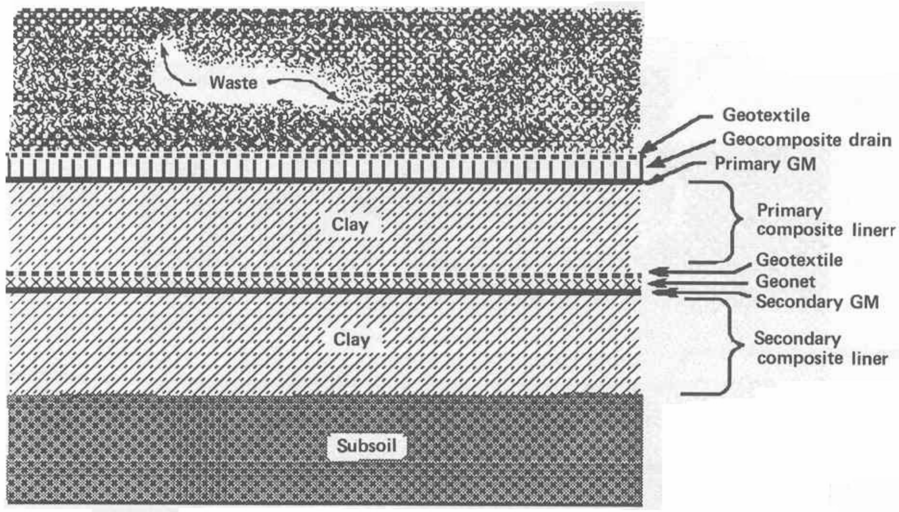


(e) Single geomembrane, single composite liner with geonet

Figura 4. (Continued)



(f) Double composite liner with geonet



(g) Double composite liner with geonet and geocomposite

Figure 4. (Continued)

2.4.2 Base liner systems

The base liner system of a landfill class II and III is the typical area of application of the composite liner. Bedded on a fine-grained geological barrier and a groundwater table near to the bottom side of the mineral liner it can be expected that no critical changes in the water content appear under operating conditions. So the mode of operation of the two different materials in intimate contact to each other can be assumed for many years. The estimated service lifetime is > 100 years. After this time the geomembrane will be furthermore completely intact but the material will become brittle and the geomembrane may became cracks resulting from induced forces resp. strains. In the described bonded system the mineral component is supported by the geomembrane in a highly effective manner.

With regard to the mineral liner material – according the Technical Instructions clay is preferred – also other material variants should be excepted, e.g. high-value mixed soils with or without additives when the equivalence can be verified.

2.4.3 Capping Systems

The advantages of the composite liner we do not find in an analogous manner on the top of a landfill. The liner system comes only in contact to rain water with low mineralization. Diffusive and sorptive effects are of no importance. Also the pressure compound can not be guaranteed because of the relatively low overburden load. In contrast to the composite liner concept for the base of the landfill in the capping system the water balance can not be guaranteed for long times. Therefore it can not be expected that after the failure of the barrier against convection (GM) the mineral liner can carry over the function as a second sealing. In the capping system it can be expected that the temperature-induced water transport in the mineral liner will be more distinct. The reduction of water content will lead to a hardening of the soil and to a reduction of the allowable tensile stresses. When using clays with a distinct plasticity no liner system can be guaranteed with a long time effectiveness which exceeds the time of full function of a geomembrane. The structure of fissures in a clay liner caused by dessication and tensile- und bending-stresses – once developed – can not be degenerated by overburden load, swelling- and clogging- or other self-healing effects. Alternatively and depending on the landfill type the potential of hazard, the required level of safety and the expected long time effectiveness other combinations of liner elements can be used, e.g.:

- Geomembranes (GM) and geosynthetic clay liners (GCL)
- GM and Trisoplast-liner
- GM and a capillary layer
- GM and soils with low plasticity and other well graded mixed soils with our without additives.

With these concepts you have to accept that at long sight (>> 100 years) the mineral liner has to take over the function as a sealing. In these spaces of time, which are completely unreal for an engineer when discussing the long term efficiency of materials and buildings, is not only to accept the loss of the function of the geomembrane but also the loss of function of the second component, especially by the uncontrollable growth of roots.

This loss of function can only be avoided or minimized by use of a recultivation layer of great thickness and an adequate high level of protection.

3. Single linear sealing systems

3.1. Standard-liner

For class I landfills standard is a two-layer mineral liner with a total thickness of 0,5 m and a maximum permeability of $k = 5 \cdot 10^{-9}$ m/s. The material selection and the process of compaction shall minimize the danger of dessication cracks. Because of the fact that there is no geomembrane as a protection layer as a rule a recultivation layer with a high protection level is necessary, that means a thickness of about 1,5 – 1,6 m and a usable field capacity of 250 mm.

3.2. Alternative liners

As accepted alternative liners can be mentioned:

- Mineral liners with reduced thickness but with simultaneously considerably reduced permeability compared with the standard liner,
- Geosynthetic clay liner (GCL),
- Trisoplast,
- Mineral soil mixtures with additives,
- Asphalt-liner,
- Capillary-barrier,
- Geomembrane (GM),
- Mineral layers with pronounced water balance and high thickness.

Other alternative components are possible when the equivalent quality and applicability can be proved.

4. Special requirements for geomembranes in landfills

4.1. Preliminary remarks

The use of geomembranes in landfill liner systems is state of the art and can be extremely evective. Preconditions are however, that the geomembrane is installed free from defects and has a long service lifetime. The durability of geomembranes significantly changes and depends on material properties, manufacturing- and installation-conditions. For the choice of materials there are necessary special investigations to the ageing, the fabrication-, installation- and welding- and protection process and the investigation must follow definite technical standards (MÜLLER, 2005). With respect to the great number and different methods of testing for geomembranes, the interrelations can not easily be overlooked by persons without special knowledge in this field. In contrast to the definition of durability for common construction materials the definition of durability for liner systems in landfills must be further reaching. Durability means, that the essential sealing- and mechanical properties of liner systems must persist several hundred years. This definition is necessarily valid for geomenbranes and a certification process.

4.2. Guidelines for the certification of geomembranes

In Germany the technical conditions of geomembranes are described in the "Guidelines of Certification of Geomembranes as a Component of Composite Liners for Municipal and Hazardous Waste Landfills and for Lining Contaminated Land" by the Federal Institute for Material Resaerch and Testing in Berlin (BAM, 1999). In these guidelines the testing methods and requirements are formulated as well as the characteristic values for geomembranes, which have to be consequently controlled in the manufacturing process. The guidelines include e.g. the following specifications:

General physical requirements
- Surface condition,
- Homogeneity,
- Carbon black content and distribution,
- Skew, waviness,
- Thickness,
- Melt mass flow rate,
- Dimensional stability,
- Permeability to hydrocarbons,
- Oxidative stability.

- Mechanical requirements
- Behaviour under multiaxial tension,
- Tensile properties,
- Tear resistance,
- Resistance to static puncture,
- Resistance to dynamic puncture,
- Cold temperature brittleness,
- Relaxation behaviour,
- Seam quality,
- Resistance to concentrated liquid solutions,
- Resistance to thermal oxidative degradation in air,
- Long term behaviour under combined stressing.

Requirements for physical resistance and long time behaviour
- Weathering resistance,
- Microbe resistance,
- Root penetration resistance,
- Welding properties of resins.

4.3. Quality management system (QMS) in the production process of geomembranes

Each manufacturer of a product has to install a Quality Management System. It fulfills certain formal conditions specified in technical standards. It is essential that all elements of the system are fully identified and specified. Thus it is possible to test and to record the product quality, that means agreement of the characteristics with the given requirements. The part of the management system, which focuses on fulfilling quality requirements of the product is called Quality Control (QS). In the context of quality assurance in the production of a product independent test laboratories or inspection bodies supervise the production procedure, perform controls and inspections and examine the manufactured products using test methods, which are described in special standards or guidelines.

4.4. Quality assurance in the construction phase

Each engineering structure is an individual manufacturing process and must therefor be subject to quality management, which is based on QM-Systems of the different companies involved. From this follows that for each project a site-specific quality management system must be established for the construction of the liner system. One often speaks of quality assurance or Quality Assurance System (QAS). The quality assurance is documented in the Quality Assurance Manual (QAM), in which the individual competencies and hierarchies must be clearly regulated (MÜLLER, 2007).

On the base of long year experiences the following thesis are valid:
Quality assurance in the construction phase is the most economic method to increase the safty of a landfill.
If you take seriously the generally accepted protection goals and subjects of protection, you must have a positive approach to quality assurance and especially to the function of an independent third-party inspector in this concept.

4.4.1. Function and aims of quality assurance

The main functions are in short:

- Organized, systematical and coordinated inspections including the design and construction procedure.
- Reduction of the probabillity of material and manufacturing defects and then thus increase of total safety.
- Judicial functions referring the administrative decision and the building contract.

4.4.2 Organization of quality assurance

Quality assurance is carried out in a multi level test-procedure:

- Quality control by the manufacturer and especially by the installer of geosynthetic elements.
- Independent controller in agreement with the responsible authority (third-party inspector).
- Monitoring by the responsible authority.

From this follows that quality control within the quality assurance system must be borne by the manufactures, the installers, the independent controller and the responsible authority.

4.4.3. Functions of the independent controller (third-party inspector)

The main functions are:
- Technical checks of the design and the tender documents in the forefront of the construction phase,
- Participation when formulating the quality assurance manual,
- Execution of checks and tests in the construction phase including test fields in accordance to the QAM,
- Supply of the services as controller contemporary and thus direct assistance of the construction process (rapid and smooth),
- Documentation of all results of quality control and evaluation in a final report in a distinct and comprehensible mode.

4.5. Qualification and equipment

In the quality assurance system special importance is attributed to the independent controller. Only controller which have the necessary machines, personal and technical capacity to perform rapidly the necessary tests and who possess sufficient specialist knowledge and experience can solve this important task (MÜLLER, 2007).

According to the BAM-guidelines the main requirements are:

Accreditation in accordance with EN/ISO/IEC 17020:2004 “General criteria for the Operation of various Types of Bodies Performing Inspections for inspection measures” within the frame work of controlling geomembrane liner system by the independent controller and designation of trained specialists with expert knowledge and experience in plastic engineering and quality management as well as landfill-specific geotechnical engineering procedures.
Operation of a own laboratory in accordance to EN ISO/IEC 17025:2004.

4.6. Conditions placed on installation companies

In Germany exists e.g. the German association of geomembrane manufactures and installers (AK GWS), which founded 1997 a certification program for specialist installer companies based on the recommendations of BAM “Installation Contractors for the Installation of Plastic Components in Liner Systems”. The essential requirements are:

- Installation of geomembranes only with experienced and qualified persons.
- Sufficient equipment, machinery and devices for installation and welding.
- Supervision by an independent accredited institution.

5. Summary

The safety of a landfill can only be guaranteed by a multi barrier concept, which includes not only technical barriers at the bottom and on the top of a landfill but also the deposited waste (waste barrier) and the geological conditions of the site (geological barrier). In the 80's and early 90's first Technical Instructions have been formulated. In this time it was thought that geomembranes have only a restricted service lifetime of less than 100 years and that soil layers, especially compacted clay liners were considered as the long-term component in the landfill basal liner and capping system. In the so called composite liner the different sealing materials have been brought together, which add their individual qualities to a highly effective compound at the base of a landfill even for wastes with high amounts of hazardous substances. With regard to the capping system and to the lifetime of geomembranes the view has nowadays completely changed. It can be shown that the time for the functional engineering properties of certified and properly installed HDPE geomembranes to become significantly affected by ageing processes in so long (many centuries) that ageing is not relevant for design considerations in landfill capping systems. On the other hand it can be revealed that a single conventional compacted clay liner on top of the waste body can be destroyed by desiccation effects and root penetration. Therefore today the HDPE geomembrane is considered as the part of the composite liner having equal, if not greater importance than the compacted clay liner. This leads to completely new liner concepts, e.g. HDPE geomembranes in combination with various other components (leak monitoring systems, geosynthetic clay liners, capillary barriers, mineral mixtures with additives). The safety of the liner systems depends not only on the materials but also to a high degree on the quality of manufacturing and installing the single components. Therefore quality control and quality assurance are of exceeding importance. The landfill liner construction requires an independent qualified controller in agreement with the responsible authority.

6. References

ALBERS, K.; MÜLLER, W. (2006) – Kunststoffdichtungsbahnen als Abdichtungselement in Oberflächenabdichtungssystemen. Status-workshop Höxter.

AUGUST, H., TATZKY-GERTH, R.; PREUSCHMANN, R.; JACOB, I. (1992) - Permeationsverhalten von Kombinationsabdichtungen bei Deponien und Altlasten gegenüber wassergefährdenden Stoffen. F+E-Vorhaben 10203412, BAM, Berlin, Abschlussbericht 1992.

AUGUST, H., TATZKY-GERTH, R. (1992) – Die Wirkungsweise der Kombinationsabdichtung aus wissenschaftlicher Sicht. Veröffentlichungen des LGA-Grundbauinstituts, Heft 65, S. 45-64.

BAM, Berlin (1992) – Richtlinie für die Zulassung von Kunststoffdichtungsbahnen als Bestandteil einer Kombinationsdichtung für Siedlungs- und Sonderabfalldeponien sowie für Abdichtungen von Altlasten.

BAM, Berlin (1999) – Richtlinie für die Zulassung von Kunststoffdichtungsbahnen für die Abdichtung von Deponien und Altlasten.

DGGT (Herausgeber) (1997) – GDA-Empfehlungen Geotechnik der Deponien und Altlasten; Verlag Ernst & Sohn.

DIBt (1995) – Grundsätze für den Eignungsnachweis von Dichtungselementen in Deponieabdichtungssystemen. Deutsches Institut für Bautechnik AöR (DIBt), November 1995, veröffentlicht im Anhang der GDA-Empfehlungen, 3. Auflage, 1997, S. 637-708.

DÜLLMANN, H. (1999) – Protection goals and safety of landfills. Geospektrum 3, p. 26-28.

DÜLLMANN, H. (2006) – Deponieabdichtungselemente – Mineralische Lösungen versus Geokunststoffe.

DÜLLMANN, H. (2006) – Aufgaben, Verantwortung und Beauftragung der Fremdprüfung bei der Planung und Ausführung von Deponieabdichtungssystemen. Süddeutsches Kunststoffzentrum (SKZ), Fachtagung „Die sichere Deponie", Würzburg.

KOERNER, R.M. (1990) – Designing with Geosynthetics, 2nd Ed., Prentice Hall (UK), London.

MÜLLER, W. (1994) – Wie dicht sind Kombinationsdichtungen? Die sichere Deponie, SKZ Würzburg.

MÜLLER, W. (ed) (1995) – Anforderungen an die Schutzschicht für die Dichtungsbahnen in der Kombinationsdichtung. Zulassungsrichtlinien für Schutzschichten. BAM, Labor Deponietechnik, Berlin.

MÜLLER, W. (ed) (1999) – Richtlinie für die Zulassung von Kunststoffdichtungsbahnen für die Abdichtung von Deponien und Altlasten. Wirtschaftsverlag NW, Verlag neue Wissenschaften GmbH, Bremerhaven.

MÜLLER, W.; JACOB, I. (2003) – Oxidativ Resistance of HDPE. Polymer Degradation and Stability 79, p. 161-172.

MÜLLER, W. (2004) – Oberflächenabdichtungen aus PE-HD-Dichtungsbahnen für Altdeponien. Bautechnik 81: 699-709.

MÜLLER, W. (2005) – Hauptsache "schwarz und billig? Zur Eignung „alternativer" PE-HD-Dichtungsbahnen für endgültige Oberflächenabdichtungen. Müll und Abfall 8, p. 392 – 397.

MÜLLER, W. (2007) – HDPE geomembranes in geotechnics. Springer Verlag, Heidelberg, Germany.

RODIĆ, L. (2000) – Reliability of Landfill Technology. Dissertation TU Delft (NL).

ROWE, K. (2006) – Some Factors affecting Geosynthetics used for Geo-Environmental Applications. 5th ICEG Enviromental Geotechnics, London.

SCHICKETANZ, R. (1992) – Wirkungsweise der Kombinationsdichtung und Anforderungen an die mineralische Oberfläche. Müll und Abfall 5/92.

TA Abfall (1991) – Zweite Allgemeine Verwaltungsvorschrift zum Abfallgesetz. 2. AbfVwW, Teil 1: Technische Anleitung, Anhang E: Material- und Prüfungsanforderungen, 12.03.1991.

TA Siedlungsabfall (TASi) (1993) – Dritte Allgemeine Verwaltungsvorschrift zum Abfallgesetz. 3. AbfVwV, Technische Anleitung, 14.05.1993.

WITT, K.-J. (2006) – Überlegungen zu geotechnischen Anforderungen an Oberflächenabdichtungssysteme. Status-workshop, Höxter.