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Landfill liners and covers

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ABSTRACT: Basal liners and covers are essential barriers of solid waste landfills. They comprise sealing and dewatering layers which have to be designed and constructed as integral parts. Mineral and geosynthetic materials are used for liners and covers. Compacted clay liners and geomembranes in intimate contact act as composite bottom seals. In cover systems geomembranes efficiently prevent the infiltration of rain water. They are complemented by geocomposite drains.

1 INTRODUCTION

Solid residues from production processes and from daily life shall be reused or recycled where ever possible, in order to reduce the amount of waste that has to be treated and finally disposed of. During the last few years, in some countries, legal, economical and educational efforts have led to a significant reduction in the generation of waste. So, for example, in Swiss and German communities, the predictions of the landfill space required for the coming decades, are currently being revised. In some cases, the design of landfill facilities is delayed or can even be given up completely due to the decreasing amount of refuse. In spite of this development, there still is and will be a great demand for solid waste landfills in most parts of Europe. And the design and construction of landfills remains a major challenge to the civil engineer.

Waste material may contain substances that can be harmful to the environment. It is therefore mandatory to handle and store waste in such a way that any contamination of the ground as well as of the ground water is prevented. So, the primary engineering assignment in designing, constructing and operating solid waste landfills is to provide efficient barriers against contamination. Since water is the most important transporting agent for pollutants, the infiltration of water into and the extraction of water out of the solid waste body must be controlled by reliable technical means. Liners and landfill covers are the most significant technical members of landfill structures for this purpose. In connection with dewatering facilities and the leachate collection and removal system, the basal liner and the cap seal are crucial elements with respect to landfill safety.

There is a close relationship between sealing and dewatering elements of the basal and of the cover barrier. Drainage facilities must maintain minimum gradients to facilitate gravitational flow. So to some extent, the dewatering systems dictate the geometry of the surfaces of sealing layers. On the other hand, leachate collection pipes should be placed in such a way that the unavoidable penetrations through the sealing layers do not impede the efficiency of the liners. These few examples show that the sealing layers and the dewatering elements form integral parts of barrier systems and have to be designed accordingly. They also influence each other during and after construction. Obviously, the placement of drainage gravel above geomembranes must be executed with greatest care to avoid perforations of the liner. To account for the close interrelationship between sealing and dewatering elements, the present paper on liners and covers includes some aspects of dewatering systems.

The physical, chemical and biological properties of the solid waste, as well as the availability of construction material are important parameters for the design of liners and covers. The geologic, the hydrologic and the climatic conditions at the landfill site are also major factors. There are various possibilities to construct safe technical barriers for solid waste landfills. Since the interactions between the waste material, the natural climatic influences and the liners or covers are complex, the performance of landfill liners and covers can hardly be quantified appropriately by simple analytical formulas. During the last few years considerable

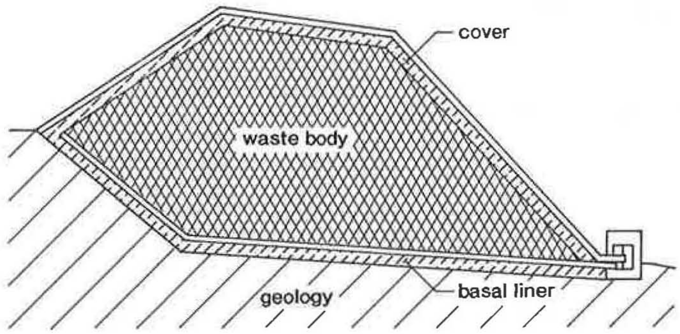


Figure 1. The barriers of landfills

progress has been achieved in scientific research, but up to now there are no encompassing rational computational design models for landfill liners and covers. Many geotechnical questions related to the performance of landfills are still open (Van Impe 1995).

However, landfill construction cannot be delayed until all of the relevant scientific problems have been solved. Landfills are needed and have to be built now. So, the currently applied design fundamentals had to be established on the basis of experience, engineering judgement and analytical procedures in combination.

Aiming at a justifiable degree of safety with respect to the environment, nationally or regionally responsible authorities issued minimum requirements and some basic rules for the design of liners and landfill covers. These rules differ from one country to another, and sometimes even within one country. Since the German Chapter of IGS has been assigned the task to present this lecture on liners and landfill covers, the German practice rather than all the different European approaches will be discussed in greater detail. This does not mean that German landfill standards are recommended to other countries. But we feel, that especially in the application of geosynthetics to landfills, the German experience, technical developments and research results are worth while being noticed and can serve as base for discussion among European engineers.

2 MULTIBARRIER CONCEPT

The landfill structure essentially consists of a large containment with the solid waste body inside (Figure 1). The migration of harmful substances is prevented by several barriers. The geology of the site is an important barrier. The ground should have a low hydraulic conductivity and a high capacity for the adsorption of toxic material, it must be sufficiently stable and should not undergo excessive settlements under the load of the landfill body.

The next barrier is the lining system at the bottom of the landfill. It has to cut off the migration path of the contaminants and must consist of engineered structural components placed under quality control.

After closure, the capping system has to be installed. It covers the waste body and prevents ingress of surface water, emission of gas, odours and dust from the waste, and it facilitates landscaping.

Special attention is paid to the properties and the placement of the waste material. The waste body is considered a barrier by itself. The refuse should be in such a condition, that the stability of the landfill is granted, there is little or no tendency for harmful material to being dissolved and transported with seeping water, and the deformation due to settlements should be predictable and small. So the integrity of the cover would not be impaired in the long term. In summary, the landfill structure forms a multibarrier system (Stief 1986). Each of the barriers has to meet certain technical minimum requirements, independent of the performance of the other barriers.

3 LANDFILL CATEGORIES

Like in some other countries e.g. in Switzerland, in Germany three categories of solid waste landfills are distinguished with respect to the deposited waste material (TVA 1990, TA Siedlungsabfall 1993). The chemical composition of the constituents of the waste is the governing criterion for the assignment to the landfill category. There are some differences in details of the limiting values for harmful substances listed in the Swiss and in the German instructions. The delivered waste material is analysed by tests at the entrance of the landfill site to make sure that the acceptance criteria are met. The control of the waste material is quite efficient, so we know very well what the landfills, that are operated at the present time, contain. However, more landfills were placed in the past than at present. So, apart from the technical aspects of present day landfill practice, we

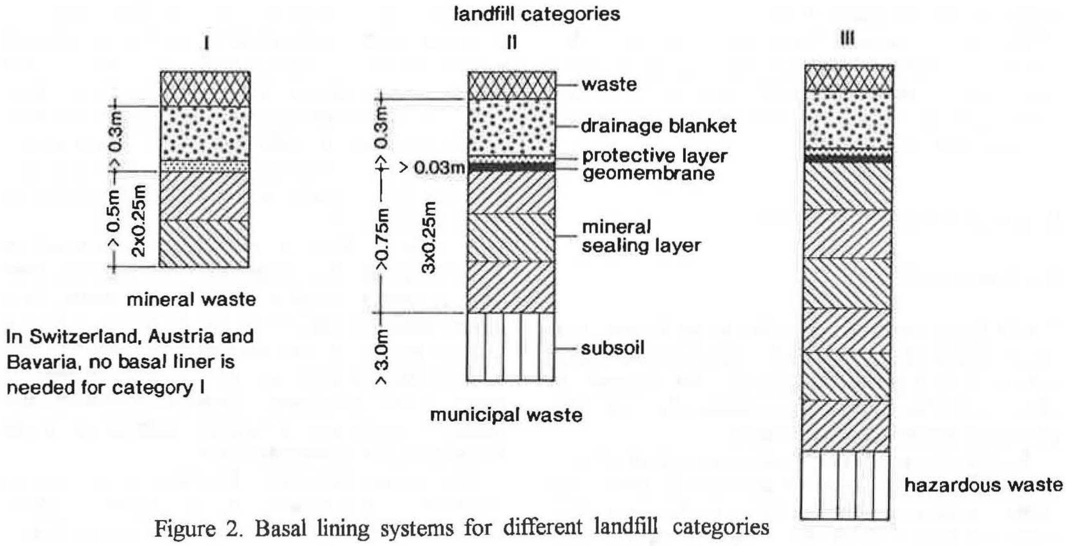


Figure 2. Basal lining systems for different landfill categories

are facing the problem that old landfills do exist which are not in compliance with our technical standards. Their environmental impact has to be evaluated. In many cases improvements by technical means are necessary, e.g. they have to be provided with covers.

Refuse with the lowest potential of harmful substances such as mineral waste and construction material or demolition debris are assigned to landfill category I according to the German regulations. Except for the general requirements of sufficient bearing capacity and predictable, not excessive settlements, the geological conditions at the site do not have to meet any technical minimum standards. The German regulations recommend compacted clay liners at the bottom as well as at the cap and dewatering systems. Geosynthetic clay liners (GCLs) and drainage mats are frequently used as economical alternatives in the design of landfills of category I. Since the Swiss regulations are more stringent with respect to the content of harmful substances in the waste material, they do not request any technical liners for landfills of inert waste. The Austrian and to some extent also the Bavarian regulations follow the Swiss practice and request no basal liner for this landfill category.

Following the philosophy that the waste body itself is an important barrier against the contamination of the environment, strict criteria have to be met by the solid waste to be assigned to category II landfills. In Germany, for the future the most stringent requirement is that the content of organic carbon of the waste material is not allowed to exceed 5 % by weight (TA Siedlungsabfall 1993). This means that essentially all domestic waste must be treated in an incinerator, because no other technologies of treatment can reach such a low content of organic according to the present state of development.

The assignment criteria for the waste material were also selected with respect to the performance of the landfill structure. Waste bodies without degradable material will not exhibit major deformations in the long term, and the mechanical properties of the refuse can be determined according to common soil mechanics practice. The design rules of the standard landfill are based on this type of waste material. However, at the present time, many municipal solid waste landfills are depositing residues that do not meet the 5 % organic carbon content criterion. They still contain a lot of organic that will undergo degradation processes for a long time. This aspect is important for the capping systems. Either they have to be sufficiently flexible to tolerate large deformations without losing their integrity, or they should not be placed until the major deformations associated with the degradation process have ceased.

The landfill category II comprises the majority of solid waste landfills, residues from incinerators, but also typical municipal waste and similar materials with respect to their contents of dangerous substances are assigned to them. Landfills of this category are provided with liners at the bottom and covers at the top consisting of geomembranes and compacted clay liners.

Waste that contains harmful substances exceeding the criteria for municipal waste landfills has to be disposed of in hazardous waste landfills. Those are constructed according to the same basic principles.

However, the thickness of their mineral component of the basal composite liner has to be twice the thickness of liners of municipal waste landfills, and a few other details differ slightly (Figure 2). In the following text, mainly liners and covers of category II landfills will be discussed.

4 BASAL LINING SYSTEMS

4.1 *Functional layers*

The landfill containment is sealed at the bottom by a basal lining system composed of several layers, each one serving a particular purpose. An example is shown on Figure 2. It comprises the seal, the protector, and the drainage blanket.

In order to provide a continuous system of low permeability, the seal is placed directly above the subsoil without a drainage layer in between. The main seal may consists of a single or of a double liner, and the liner itself could consist of an impervious mono-layer or of a composite. The example shows a composite liner, composed of a compacted clay layer and a geomembrane.

Since the geomembrane is rather thin and sensitive to mechanical damage, a special protective layer is needed above the geomembrane. This layer can be a geosynthetic product, a soil or a composite of both materials.

In order to prevent any build up of leachate pressure head above the sealing layers, a drainage blanket is incorporated in the basal lining system. Finally it may be necessary to place a transition or filter between the drainage blanket and the waste body to maintain the long term performance of the drainage system.

4.2 *The concept of the composite liner*

Extensive research by August et al. (1992), during the past decade has lead to the conclusion, that a composite liner of the type sketched on Figure 2 is the most efficient seal against the migration of harmful components of the leachate. Accordingly, the German instructions request such a composite liner at the bottom of municipal solid waste landfills and of hazardous waste landfills as standard solution. In Austria and in Switzerland similar composite liners are recommended and constructed.

The polymer component acts as a cut-off for the flow of water. Due to its nonpolar molecular structure, it prevents the diffusion of polar substances and therefore it is an absolute barrier against heavy metal cations. Nonpolar molecules of hydrocarbons or chlorinated hydrocarbons that may permeate through the geomembrane are retarded at the surface of the compacted clay liner due to its strongly polar molecular structure. The effect is a decrease of the concentration gradient across the geomembrane and consequently a reduction of the rate of permeation. So, it is especially the interface of the geomembrane with the compacted clay liner which acts as an efficient barrier against the movement of contaminants such as hydrocarbons, provided both components of the sealing system are in intimate contact.

In order to achieve in actual practice the excellent performance of the composite liner that has been demonstrated by small scale laboratory testing, high quality standards have to be met by the properties of the geomembrane, by the material used for the mineral sealing layer and by the workmanship in construction execution. Quality assurance and quality control are of utmost importance in the construction of composite liners.

The composite liner described here, has an excellent performance as a barrier against contaminant emission. But like any other system, it has also certain limitations (Gartung 1992) mainly with respect to its mechanical behaviour. For example, the frictional resistance at the surface of smooth geomembranes is limited, which may result in slope stability problems.

4.3 *Alternative liners*

In situations, where it is not easy or even impossible to construct the composite liner, e.g. at very steep slopes, or in cases of landfills where the waste material undergoes substantial exothermic processes and the temperature development would be detrimental for the polymer geosynthetics, or if other limitations of the system are approached, alternative bottom liners can be used. Alternatives should be equivalent to the standard systems in their performance. Some fundamental criteria for the equivalency assessment have been compiled by a group of experts under the direction of the German Institute for Construction Technology DIBt. (Herold 1996). In order to achieve the composite effect described in the previous chapter, alternative sealing systems should also consist of at least two elements, one that retains polar and another one that retains nonpolar potential contaminants. Combinations of asphalt with well compacted mineral layers of low hydraulic conductivity probably meet this requirement. (Arand et al. 1992).

In some areas of Switzerland where cohesive soils suitable for mineral liners hardly can be found, landfills are often provided with asphalt liners. Their thickness typically amounts to 70 mm and the void ratio is less than 3%. The asphalt layer is placed on a bituminous supporting layer above compacted gravel. Apart from these asphalt liners and composite liners, the Swiss regulations also permit mineral liners of 0.8 m thickness without a geomembrane (SIA 1995).

Before the development of the composite lining technique, in Germany most basal liners were constructed as single compacted clay liners. A recent, very comprehensive investigation into the properties of a 12 to 15 years old compacted clay liner below a municipal waste landfill with a functioning drainage system led to the conclusion that the mineral liner had performed very satisfactorily. Extensive testing of samples across the entire thickness of the liner, applying soil mechanics, geochemical, mineralogical and microbiological methods, revealed that there were no traces of contaminant migrations (Gartung et al. 1996).

For permanent landfill structures basal liners consisting of geomembranes without supplementary mineral liners were seldom carried out in Europe. An example of a special double geomembrane system with leak detection and provisions for repair by grouting called „*Contrep*“ was built some years ago south of Ludwigshafen in Germany (Quick & Kochendörfer 1992). It has been functioning without any problems for 9 years.

Single sheet geomembrane liners without mineral sealing layers are used for temporary storage of waste. For permanent structures, they are normally considered inappropriate in view of their sensitivity to mechanical damage and lack of redundancy with respect to the long term performance.

Multilayer sealing systems with compacted clay liners and with more than one geomembrane are not very common in Europe. It is difficult to install a high quality, well compacted clay layer above a geomembrane. So an additional geomembrane in a basal liner system not necessarily leads to a substantial increase in safety against leachate migration.

In America, double composite liners are favoured. Below the primary geomembrane in combination with a GCL or a compacted clay layer, there is a geosynthetic leak detection layer and then the secondary geomembrane follows, again as part of a composite liner including a compacted clay layer (Koerner 1993). In Europe the philosophy of leak detection at the base of waste deposits has been followed only in a few special cases. The design concept of double liner systems is not very well established here. Some mineral double liners with either gravel or geosynthetic leak detection blankets were executed. At the present time, alternative landfill bottom liners play only a minor role in Central Europe. The composite liner consisting of a geomembrane and a mineral layer of low hydraulic conductivity as sketched in Figure 2 is the most common standard solution.

5 COMPONENTS OF THE COMPOSITE LINER

5.1 *Compacted clay layer*

The characteristic property of the mineral sealing layer is its low hydraulic conductivity. In Switzerland the regulations specify that it must be smaller than $1*10^{-9}$ m/s, in Germany it has to be smaller than $5*10^{-10}$ m/s. The soil shall have a content of clay size particles of at least 20 %, half of which shall consist of clay minerals. The clay has to be compacted wet of optimum water content to at least 95 % Proctor density. The suitability of the selected soil has to be proven by laboratory tests. In test fields the contractor has to demonstrate his proficiency and the adequacy of his equipment prior to the start of production.

The required minimum thickness of the compacted clay layer for composite liners is 0.5 m in Switzerland, and 0.75 m for category II landfills in Germany. For hazardous waste landfills the German instructions specify a minimum thickness of 1.5 m placed in lifts of 0.25 m each.

Since it is difficult in some parts of Europe to provide enough natural clay that meets the specifications for a qualified compacted clay liner, alternative mineral seals have been developed on the basis of blended granular soil with a small amount of bentonite. Horn (1989), described such mineral seals under the name of „*Bentokies*“, they have been used in landfill construction in southern Bavaria to a great extent. Other blended mineral sealing materials are the patented „*DYWIDAG Mineralgemisch*“, developed by Finsterwalder and Mann (1990) and „*Chemoton*“, a mixed in plant sealing material that uses waterglass and chemicals to gain extremely low permeability and a very high resistance against aggressive chemicals (Lauf & Müllner 1993). The components of such mineral sealing materials are mixed in plant, transported to the site and placed and compacted with modern construction equipment. Often their performance is superior to that of sealing layers of compacted natural clays because the components are specially selected, processed and blended under controlled working conditions.

5.2 *Geomembrane*

The function of the geomembrane in the basal liner system of a solid waste landfill is to retain leachate, a liquid that may be composed of many different substances, some of which can be harmful. In most cases the composition of the leachate cannot be predicted with a sufficient certainty, it may vary with time. The only basis for an assessment of the properties of leachate are chemical analyses carried out on a great number of samples taken at many different landfill sites.

Geomembranes used for landfill liners should be impervious for all the components found in the leachate and also to those that might occur. And the geomembrane should resist the chemical and biological attack in the landfill milieu without losing its functional properties. Furthermore, geomembranes must be mechanically strong enough to survive transport, handling, placement and subsequent construction activities. The deformation behaviour has to be within acceptable limits, it has to be compatible with the deformations of the other components of the landfill structure, and it has to be predictable. The strength and the interface frictional resistance have to be in agreement with the stability requirements of the landfill structure.

In summary, the geomembrane has to meet a number of requirements concerning its physical, mechanical and endurance properties. Koerner (1994) lists 20 test methods for the determination of the parameters that describe the relevant properties of geomembranes. All important material parameters have to be specified to make sure, that the geomembrane is suitable for a landfill liner.

There is a great variety of materials and processing techniques for the production of geomembranes. The manufacturers are capable of meeting specified requirements in different ways, focusing on the subjects that seem most important in a particular case. Optimising plastics for one criterion, e.g. chemical durability, can lead to deficiencies in other properties, e.g. deformation characteristics. If all possible variations would be exercised in practice, there would be countless types of different geomembranes, and the designer, the contractor and the regulator would hardly be able to evaluate the suitability of a product for a particular application unless all the parameters would be tested each time. This would be prohibitive with respect to costs and delays. The practising civil engineer would need the help of a polymer expert if all the characteristic material parameters of a geomembrane would have to be selected for each specific project. For a successful application of geomembranes in landfill construction it is more appropriate to limit the variation of geomembrane properties by standardisation.

Most European countries have instructions for landfill geomembranes. In Germany an approval system has been installed by legal action. The Federal instructions TA-Abfall (1991) and TA-Siedlungsabfall (1993) specify that only approved geomembranes shall be used in landfill construction. The approval criteria were agreed upon by experts representing the geomembrane manufacturers, the testing and research institutions the designers and the regulators.

The procedure for the approval of geomembranes for landfill applications is executed by the Federal Institution for Material Research and Testing (BAM 1992). On the basis of more than 20 years experience with polyethylene in civil engineering applications and comparative testing of different other geomembrane materials in the laboratories for polymers of BAM (August et al. 1984), it has been decided, that only polyethylene should be used in sealing systems of landfills.

The geomembranes approved by BAM, exhibit excellent chemical resistance and sealing performance against a large variety of substances that could be encountered in the leachate of municipal or hazardous waste landfills. Polyethylene with a density between 0.932 and 0.942 g/cm^3, commonly named polyethylene of high density, HDPE, is used. It must have a carbon black content of 1.8 to 2.6 % and meet a number of strict requirements with respect to physical and chemical properties.

By suitability tests, it has to be demonstrated that the geomembranes meet certain general physical requirements, specific physical requirements, requirements under combined physical-chemical action, chemical and biological requirements. Altogether 22 tests have to be performed on the geomembrane, including some rather time consuming long term examinations. The results of the suitability tests are documented and used as reference parameters in the manufacturing quality control. The allowable deviations from the reference values set by BAM are very small.

In order to warrant a sufficient robustness of the geomembrane in handling, the specified minimum thickness of approved geomembranes is 2.5 mm. This thickness also happens to be very satisfactory with respect to the sealing function. However, HDPE-geomembranes of 2.5 mm are not very flexible.

The minimum width of the geomembrane roll is 5 meters in order to minimise the amount of field seaming needed to create large waterproof sheets. The size and weight of the geomembrane rolls are specified, to make sure that they can be transported to the site and placed without severe handling problems.

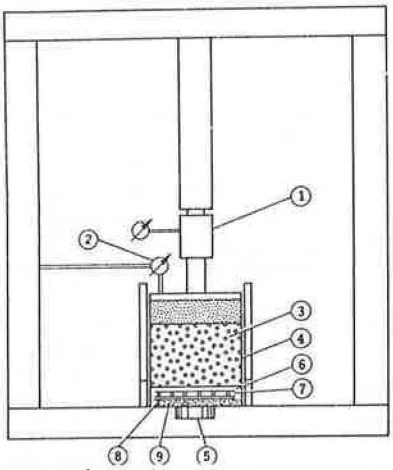
The approval documents also contain specifications on the quality assurance system of the geomembrane manufacturer. The manufacturer must follow the quality assurance procedures. In addition the production is supervised by an external inspector, and some of the most critical material parameters are checked for conformance. Emphasis is placed on the homogeneity of the product with respect to carbon black content, carbon black distribution, geometry, thickness, straight edges surface properties and permeability.

Due to the approval system, the variability of geomembranes used in German landfill construction is limited. But the design engineer can rely on the properties declared in the product documents.

5.3 *Protective layer for the geomembrane*

The basal lining system includes a drainage blanket above the geomembrane liner. As explained in chapter 7, it consists of very coarse gravel or crushed rock of typically 16 to 32 mm grain diameter. Below the waste body of tens of meters thickness, and also below moving construction equipment, the coarse grains exert considerable point loads on to the basal sealing layers. In order to avoid perforations of the geomembrane, a special puncture protection is needed.

Comparative testing in different German geosynthetics laboratories and subsequent discussions by experts, led to preliminary criteria for geosynthetic protective layers (GDA 1993). A loading test was developed, to which the geomembrane covered by the protective layer and the drainage material has to be submitted (Figure 3). After 1000 hours under the specified load, the geomembrane is inspected visually. No scratches, groves, indentations or holes are tolerated at the surface of the geomembrane. A metal sheet with



① hydraul. jack
② settlement gauge
③ drainage gravel ⑦ geomembrane
④ lubricated sheet ⑧ ductile soft metal sheet
⑤ load measurement ⑨ elastomer
⑥ protective geosynthetic layer

Figure 3. Test set-up for protectors

plastic deformation properties placed below the geomembrane records its deformations. The maximum allowable local strain at the lower surface of the geomembrane after the test is 0.25 %. This value was derived from the maximum allowable design strain in the geomembrane of 3 % due to settlements or other influences to which the value of local strain of 0.25% is superimposed.

Due to these severe mechanical performance requirements, protective layers in German landfills consist of heavy geosynthetic products, or geotextiles in combination with mineral material. A typical example is a needle punched nonwoven HDPE of 1200 g/m^2 plus 100 to 150 mm of sand or crushed stone of 0 to 8 mm grain size.

There is some concern about the durability of geosynthetic protectors. If the same criteria apply for the durability of protecting geosynthetic layers as for the geomembranes themselves, it becomes necessary, to combine mineral and polymer components in protective layers, because most of the fine fibres of polymer products do not pass the severe incubation tests with highly oxidising chemicals.

German geosynthetics manufactures have developed special composites of geotextiles and sand to serve as protective layers above geomembranes at the base of landfills. If the geotextile components of these composites degrade under the influence of leachate in the long run, the mineral components are left and still perform their function. Saathoff & Sehrbrock (1994) report on a method of filling the voids of a drainage geocomposite with sand at the site. Kirschner & Kreit (1994) describe geotextile mats which are filled at the site by a sand bentonite slurry. Müller-Rochholz & Asser (1994) present flat sand filled cushions manufactured industrially and placed by hand at the site. In the meantime this latter system has been developed further, and now sand filled mats are available which are transported to the site on rolls and installed very conveniently by unrolling.

The evaluation of the performance of protective layers for geomembranes is still a topic of scientific research. Brummermann et al.(1994), suggest new testing methods and new equipment leading to more consistent results than the technique presently used. For American landfills Wilson-Fahmy et al. (1995) developed a design concept for puncture protection based primarily on theoretical studies and laboratory tests.

Regarding the performance of protectors, there is little or no experience from the field in Europe. In large scale model tests Zanzinger examined some German protectors by exposure to a uniformly distributed load of 800 kPa for more than 1000 hours. He observed considerably greater deformations of the geomembrane at large scale tests than in his previous standard tests with the equipment shown on Figure 3 for comparable systems. These results have not yet been published.

According to this most recent information, the German approach may be less conservative than it appears at first glance. Most likely, under actual field conditions the geomembranes at the base of large landfills will experience strains in excess of 0.25 % in spite of the heavy protecting layers.

6 CONSTRUCTION OF LINERS

6.1 *Preparations*

The construction materials of the composite basal liner, clay soils and geomembranes, differ greatly in their material properties. While the mineral component can follow any three dimensional geometrical feature as long as it can be shaped by earth moving and compaction equipment, geomembranes are plane elements. That is why the bottom of the landfill has to be designed such that the geomembrane can be spread evenly without distortions. Therefore, in the ideal situation, the surface of the mineral liner consists of planes only that intersect at straight lines.

Since all landfills differ in their geometry, it is necessary to prepare individual detailed drawings for the placement of the geomembrane. The drawings show the size, shape and designated number of the individual geomembrane sheets and the seams. Often, the geometry of the landfill requires triangular or other specially tailored pieces. Information on geometrical details, and the predetermined sequence of placement of the individual sheets is transmitted from the designer to the geomembrane construction personnel via drawings.

6.2 *General aspects of installation*

The placement of the basal liner of a solid waste landfill is a very important and a very delicate construction work. It involves the operation of heavy earth moving equipment as well as the minute handling of sensitive geosynthetic products. Soil layers of several decimetres thickness with a mass of tons per square meter and geomembranes of 2.5 mm thickness with the mass of grams per square meter are installed together. The installation of the basal liner must be executed without faults, because any existing defects not noticed before the start of waste filling operations, would be practically irreparable. Defects of the basal liner cannot be tolerated.

The construction personnel must be highly quality minded. They have to develop the right craftsmanship to achieve at large scale under difficult conditions in the field the efficiency of the impervious composite liner, which has been confirmed at small scale under ideal conditions by scientists in the laboratory. These requirements ask for thorough preparations, scrutiny in the execution of the construction work and perfect timing of the different construction operations. The contractor doing the earth work and the installer of the geomembrane must match perfectly under the co-ordination of the construction manager.

It has to be taken into account, that all construction operations at a landfill site are sensitive to weather conditions. Obviously, the placement of a clay liner is impossible during heavy rain, snowfall or frost, and partly finished clay blankets must be protected against water and against desiccation due to dry wind and sunshine when the construction work is interrupted for week ends, due to bad weather or for any other reasons. For such a temporary protection, thin plastic membranes are used.

The installation of geomembranes requires favourable weather as well. It cannot be done in the rain. The minimum temperature for seaming polyethylene sheets is 5 degrees Celsius. Sufficient time has to be allocated to the placement of geomembranes to cope with unavoidable delays due to unfavourable weather occurring frequently in many parts of Europe.

If there is great pressure to finish the construction until a certain specified date, it may be necessary to execute the work under a roof. Krath & Schwarz (1993) published a case history of the construction of a basal liner for a municipal waste landfill during the winter season. All construction work was executed under a large movable tent, 40 meters wide and 160 meters long. The complications reported, which were associated with the earth work and the handling of geosynthetics on a relatively small working space in the heated tent, are quite exciting, and the cost of the efforts were significantly higher than when landfills are built during the summer season.

The manufacturer of the geomembrane must establish his own instructions for handling and installation. If he does not execute the construction work by himself, he has to subcontract it to a specialist. The approval documents of the geomembrane manufacturer list authorised firms for the placement and seaming of the specified geomembranes. The construction personnel must be qualified by education and experience. The technicians must be certified welders, in Germany according to the requirements of the guidelines: Seaming of Polymer Geomembranes in Earth- and Hydraulic Construction (DVS). The seaming methods to be applied are specified in the approval documents. Strict rules are to be followed for the execution of the construction work.

6.3 *Placement of the geomembrane*

Great attention is paid to the preparation of the surface of the compacted clay liner. In order to obtain the intimate contact needed for the composite sealing effect aimed at, the clay surface must be plane, smooth and free from stones, gravel or any other objects. The surface layer of the mineral liner may not contain single grains of more that 10 mm diameter. Such grains must be fully embedded in the clay matrix. No mineral grains with sharp edges are allowed at the surface. Deviations from the theoretical plane surface should not exceed 20 mm over a distance of 4 m. The ruts of the compaction equipment may not be deeper than 5 mm. The clay liner must retain its compaction water content, no desiccation cracks are allowed.

In order to reach the composite effect of the geomembrane and the compacted clay liner, the geomembrane has to be placed without any voids trapped between it and the clay surface. So ideally, the spread geomembrane should not exhibit any waves. This is very difficult to achieve in practice. Especially when the weather is good and sunny, the black polyethylene membrane heats up due to its high coefficient of thermal expansion. The formation of waves in the geomembrane cannot be avoided under such conditions. However, at night, when the sun disappears and the air temperature goes down, the geomembrane will contract, and the waves will disappear. This physical effect is used systematically in order to get the desired intimate contact between the geomembrane and the clay liner. Schicketanz (1992), has developed great expertise in a technology for the placement of geomembranes that follows the daily rhythm of temperatures at the construction site.

The rhythm of temperature differences governs the construction sequence. The clay liner is prepared to almost finish at least one day in advance of the placement of the geomembrane. Very early in the morning, the final surfacing work of the clay layer is done. Subsequently, the geomembrane is placed and seamed. As mentioned before, the geomembrane will form waves during the day as the temperature is increasing, and it is very important that the welders are experienced in their work so they can seam the geomembrane sheets together without creating any pockets in spite of the waves that invariably exist. The seaming operation must be finished before the evening. Then the geomembrane is covered by a nonwoven geotextile or other protector, and at specially selected locations soil material is placed in such a way that, while the geomembrane contracts at night it reaches the desired position. By this technique the geomembrane is stretched and intimate contact with the clay surface is obtained. The geomembrane experiences a certain amount of prestress. However, the resultant tensile forces are small and of no concern because they are reduced by relaxation of the polymer material with time.

The described operation is somewhat complicated in practice, because the base of the landfill does not consist of a single continuous plane. The bottom liner system has to accommodate for gradients of the dewatering layer and the pipes. Hence, the surface of the bottom liner is composed of a sequence of roof shaped planes inclined at least 3 % towards the leachate collection pipes, and 1 % in their longitudinal direction (Figure 4). Shallow grooves have to be prepared for the construction of the bedding layers of the pipes. Since the geomembrane has to follow this profile, the placement of ballast is necessary, to prevent uplifting of the geomembrane during contraction at night. Obviously, such details require a lot of manual work and great skill. Their preparation is time consuming, and these details are the most vulnerable spots of the bottom liner system.

The geomembrane sheets are seamed together by dual hot wedge fusion. Automatic seaming machines are used which control and record the important parameters: advance rate, temperature, contact

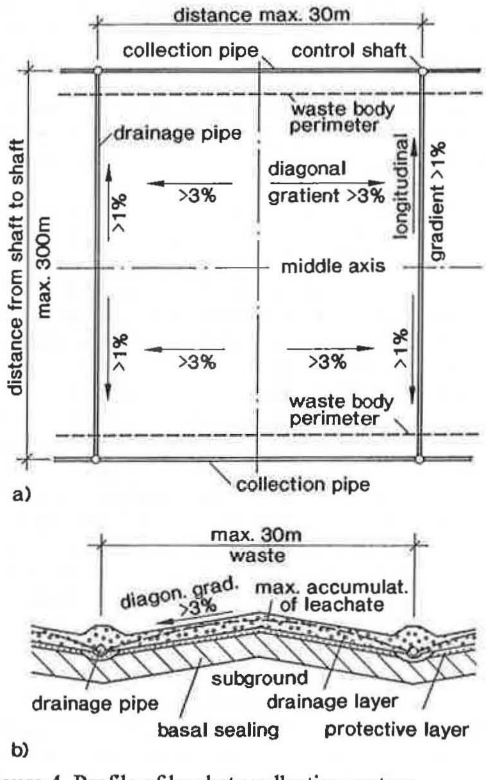


Figure 4. Profile of leachate collection system

pressure, and the length of advancement. If any irregularities occur, they are noticed and can be traced back and located precisely on the basis of the printed welding records. After finishing, each air channel of the dual seam is tested by inflation. It has to withstand an air pressure of 5 bars for 10 minutes without noticeable loss of pressure.

In areas which are not accessible for the automatic hot wedge welding machine, for example sump bottoms, pipe penetrations or patches, the extrusion fillet method is applied. It requires a great deal of good craftsmanship to reach the same quality as the automatic dual hot wedge fusion technique.

6.4 *Quality assurance*

The placement of the bottom liner system is executed under the construction quality control program of the contractor and the construction quality assurance of an external inspector. All personnel responsible for quality management must be experienced in construction with geosynthetics.

Only geomembranes without any visible flaws are accepted. Experience shows, that the quality of geomembranes manufactured under a quality assurance system like the one approved by BAM, is generally very good. If a geomembrane roll has to be rejected upon delivery at the construction site, the objections are usually due to damage that occurred during loading, transport or unloading. Sometimes the action of unloading the bulky, heavy geomembrane rolls from their shipping containers is very tricky, and exercise is needed for the personnel to handle geomembrane rolls successfully without damage.

The quality inspectors have to check whether the seaming equipment is suited for the job, and whether it functions properly. Especially, the generator for electric power has to meet the demand of the welding operations to warrant uniform seams. Every day at the beginning and at the end of the seaming work, the controlling parameters of the seaming machine have to be determined by a test strip. The geometry is checked, the seam is examined visually and by peel tests. Once the welding parameters have been established for the day, the work proceeds at a rather constant rate. If the weather conditions change, adjustments have to be made on the basis of new test strips. The data of advance rate, temperature and pressure are recorded automatically by the seaming machine and occasional checks are made by the inspector.

Experience shows, that a reliable execution of the construction quality assurance program is of utmost importance for the geomembrane. Even though the education of the installers is generally very good, and although the construction personnel is aware of the importance of their work, mistakes do occur. Fortunately they are detected in time and can be corrected without delay, provided the construction quality assurance personnel is at the site continuously. Sometimes, owners of landfills do not recognise the necessity of the external inspector being present at the site during the entire period of geomembrane installation, and they order only his occasional visits. Chances are, that in such cases, the savings in expenses for the presence of the external supervisor will be more than compensated by extra expenses for corrections and for delays due to deficiencies noticed at later time.

7 LEACHATE COLLECTION AND REMOVAL

7.1 *Drainage blanket and filters*

As long as the landfill is operated, there is no cover to prevent the infiltration of rain water and snow melt. Together with the placement moisture content of the solid waste, these liquids generate leachate which must be collected at the bottom of the landfill and removed to be submitted to proper treatment. The leachate collection system comprises a coarse grained mineral drainage blanket, a transition at the top of the drainage blanket, leachate collection pipes, and access shafts or tunnels.

In municipal waste deposits, which contain plastics, paper, and other typical domestic refuse, no special filter is installed in bottom dewatering systems. Experience shows, that untreated domestic waste forms a filtering transition zone by itself. On the other hand, it was observed in model tests by Ramke & Brune (1990) that filters above drainage blankets percolated by biologically very active leachate from municipal waste were encrusted completely under optimal conditions for microbial growth.

Kossendey et al. (1996) studied the effect of microbial life on the long term performance of geotextile filters at the base of landfills more specifically in large scale permeation tests with well defined hydraulic and biologic boundary conditions. They found that the rate and the extent of bio-clogging depends on the living conditions of the micro-organisms. The amount of nutrition contained in the leachate is the governing factor. The species of micro-organisms cannot be controlled. There are always enough different types of germs present in the environment, to initiate the development of a mixed population of various bacteria, fungi, algae and other microbes. While they are growing, they occupy some of the void space of the waste above the filter, of the geotextile filter and of the drainage gravel below, and the hydraulic conductivity of the system decreases. When the supply of nutrition is reduced, the amount of biological matter contained in the geotextile filter is decreasing, and the hydraulic conductivity is recovering.

Kossendey's study reveals that considerable bio-activity is developing even under poor nourishment conditions such as may be expected at the base of hazardous waste landfills or landfills for residues from incinerators. But in such cases the growth rate is slow, and most likely the remaining hydraulic conductivity after long time permeation is sufficient with respect to the filtration function of the tested nonwoven geotextiles.

This result is quite important with respect to the modern landfills which we are going to operate in Europe in the future, landfills that will mainly contain residues from incinerators. A filter is needed in this type of landfills. It can either be composed of mineral granular material or preferably consist of suitable geotextiles. Geotextile filters have the advantages of easier handling and installation, smaller mass and volume.

7.2 *Leachate collection pipes and access shafts*

As mentioned before and shown on Figure 4, the bottom of the landfill is profiled in a roof shape, and perforated pipes are installed at 30 meters or less spacing. The material of the pipes consists of HDPE or PP. There have been many structural failures of rigid clay- and concrete pipes which were used more than 10 years ago. So, these materials are totally excluded from landfill construction now, and only polymers are accepted. The structural analysis of flexible pipes installed at the bottom of a landfill is a subject of research. Based on finite element computations and large scale model tests Zanzinger & Gartung (1995) report first results which indicate, that currently applied structural analyses most likely underestimate the pipe-deformations.

Pipes must be accessible for cleaning, maintenance, camera inspection, measurements and for leachate sampling. So they lead to access shafts, or in some cases to tunnels where the necessary operations can be executed. The shafts should be placed outside the landfill body and be manufactured of polymer material. If they are made of reinforced concrete their external surfaces have to be lined by geomembranes. The same applies to concrete tunnels below landfills. If vertical shafts are placed within the waste body they are submitted to the internal deformations of the waste, to lateral pressures, vertical frictional forces, to elevated temperatures, chemical attack, gases etc.. As a rule, vertical shafts in landfills should be avoided. In cases where this is impossible, design recommendations can be drawn from field observations, measurements and theoretical studies (Gartung et al. 1993).

Vertical shaft structures in landfills must be founded above the basal liner in order to avoid leaks which would most likely occur if the shafts would penetrate through the bottom sealing.

7.3 *Consequences for the basal seal*

The various components of the leachate collection and removal system of a solid waste landfill require a great deal of special skill and intelligent engineering. The placement of the drainage blanket is very delicate, because the geomembrane liner must not be damaged. The design and installation of pipes above the bottom liner involve many technical details, e.g. the bedding of the pipe, pipe penetrations through the seals, connections of pipes and shafts or tunnels. The construction of shaft- or tunnel structures is a major engineering assignment.

All technical details of the leachate collection and removal system are of great importance with respect to the safety of the entire landfill structure. If they are not built correctly, leaks develop at these details, and the efforts for the construction of efficient liners are strongly impaired. The bottom liner and the leachate collection and removal system together act as the basal barrier of the landfill.

8 COVER SYSTEM

8.1 *General*

When the filling process of a solid waste landfill or of a larger portion of it is completed, the surface of the waste body has to be covered by a cap. The cover system has to prevent the infiltration of rain water, the emission of odours, dust and gas, and it has to facilitate landscaping and the growth of vegetation.

The main components of the cover of a landfill are: a regulating soil layer immediately above the waste body, a gas venting system, the sealing layers, a drainage system and the restoration profile. Depending on the requirements for the different landfill categories, these layers vary to some extent.

The properties and the behaviour of the waste influence the performance of the cap. They have to be taken into account in design and construction. For waste bodies which contain mineral solids that do not undergo chemical or biological reactions, no major long term settlements are expected. This applies to landfills which mainly contain ashes from incinerators with less than 5 % by weight of organic carbon and it should apply to hazardous waste as well.

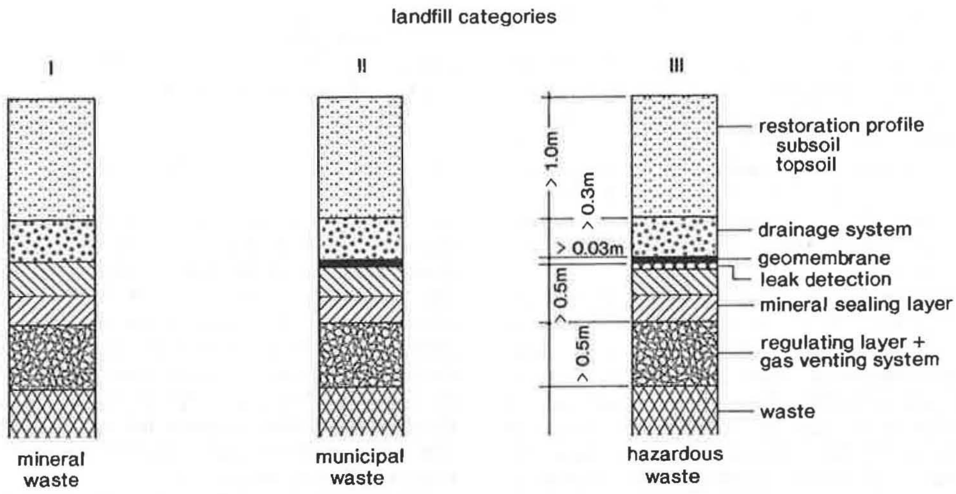


Figure 5. Cover systems for different landfills

For landfills without long term differential settlements, the placement of the cover can be carried out as soon as the design height is reached.

Common municipal waste landfills are essentially bio-reactors, where degradation processes take place in the waste body, associated with significant volume changes and gas production. The surfaces of this type of landfills usually experience large settlements for quite some time. It is likely that also substantial settlement differences occur locally which sometimes cannot be followed by mineral seals without the development of leaks. Since the bio-reactors need a certain amount of water to continue the degradation processes, some leakage is probably of no concern. It makes sense to provide municipal waste landfills with compacted clay liners or GCLs, mineral layers of low hydraulic conductivity, as interim covers. Later these interim covers become parts of the final capping systems which contain a geomembrane as the main seal. The geomembrane should be placed when most of the anticipated differential settlements have occurred. To determine the right time for this action the deformation of the interim cover surface should be monitored.

Solid wastes are not suited for finish profiling, a regulating soil layer is needed for this purpose. If gas is generated in the landfill body a gas venting system has to be installed below the cover. The functions of the regulating layer and the gas venting layer may be combined by sufficiently pervious soil.

8.2 *Mineral sealing layer*

For covers on deposits of inert mineral residues and for interim sealing layers of municipal waste landfills, a compacted clay layer placed in two lifts of 0.25 m thickness each with a coefficient of permeability of no more than $5*10^{-9}$ m/s is commonly used. Alternatively, a geosynthetic clay liner (GCL) can be installed. The questions of equivalency of GCLs with compacted clay liners have been discussed by Koerner & Daniel (1995) and by Stief (1995) among others. The properties, testing methods and quality assurance aspects of GCLs are compiled in a book, edited by Koerner et al. (1995).

Practical experience shows, that GCLs as members of capping systems have some advantages over compacted clay liners. Handling and installation are much easier, less time is needed for placement, waste storage space can be saved due to the smaller thickness and the quality of the manufactured geosynthetic product shows less scatter than of the natural clay soils.

Mineral liners in capping systems are exposed to fluctuations in their water content. Under Central European climatic conditions, the evapotranspiration rate is relatively high during the growing season from about April until late September, at the same time precipitation may be low. During this time the water content of the clay layer is reduced. In autumn and in winter, evapotranspiration is decreasing, precipitation may be high and the mineral liner is rewetted. Observations by Melchior (1993) at large test fields indicate, that under certain unfavourable boundary conditions desiccation causes the formation of micro-fissures and cracks in the cohesive cover soil in summer. These defects do not heal, they are preferably utilised by the plants for root paths, and the detrimental effect of the desiccation due to thermal gradients is further increased by suction of the roots. As a result, within two to three climatic cycles, the mineral liner experiences fissuring to a considerable extent, the overall hydraulic conductivity increases, and the sealing function is impeded.

8.3 *Geomembranes*

Fissuring and growth of roots in mineral seals of landfill capping systems can be prevented by the placement of a geomembrane. A geomembrane is functioning as a barrier against root penetration as well as against moisture migration. The final sealing layers of cover systems of landfills should consist of the combination of compacted clay liners or GCLs with geomembranes. Since the seal at the top of the landfill is not acted upon by chemicals, the synergistic composite effect of polymers and clay soils that facilitates the retention of polar as well as nonpolar substances at the bottom of the landfill is not becoming effective in the capping system. So at the cover the two components do not really act as a composite but rather as a double liner.

Even though geomembranes of covers are not exposed to a corrosive chemical environment, in Germany the same types of geomembranes are used for caps as for basal liners. They are made of HDPE, their thickness is 2.5 mm, and only BAM-approved geomembranes are used in landfill caps. The advantages are high robustness and reliable quality. Their limited flexibility is of some disadvantage. The installation of thinner geomembranes or of softer polymers such as VLDPE would be more favourable with respect to the anticipated deformations of the landfill surface.

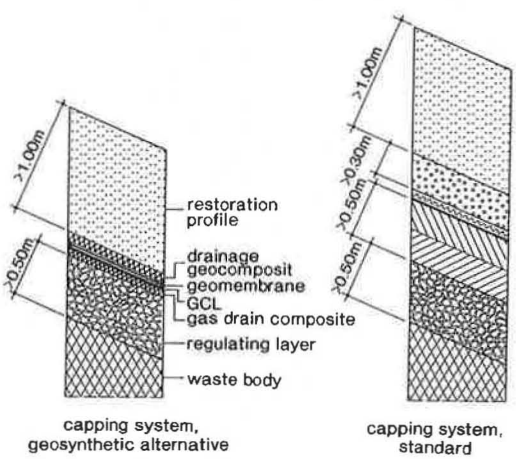


Figure 6. Steep slope of landfill cover

The German instructions permit the use of recycled polymers for geomembranes in capping systems, arguing that a smaller degree of safety is acceptable for the cover than for the basal liner because any detected leaks in the cover layers could be repaired, whereas such repair would be practically impossible at the base. However, no geomembrane manufactured from recycled HDPE has been approved by BAM yet. So up to now the quality of geomembranes used in cover systems fully matches the quality of the geomembranes of bottom liners.

The construction requirements and installation techniques are essentially the same for geomembranes of the cover as of the bottom liner. The seaming technique and all details of construction quality control and construction quality assurance described in the chapter of the basal liners, apply to covers as well.

The surface of the landfill or of the regulating layer has to be modelled to a shape, which allows plane geomembranes to be spread without distortions. This design requirement is especially important, when HDPE membranes of 2.5 mm thickness are used. It is impossible to place them on three dimensionally curved surfaces with small diameters of curvature.

Usually landfills are hills with sloping surfaces. So slope stability is a very important issue in designing and constructing landfill covers. Often it is not possible to mobilise enough shear resistance for stability on smooth geomembrane surfaces. Then geomembranes with specially structured rough surfaces are used in cover construction. These structured geomembranes undergo the same stringent suitability tests as the smooth geomembranes for the basal liner do. Particular attention is paid to their long term tensile strength and stress cracking resistance. In order to avoid tensile forces in the geomembrane, the mobilised friction at the lower surface of the geomembrane should be greater than at the upper surface. If the slope stability analysis leads to the conclusion that a sufficient safety in the balance of forces can only be reached by additional reinforcing elements, geogrids are placed above the sealing layers of the capping system.

8.4 *Dewatering of cover systems*

A small amount of the precipitation runs off from the landfill surface directly. Most of it evaporates, or is stored in the top soil layer where it is available for plant growth. The remaining water percolates through the top soil layer and reaches the sealing barrier. In order to avoid the build up of water pressure acting upon the seal, a dewatering layer is installed in the capping system above the sealing layer.

The minimum gradient of the cap drainage layer is 5 % in German landfills. For long slopes the maximum inclination should not be steeper than 1 vertical on 3 horizontal for practical reasons with respect to landscaping and maintenance work. Of course, the maximum permissible slope angle is determined on the basis of the slope stability analysis that has to be carried out for the most critical section of each landfill individually.

There are a number of mostly older landfills with slopes 1 vertical on 2.5 or locally even 2.0 horizontal. When these steep slopes have to be provided with a dewatering layer above the sealing element of the capping system, it is often necessary to install a geogrid reinforcement, because the frictional resistance at the interfaces of the various layers of the capping system is insufficient for the required slope stability.

The standard profile of landfill covers according the German instructions contains a layer of granular soil of minimum hydraulic conductivity of $1*10^{-3}$ m/s and a thickness of at least 0.3 m. Geosynthetic drainage layers are often used instead. In both cases the design engineer has to undertake hydrologic and hydraulic studies in order to determine, whether additional relief drainage pipes have to be incorporated into the dewatering system. Design analyses are also needed to specify the final gradients, select the granular drainage material or geocomposites and prepare the project documents including drawings for details, specifications and the quality assurance plan. The principle design criteria and analytical methods are described by Ramke (1995). They are also included in the technical recommendations of the German Geotechnical Society (GDA 1993).

The criterion of minimum hydraulic conductivity allows fractions of clean coarse sand or fine gravel to be used for the drainage layer. But sometimes the same coarse gravel is used for the cover drain as for the leachate collection system. If such a coarse granular drainage layer is placed onto a geomembrane, it is necessary to protect the geomembrane against puncturing. Geosynthetic drains usually exhibit a sufficient robustness to act as cushions, so no special layer is needed for puncture protection at the bottom of the restoration profile layer when geocomposite drains are used.

8.5 *Drainage geocomposites*

Drainage geocomposites have some advantages over granular drains. The masses of construction material to be handled are much smaller, their thickness is small and waste storage volume can be saved. Their placement is fast and easy. The quality of industrially manufactured geocomposites is more uniform than that of natural soils used for drainage layers. In some parts of Europe it may be difficult to find suitable granular drainage materials. Finally synthetic drains often turn out to be cheaper than granular layers. For these reasons, drainage geocomposites are increasingly being used in landfill capping systems.

Drainage geocomposites have to meet mechanical and hydraulic requirements. Their internal shear strength and the shear resistance at the interfaces in contacts with soils or geomembranes have to be in agreement with the slope stability demands. The specific shear parameters have to be determined experimentally by laboratory tests on samples of 300 mm by 300 mm. It is necessary to conduct the tests with dry and with water saturated drainage layers, because the shear parameters can be significantly different under both conditions.

Since most geosynthetic drains are compressed under loads, their hydraulic conduction capacity depends on the load applied perpendicular to the plane of the geocomposite. The hydraulic flow capacity has to be measured in laboratory tests under the pertinent stress conditions for adequate hydraulic gradients. Since some geosynthetic drainage products are sensitive to shear forces and may even collapse structurally at a certain shear stress level, it is necessary to test them under a combined normal and shear force. Creep may also be of concern and has to be considered. Zanzinger & Berkhout (1995) have summarised the aspects of testing drainage geocomposites. They recommend to determine the hydraulic capacity of the geocomposite in contact with the adjacent soil in order to include the effects of intrusion of soil particles which depends on the structure of the geosynthetic, on the grain size distribution and on other properties like stiffness and consistency of the soil as well as the state of stress.

Most of the drainage mats used in Europe, consist of three layers, an upper and a lower nonwoven filter layer and a spacer in between. Geonets common in the USA, are less frequently used in Europe.

Recently, a new product manufactured in the Netherlands appeared on the market. It is a mat of about 40 mm thickness consisting of granulated polyethylene.

Other types of geosynthetic drainage products may be developed in the future from recycled plastic. All the different drainage geocomposites can vary considerably in their mechanical and hydraulic properties, and according to project specific conditions also in their drainage performance. So their suitability for the function of cover dewatering at a particular site should be determined by laboratory tests and design calculations.

Regarding the boundary conditions at a site, it may be advisable to carry out large scale test constructions, particularly if new products are applied, if steep slopes have to be covered, or if very heavy construction equipment will be used. In the past some drainage geocomposites were encountered that suffered severe damage during installation because their structural strength was marginal. Such products should not be used. The robustness of the geocomposite, the size of the delivered unit, whether it is completely prefabricated or has to be composed at the site, are important selection criteria. Seaming and connections with drainage pipes have to be considered.

The placement of geosynthetic drains, which are essentially very thin and sensitive sheets, has to be executed under a construction quality control program of the same type as the installation of geomembranes.

9 SUMMARY AND CONCLUSIONS

During the past 10 years, the activities in design and construction of liners and covers of solid waste landfills have seen a steady development. Based on observations in the field and on research into the performance of the components of the landfill structure, technical instructions have been issued. They specify minimum requirements for sealing and for dewatering systems on a high technical level.

Great emphasis is placed on quality assurance in manufacturing and in construction in order to achieve the efficient performance of the sealing and the dewatering elements that have been established theoretically and experimentally by numerical and physical modelling. The components of liners and covers consist of mineral materials and of geosynthetic products in combination. Geomembranes, geocomposite drains, geotextiles, geosynthetic clay liners and geogrids are generally accepted as reliable members in the construction of landfills. The workmanship in the installation of geosynthetics has improved steadily with the experience of the personnel.

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