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In situ studies of the performance of landfill caps (compacted soil liners, geomembranes, geosynthetic clay liners, capillary barriers)

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Abstract

Since 1986 different types of landfill covers have been studied *in situ* on the Georgswerder landfill in Hamburg, Germany. Water balance data are available for eight years. The performance of different barriers has been measured by collecting the leakage on areas ranging from 100 m^2 to 500 m^2. Composite liners with geomembranes performed best, showing no leakage. An extended capillary barrier also performed well. The performance of compacted soil liners, however, decreased severely within five years due to desiccation, shrinkage and plant root penetration (liner leakage now ranging from 150 mm/a to 200 mm/a). About 50% of the water that reaches the surface of the liner is leaking through it. The maximum leakage rates have increased from 2×10^{-10} m^3 m^{-2} s^{-1} to 4×10^{-8} m^3 m^{-2} s^{-1}. Two types of geosynthetic clay liners (GCL) have been tested for two years now with disappointing results. The GCL desiccated during the first dry summer of the study. High percolation rates through the GCL were measured during the following winter (45 mm to 63 mm in four months). Wetting of the GCL did not significantly reduce the percolation rates.

INTRODUCTION

Covers for landfills and contaminated sites have a variety of tasks. Usually they prevent the direct uptake of contaminants by organisms, control gas fluxes, and reduce the infiltration of rainfall and snowmelt. The design of covers depends on several factors such as the climatic conditions of the site, the geomechanical properties and the environmental risks of the contaminated area, the planned use of the site, and costs. Sites to be used for industrial purposes may be sealed at the surface by layers of asphaltic concrete. In most cases, however, contaminated sites are covered to enable plant growth and recultivation. Such a ‘green’ cover usually should have an erosion-resistant top layer to support the vegetation above several layers which are designed either to laterally drain water or gas or to form barriers against vertical transport of water and gas. The service life of a cover usually is long compared to most other engineered constructions. It varies from several decades to hundreds of years. Though there is a lot of practical experience with the design and construction of covers, little is known of their practical performance. Unlike base liners of landfills, covers are exposed to a variety of environmental stresses (e.g. erosion, heat, frost, desiccation, biological turbation, transport and precipitation of colloids, hydroxides, carbonates) in addition to the impact of the waste body (gas and gas condensate, contaminated liquids, subsidence). Therefore it is hard to predict the long-term performance of a cover on the basis of theoretical considerations and laboratory data. For this reason a team of researchers and technicians has set up and operated several *in situ* test facilities during the last ten years to study and monitor the performance of multilayered covers with the following barrier layers: compacted soil liners (CSL), geosynthetic clay liners (GCL), capillary barriers (CB), and composite liners (CL) with geomembranes above compacted soil liners. This paper gives a brief overview of the most important results.

THE SITE AND CONCEPT OF THE STUDIES

The Georgswerder landfill is located in Hamburg, Germany. The area of the landfill is 44 ha, its height 40 m. It contains 7×10^6 m^3 of municipal waste of which 3% is highly toxic liquid industrial waste. The landfill has been closed since 1979. After the detection of high concentrations of 2,3,7,8 TCDD a complex remedial action program was started in 1985 including a multilayered cover (from top to bottom: topsoil / drainage layer / composite liner (geomembrane/compacted soil liner) / gas ventilation layer). Subsidence of the landfill is rather uniform. The average rate is 10 cm/a eight years after capping. Gas collection decreased from 600 m^3/h (1986) to 300 m^3/h (1995). The temperature within the landfill is 35°C. The vegetation is formed by grasses and perennial weeds, cut twice a year. In 1995 shrubs, bushes and trees were planted on selected areas of the cover. The climate of Hamburg is humid and temperate, influenced by the close North Sea (there is no comparable climate in the U.S., the closest you can get is Seattle, WA). The average precipitation is 865 mm/a, distributed almost uniformly over the year. Rainfall intensity usually is low, maximum intensities being around 3 mm/10 min and rarely above 10 mm/h. The long-term average air temperature is 8.7°C with average values of 0.1°C in January and 17.5°C in July. An average of 23 days per year (d/a) show a maximum temperature above 25°C, 25 d/a have a maximum temperature below 0°C. The average potential evapotranspiration is 540 mm/a.

In 1987 six test fields with a size of 10 m by 50 m each have been integrated into the northern slopes of the landfill cover to study the water balance and the liner performance of different caps. The layer design is shown in Figure 1. Fields named F are ‘flat’ with an inclination of 4%, the ‘steep’ fields S have a slope of 20%. All fields were constructed with the same state-of-the-art technology, materials and quality control as used during the construction of the cover of the whole landfill. No artificial materials cut through the liners at the boundary of the test fields to avoid the formation of preferential flow paths (details in Melchior and Miehlich 1989; Melchior 1993). Meteorological data, soil hydrological parameters, surface runoff, lateral discharges within the soil layers as well as the leakage through the liners are measured directly, the latter by collecting the flow in gravel-filled underpans. Topsoil and drainage layers are uniform on all fields, the topsoil (0.75 m) being a sandy loam (25% < 0.063 mm, 1.1% organic carbon), the drainage layer (0.25 m) being a sand/gravel mixture (56% < 2 mm, 38% from 2 mm to 6.3 mm) with 8.8% $CaCO_3$. The storage capacity for plant-available water in topsoil and drainage layer is 105 mm (field capacity minus wilting point). Underneath the drainage layer the various test plots contain compacted soil liners, composite liners and an extended capillary barrier. All test fields have been monitored for over eight years now.

The test fields B1 and B2 with a size of 100 m^2 each were constructed in 1994 to monitor the performance of the geosynthetic clay liners Bentofix D 3000 and NaBento under a shallow cover of 0.3 m of topsoil and 0.15 m of drainage layer (Fig. 1). Gundseal, Bentomat, and Claymax SP 500 are installed on three additional small observation plots underneath a similar cover, but without collecting the leakage in underpans.

WATER BALANCE DATA

The water balance data are listed in Table 1. Evapotranspiration and lateral drainage above the liners are the dominant parameters in the water balance. Significant surface runoff only occurred during the first year with scarce vegetation. Later on it is very low and almost independent of inclination. During the eight years of measurements, however, there have been unusually few thunderstorms with high rainfall intensities and only very few snowmelt events compared to the long-term average. Lateral drainage within the topsoil (inter-

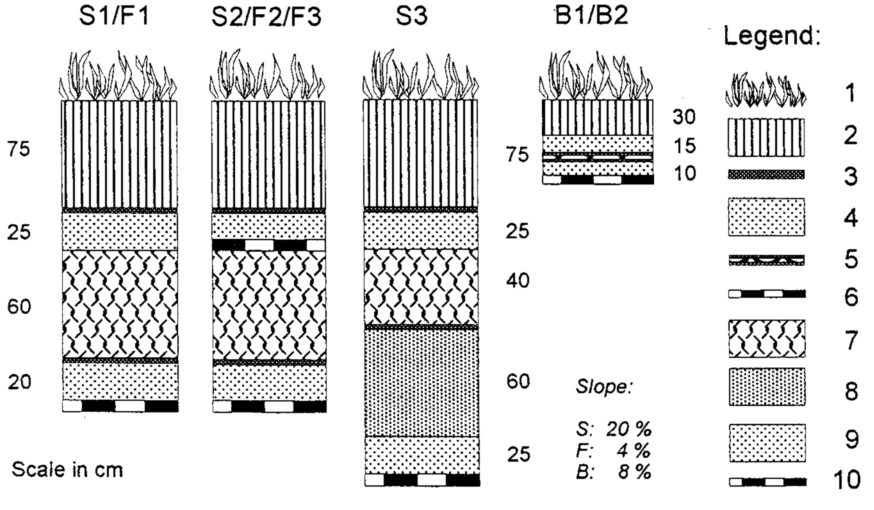

Figure 1 Layer Design of the Test Fields
(1: vegetation; 2: topsoil; 3:geotextile; 4: drainage layer; 5: geosynthetic clay liner; 6: geomembrane (HDPE, 1.5 mm); 7: compacted soil liner; 8: capillary layer; 9: capillary block (only on field S3); 10: geomembrane of underpan)

flow) only occurred under steep slope conditions and even then contributed only a few millimeters to the water balance (maximum flow rates around 0.4 mm/d or 0.1 mm/h). There is some variation in the drainage and evapotranspiration data over the years and between the individual fields. In general, the amount of drainage discharge per year is independent of inclination (maxima 40 mm/week and 39 mm/week on fields S and F respectively). The short-term flow rates however are higher on the steep fields (maxima around 23 mm/d or 3.7 mm/h) than on the flat fields (maxima 15 mm/d or 0.9 mm/h). The annual evapotranspiration is higher on the flat fields than on the steep fields due to a higher input of solar radiation in winter, spring and fall. In consequence the annual drainage rates are lower on the flat fields.

LINER PERFORMANCE

Compacted soil liner (CSL)

Compacted soil liners have been monitored in three test fields. On fields F1 and S1 three lifts and on S3 two lifts of glacial marl have been compacted to a total thickness of 0.6 m (S1, F1) and 0.4 m (S3) after compaction. They have the following average properties: 17% clay, 26% silt, 52% sand, and 5% gravel; no organic matter; carbon content, 9.8% CO_3; 50% of the clay minerals are illite, 30% smectite, 20% chlorite and kaolinite; liquid limit, 20.4%; plasticity index, 8.9; consistency index, 0.8; bulk density, 1.950 g/cm^3; water content 12.1% dry weight or 23.6 vol.-%; Proctor density, 2.039 g/cm^3; optimum water content, 9.6%; compacted >95% Proctor density on wet side of optimum water content; pore volume, 27.0%; degree of saturation, 0.87; geometric mean of saturated hydraulic conductivity in the laboratory, 2.4 x 10^{-10} m/s. Due to its graded particle size distribution, its low clay content, and the dominance of relatively inactive clay minerals, the marl shows a low potential for shrinkage compared to other 'clay liners'.

Figure 2 shows the discharges in the drainage layer above the liner and the liner leakage (the scale of the Y-axes of both discharges differs by the factor 10). The drainage discharge above the liner is high during winter and spring, whereas little happens during the summer. The liner leakage was very low during the first 20 months. In August 1989, however, it rose sharply within a few days after a rather small discharge event above the liner following heavy rainfall. From that time on, both discharges had a similar pattern. This flowpattern and the results of a tracer experiment prove the existence of continuous preferential flowpaths within the liner that allow rapid percolation. In fall 1992, the liner leakage increases again and reaches maximum values. The maximum flow rates have increased from 1 x 10^{-10} m^3 m^{-2} s^{-1} (1988/89) to 2 x 10^{-9} m^3 m^{-2} s^{-1} (1990 and 1991) to 4 x 10^{-8} m^3 m^{-2} s^{-1} (1993 and 1994) on test field S1. On field F1 maximum flow rates increased simultaneously and reached 1 x 10^{-7} m^3 m^{-2} s^{-1} in 1993. The measured soil hydrological data (water content and matric potential) clearly show that upward directed water transport into the dry drainage layer and topsoil has caused a desiccation of the liner and consequently the formation of cracks (details in Melchior 1993 and Melchior *et al.* 1994). Excavations of the liners in 1993 and 1995 revealed very small fissures between soil aggregates in liners which were not yet penetrated by plant roots (field F1). On field S1 further damage was visible in 1995. Plant roots had massively intruded and completely grown through the soil liner to

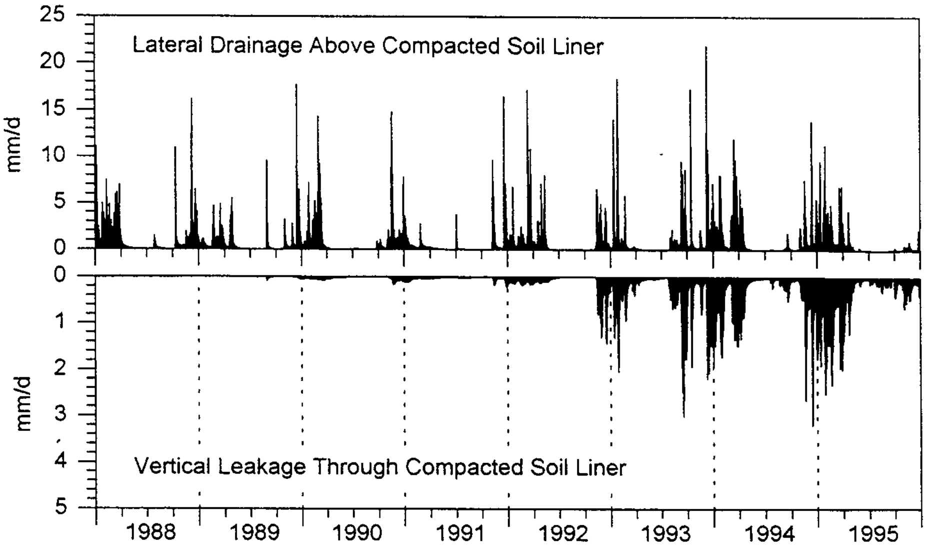

Figure 2 Compacted Soil Liner on Test Field S1: Lateral Drainage and Liner Leakage

mm/a		1988	1989	1990	1991	1992	1993	1994	1995	Avg.
Precipitation		854.8	713.9	917.3	744.1	853.7	1032.3	1019.9	780.2	864.5
Surface Runoff S1		19.6	1.8	0.9	0.6	0.6	1.0	0.8	0.2	3.2
Surface Runoff F1		5.5	1.2	1.9	1.0	1.7	3.3	1.9	1.0	2.2
Compacted Soil Liners										
S1	II	5.8	2.5	4.1	2.3	4.2	5.3	5.2	3.5	4.1
	III	385.8	246.5	317.9	176.9	289.4	343.1	343.8	229.4	291.6
	IV	1.9	3.1	13.3	13.5	48.1	136.2	150.4	149.8	64.5
	ET+dW	441.7	460.0	581.1	550.8	511.4	546.7	519.7	397.3	501.1
F1	III	368.0	182.7	286.4	187.2	226.2	253.4	246.6	155.5	238.3
	IV	7.0	7.8	17.5	8.8	102.7	174.0	165.8	163.5	80.9
	ET+dW	474.3	522.2	611.5	547.1	523.1	601.6	605.6	460.2	543.1
S3	II	12.1	6.2	8.3	5.2	7.6	8.0	7.4	5.9	7.6
	III	395.9	233.8	318.8	200.1	278.6	263.2	248.4	150.6	261.2
	V+VI	8.4	13.9	31.0	32.5	116.8	171.0	184.0	201.4	94.9
	ET+dW	418.8	458.2	558.3	505.7	450.1	589.1	579.3	422.1	497.6
Capillary Barrier										
S3	V	8.4	13.9	31.0	32.5	101.7	169.9	172.0	152.7	85.3
	VI	0.0	0.0	0.0	0.0	15.1	1.1	12.0	48.7	9.6
Composite Liners (Geomembrane Above Compacted Soil Liner)										
S2	II	13.2	5.9	8.5	5.3	8.3	10.8	9.7	6.8	8.6
	III	354.8	236.6	320.9	191.6	329.8	389.9	388.7	296.6	313.6
	IV	0.6	0.3	0.5	0.7	1.0	1.7	3.0	2.8	1.3
	ET+dW	466.6	469.3	586.5	545.9	514.0	628.9	617.7	473.8	537.8
F2	III	293.2	156.4	262.9	170.9	313.2	412.2	409.0	309.7	290.9
	IV	3.5	0.6	0.4	0.5	0.8	1.3	1.8	1.7	1.3
	ET+dW	552.6	555.7	652.1	571.7	538.0	615.5	607.2	467.8	570.1
F3	III	367.3	155.3	262.1	168.2	325.9	481.1	431.4	328.0	314.9
	IV	4.1	1.4	2.6	2.0	3.5	5.0	5.2	5.2	3.6
	ET+dW	477.9	556.0	650.7	572.9	522.6	542.9	581.4	446.0	543.8

Table 1 Water Balance Data of the Test Fields on the Georgswerder Landfill in mm/a
S1, S2, S3, F1, F2, F3: name of test field (layer design and slope see Fig. 1);
Surface runoff only measured on S1 and F1 (data extrapolated to S2, S3 resp. F2, F3);
II: interflow within topsoil (measured on all fields, no flow on fields F1, F2, F3);
III: lateral drainage within drainage layer above liner;
IV: water collected underneath liner (= V + VI on S3);
V: lateral interflow within capillary layer (only on S3) ;
VI: vertical percolation into capillary block (only on S3);
ET+dW: actual evapotranspiration and change in soil water storage.

depths below 1.6 m under the surface of the vegetative cover (e.g. Lotus corniculatus, Cirsium ssp., Rumex ssp., Armoracia rusticana). The marl was brittle, very hard and very dry with cracks several millimeters wide. Figure 3 shows the desiccation of the liner from 1987 to 1995. The average water content in 1995 (14.4 vol.-%) is much lower than the water content measured in the laboratory during the determination of the water retention data at soil water tensions of 3000 hPa (22.6 vol.-%) and 15 000 hPa (17.7 vol.-%). Therefore matric potentials within the liners must have been very low during the dry summer of 1995.

The sequence of increasingly dry summers in 1989, 1992, and 1995 has led to higher percolation rates in the following winters. From 1993 through 1995 136 mm/a to 202 mm/a have leaked through the compacted soil liners (flow 'IV' of fields S1 and F1, flow 'V+VI' on S3 in Table 1). The sum of the lateral discharge within the drainage layer (flow 'III') and the liner leakage represents the potential percolation into the landfill. In 1995 an average of 49% of the potential leakage actually leaked through the liners.

Geosynthetic clay liner (GCL)

GCL appeared on the German market in the early 90s. They are used for a variety of geotechnical purposes including covers for contaminated sites. Laboratory tests have proven a low permittivity of swollen GCL, even after several wet/dry cycles. Being aware of the threat that desiccation poses on compacted soil liners, we wondered if field conditions (root

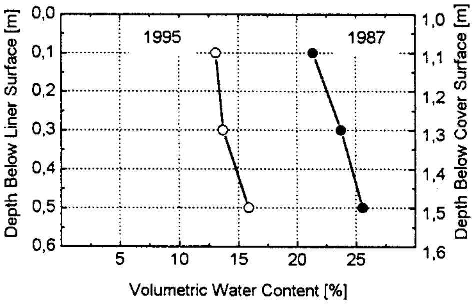

Figure 3 Water Content in the Compacted Soil Liner (S1) after Construction and 1995

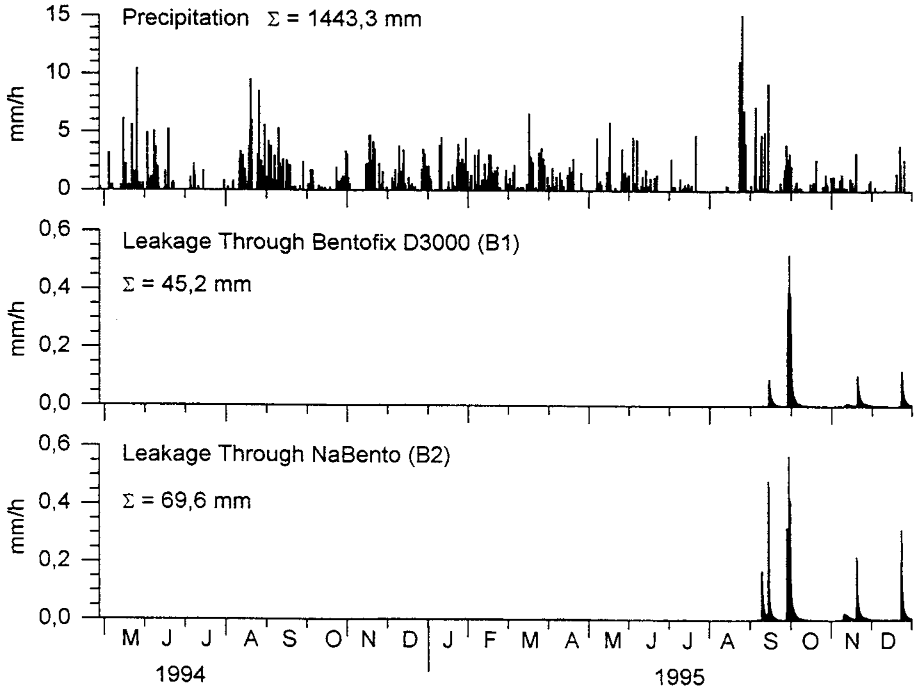

Figure 4 Geosynthetic Clay Liners: Precipitation and Leakage of Bentofix (B1) and NaBento (B2)

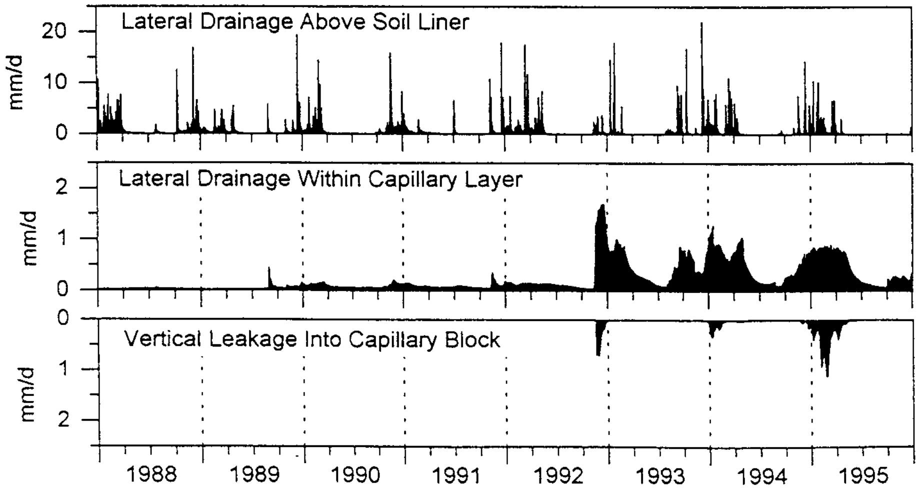

Figure 5 Extended Capillary Barrier on Test Field S3: Lateral Drainage Above the Soil Liner and Within the Capillary Layer and Vertical Leakage into the Capillary Block

penetration, chemical composition of soil water, varying velocity and intensity of desiccation and moistening) would influence the performance of GCL. Therefore we set up two test fields and three observation plots in April 1994. For two reasons we decided to test the GCL under a rather shallow cover of 0.3 m topsoil (sandy loam, 4% organic carbon) and 0.15 m drainage layer (gravel, 1 mm to 8 mm): (1) Field tests are time consuming. Therefore we wanted to be sure that plant roots and desiccation would reach the depth of the GCL during the first two years of the study; (2) GCL are used under shallow topsoils in covers for old contaminated sites (on new landfills German regulations require > 1.3 m thickness of topsoil and drainage layer above a liner). We chose a needle-punched GCL (Bentofix D 3000 with natural Na-Bentonite, Naue Fasertechnik) and a stitch-bounded GCL (NaBento with activated Ca-Bentonite, Huesker Synthetic) for the two test fields with underdrains to collect leakage. The American GCL were installed in small plots without underdrains. The concept of the study and the technical set-up were approved by the manufacturers' representatives or their distributors in Germany before the construction of the fields. The manufacturers kindly delivered the GCL at no cost. Representatives of the companies were present to supervise the installation of the GCL and to seal the overlaps personally.

The average water content of the GCL during installation had been 10.4% (April 1994). In November 1994 the GCL were swollen (water content of Bentomat and Claymax 138% and 152% resp.). Plant roots had penetrated the GCL. The summer of 1995 was extremely dry in Hamburg (water contents of topsoil and the drainage layer 5 vol.-% and 1 vol.-% resp.). The soil water tension of the GCL exceeded the measurement range of tensiometers. The measured water contents of 29% (Bentomat) and 37% (Claymax) also prove the desiccation of the GCL. In fall and winter 1995 the GCL were remoistened again with water contents above 100%. The depth of freezing did not reach the GCL. Visual inspections of Bentomat and Claymax during the summer of 1995 and also of Bentofix and NaBento in spring 1996 revealed a pronounced soil structure with up to 2 mm wide gaps and cracks between bentonite aggregates of about 1 cm in diameter.

The characteristic property of GCL is their ability to rehydrate and swell. Figure 4 shows the precipitation data and the leakage through the GCL until the end of 1995. Both GCL performed excellently during the first winter (0.0 mm and 6.2 mm leakage through Bentofix and NaBento, resp.). This result demonstrates the proper installation of the GCL including the overlaps. However, after the dry summer of 1995 rainfall first remoistens the topsoil (August) and then produces high leakage rates after every major rainfall event (up to $1 \times 10^{-7}\ m^3\ m^{-2}\ s^{-1}$). Within four months, 45 mm and 63 mm leaked through Bentofix and NaBento, resp. During the whole winter of 1995/96 the GCL did not rehydrate and swell enough to seal the preferential flowpaths formed during desiccation. Research to explain the reasons for this very fast decrease of efficiency is ongoing. First results indicate that the mineralogical structure of the bentonite is still intact. However calcium ions have exchanged sodium to a large extent. Consequently the swelling capacity of the bentonite has been reduced to values close to typical values of Ca-Bentonite. Precipitates of humic colloids, carbonates or iron hydroxides have not been found on the surfaces of the bentonite aggregates so far. The leakage through the GCL will be monitored at least until spring 1997.

Capillary barrier (CB)

The capillary barrier on field S3 consists of 0.6 m of fine sand (78% of the particles with diameters from 0.1 mm to 0.2 mm) as a laterally conductive capillary layer above 0.25 m of coarse sand and gravel (85% from 0.63 mm to 6.3 mm), which serves as capillary block. The unsaturated hydraulic conductivity of the capillary layer is 1 x 10^{-4} m/s at matric potentials above -30 hPa. The capillary barrier is covered by topsoil, drainage layer and two lifts of compacted soil to limit the vertical infiltration into the capillary layer. Figure 5 shows the lateral drainage above the soil liner, the lateral drainage within the capillary layer and the vertical infiltration into the capillary block (the annual water balance data are given in Table 1). The system performed perfectly during the first 4.5 years. In 1992 the compacted soil liner desiccated. Consequently the leakage through the soil liner along cracks increased dramatically. From November 1992 on several events occurred when the infiltration into the capillary layer exceeded the lateral drainage capacity of the capillary layer and therefore produced vertical leakage into the capillary block (up to 48.7 mm/a in 1995, see Table 1).

In an additional study we tested several material combinations for capillary barriers in a 10 m long tilted trough under various inclinations and infiltration rates (Steinert *et al.* 1996). Capillary layers with medium or coarse sands had much higher lateral drainage capacities than the material combination used in test field S3. These results show the potential for the use of optimally designed conductive capillary barriers in landfill covers.

Composite liner (CL, geomembrane above compacted soil liner)

Composite liners with 1.5 mm thick HDPE-membranes above three lifts of compacted marl (see chapter on compacted soil liners) were tested on three test fields since 1988. On two fields (S2, F2) the geomembranes are welded, on field F3 the geomembranes are installed overlapping in slope direction. The performance of the composite liners is excellent. Table 1 shows that an average of 1.3 mm/a has been collected underneath the liners of fields S2 and F2. On field F3 it has been slightly more (3.6 mm/a). Detailed interpretation of the soil hydrological and temperature data reveals that the water collected underneath the composite liner is not the result of leaks within the geomembrane but is transported out of the compacted soil liner during hot summer periods when soil temperature is higher at the surface of the soil liner than on its lower boundary. This water transport causes periodical changes of the matric potential within the soil liner. Additional studies on the thermally induced water transport in composite liners (Vielhaber 1995) have shown that the absolute temperature as well as thermal gradients induce a transport of vapor and liquid water from warm to cold regions of the soil. However, in a temperate climate and underneath a thick topsoil the thermally induced downward water transport is very slow, limited to a short period of the year and will not threaten the integrity of the compacted soil liner within several decades.

CONCLUSIONS

Test fields are very useful tools to monitor the performance and water balance of landfill covers. An appropriate technical set-up design is required and time is needed to collect and interpret valuable data. The most important conclusions after ten years of field studies in Hamburg, Germany are:

- A cover should be designed to maximize evapotranspiration and lateral drainage. However, in humid climates and in semi-arid areas with rare but intensive precipitation, a liner is needed to effectively limit the infiltration into a landfill or contaminated site.
- Compacted soil liners and geosynthetic clay liners are very sensitive to desiccation and shrinkage. Upward water transport into dry topsoil and water uptake of plant roots have caused an irreversible formation of cracks and preferential flowpaths in the tested liners. Plant root penetration and desiccation of CSL and GCL must be prevented by thick topsoils or other protective measures. At present no means are known to control the properties of clays in order to prevent the formation of preferential flowpaths during desiccation or to rapidly re-seal cracks in shrunken cohesive surface liners.
- Capillary barriers are promising components for covers on slopes. However, they must be protected against high infiltration rates into the capillary layer. In humid environments, and most likely also at many semi-arid sites, a lateral drainage component is mandatory. The conductive capillary layer should have a maximum unsaturated conductivity at matric potentials above 30 hPa, achievable with well sorted coarse sands. Well graded materials, silts, loams, and clays are unsuitable for capillary layers. The capillary block should consist of gravel and must provide filterstability to the capillary layer. Within a composite liner (e.g. under a geomembrane) a capillary barrier can provide a secondary liner as well as a system to monitor the performance of the primary liner.
- Composite liners with geomembranes above a compacted soil liner performed best. Geomembranes are very effective and make durable liners if suitable polymers are used and if they are installed properly. The cohesive soil component is able to seal local defects in the geomembrane. Unlike in base liners, however, soil liners are rarely used in covers to retard contaminant transport. Placed under an intact geomembrane, the soil liner is protected against upward directed water losses. In the long term (after at least many decades) this would no longer be true if the geomembrane would deteriorate completely. Over decades thermally induced water transport may cause desiccation of the soil liner even under an intact geomembrane. In conclusion composite liners with geomembranes are very effective and durable systems. However, there is some potential to make them more cost-effective by reducing the

thickness or the quality of the soil component or by replacing the soil liner by a different geomembrane or a capillary barrier.
- Covers should be designed carefully by taking into account the specific boundary conditions of the individual application (e.g. climate, geometry, actual or potential hazard of the site, planned use of the cover, availability of materials, critical influences like differential settlements or aggressive chemicals, and costs). Planners can choose from a variety of options to design a cost-effective and suitable cover.

ACKNOWLEDGEMENTS

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REFERENCES

Melchior, S. (1993) Wasserhaushalt und Wirksamkeit mehrschichtiger Abdecksysteme für Deponien und Altlasten (Water Balance and Effectiveness of Multilayered Landfill Covers). Ph.D. Thesis, University of Hamburg, Germany. *Hamburger Bodenkundliche Arbeiten,* 22, p. 330.

Melchior, S. and G. Miehlich (1989) Field Studies on the Hydrological Performance of Multilayered Landfill Caps. In U.S. EPA (ed.) *Proceedings of the 3rd International Conference on New Frontiers for Hazardous Waste Management in Pittsburgh, PA*. P. 100-108.

Melchior, S., K. Berger, B. Vielhaber and G. Miehlich (1994) Multilayered landfill covers: field data on the water balance and liner performance. In: Gee, G. and N.R. Wing (eds.) *In-Situ Remediation: Scientific Basis for Current and Future Technologies*. Battelle Press, Columbus, Richland, pp. 411 - 425.

Steinert, B., S. Melchior, K. Burger, K. Berger, M. Türk and G. Miehlich (1996) Dimensionierung von Kapillarsperren zur Oberflächenabdichtung von Deponien und Altlasten (Dimensioning of Capillary Barriers for Landfill Covers). Research Report no. 1440 569A-39 to the German Federal Institute of Material Testing and the German Ministry for Research and Technology (BMBF), p. 19.

Vielhaber, B. (1995) Temperaturabhängiger Wassertransport in Deponieoberflächenabdichtungen. Feldversuche in bindigen mineralischen Dichtungen unter Kunststoffdichtungsbahn (Thermally induced Water Transport in Landfill Covers). Ph. D. Thesis, University of Hamburg, Germany. *Hamburger Bodenkundliche Arbeiten,* 29, p. 200.

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