LYSIMETER FIELD STUDY OF A CLAY GEOSYNTHETIC BARRIER IN A LANDFILL COVER SYSTEM

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ABSTRACT: Clay geosynthetic barriers, also known as geosynthetic clay liners (GCL), are often used as elements of landfill cover systems instead of compacted clay liners which are favoured by the technical regulations of the EC and of Germany. As a contribution to the verification of the performance of GCL in landfill applications a lysimeter field study was conducted on a landfill in Bavaria. The large lysimeter, 520 m² in size, allows collection and continuous measurement of surface runoff on the topsoil, drainage flow in the geocomposite and leakage flow through the GCL. In addition soil moisture measurements are carried out in the restoration profile and in the GCL. The relevant meteorological data are measured continuously. Results of the monitoring period from 1998 to 2002 are presented here. The test site is characterised by cool temperate, humid conditions with average annual precipitation of approx. 750 mm. Approximately 2/3 of the total precipitation were returned to the atmosphere as evapo-transpiration. Some 30% were drainage flow in the geocomposite and only about 1% of the precipitation resulted in leakage flow through the GCL. Thus the landfill cover system including a calcium-GCL proved to be an effective landfill cover system within the observation period.

1 INTRODUCTION

The EC landfill directive (1999) defines in article 1 (1) as general aim “to reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment [...] from landfilling of waste, during the whole lifecycle of the landfill“. The surface sealing has special importance as a long-term barrier in the sense of this ambitious goal.

The surface sealing of a landfill serves as long-lasting barrier between the body of waste and the atmosphere and biosphere. Its main tasks are to minimize infiltration of water into the landfill, to prevent the escape of landfill gas and dust and to facilitate landscaping and sustaining recultivation of the surface. According to German waste disposal and landfill regulations (TA Siedlungsabfall, 1993), untreated municipal waste may only be deposited on landfills until the year 2005. Landfills, which do not meet the standards of the EC-landfill directive and its German counterpart, will have to stop operation by the year 2009. Therefore, during this decade, a large number of landfills will have to be closed and will eventually have to be covered with an adequate surface sealing system.

The basis for the design of surface sealing systems is given in the EC-landfill directive and – for Germany - in the German “*Deponieverordnung”* of 2002. The *"Deponieverordnung"* gives specific regulations for a standard surface sealing system consisting (for municipal solid waste landfills) from bottom to top of:

- mineral sealing layer (d > 0.5 m; k < 5 x 10^{-9} m/s), artificial sealing liner (geomembrane; d > 2.5 mm),
- protection layer,
- drainage layer (d $\geq$ 0,3 m; k $\geq$ 1 x 10^{-3} m/s),
- top soil cover (d > 1.0 m).

Alternative surface cover systems may be permitted, if they consist of functionally equivalent system components.

Research concerning landfill construction in Germany in recent years has focussed on surface cover systems. The main interest was to test the efficiency of alternative surface cover systems and materials (such as geosynthetic clay liners , capillary barriers and others).

In this paper we present results on a research project concerning GCL, which was financially supported by the Bavarian State Ministry for Regional Development and Environmental Affairs.

2 TEST FIELD SETUP

2.1 *Concept of the study*

There are different ways to assess the effectiveness of landfill surface cover systems:

The expected performance of a surface cover system is often calculated on the basis of hydrologic modeling, e.g. with the HELP-model (Schroeder et al., 1994).

The suitability of GCL can be examined by excavations after a certain time span. However, the tests on exhumed samples provide only a snap-shot-view of the conditions of the materials.

Sporer & Gartung (2002) propose a laboratory test to study the desiccation behaviour of GCL with a test setup, which takes into account the major factors affecting the desiccation process: temperature, temperature gradient and soil properties.

Comprehensive studies of the water balance of landfill cover systems are possible through large-scale lysimeter test fields, which are installed at landfill sites.

The lysimeter test field discussed in the present paper of an area of some 520 m² is equipped at its base with a HDPE geomembrane which acts as collecting pan. The surface sealing system under scrutiny is built inside the large lysimeter on a 1 : 1 scale. The lysimeter is equipped with devices to separately collect and measure surface runoff, drainage flow and leakage through the sealing layer. Finally the surface cover is vegetated and exposed to natural climatic conditions of the landfill site.

2.2 *Test field*

The test site at Aurach, Bavaria, is located some 60 km southwest of Nuremberg in a gently hilly region at an elevation of 500 m above sea level. The test field of 520 m² was constructed on the southern slope (inclination: 20%) of the landfill in summer of 1998. The surface cover system under scrutiny includes a GCL and a drainage geocomposite. A profile of the cover system in the test field is shown in Figure 1. It consists of the following layers:

- top soil: loamy sand (0.2 m),
- subsoil: slightly loamy sand (0.8 m),
- drainage geocomposite,
- calcium-GCL
- regulating layer (slightly loamy sand)
- leakage collection system (bottom drainage geocomposite and HDPE-geomembrane).

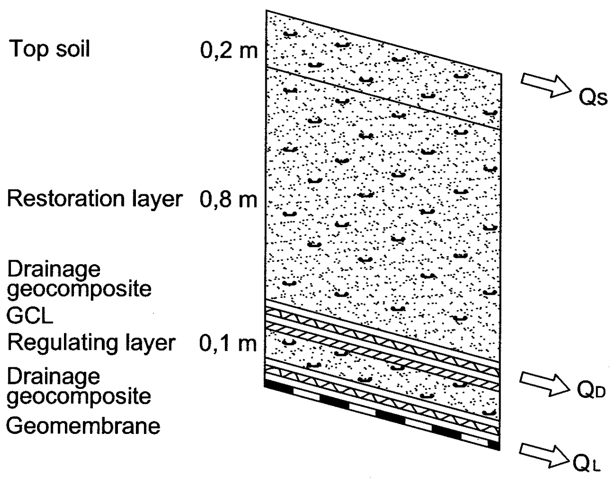


Figure 1 Profile of the lysimeter test field at Aurach landfill

A calcium-bentonite GCL was used in the test field in order to avoid changes in material properties due to ion-exchange effects, which are known to occur in sodium-bentonite GCL (e.g. Egloffstein, 2000). The lower swelling capacity and higher hydraulic conductivity of Ca-GCL compared to Na-GCL is accounted for by higher mass per unit area for the Ca-GCL (Alexiew, 2000). The product which was used in the test field has a mass per unit area of 9500 g/m² and a permittivity Ψ of 8.3×10^{-9} s^{-1} (permittivity = hydraulic conductivity divided by thickness).

Figure 2 Test field under construction: emplacement of the GCL (July 1998)

A drainage geocomposite was used as drainage layer above the GCL. Under a normal load of 20 kPa it has a thickness of 11 mm and a water flow capacity of q_{20} = 0.7 l/(s x m) at i = 0.1.

The major task of the restoration profile is to protect the mineral sealing layer from adverse effects such as desiccation, penetration of roots or freezing. Therefore a loamy sand with a high water retention capacity was chosen as top soil, and a sand which is poor in clay content was selected as subsoil. A photograph of a test-pit through the restoration layer is shown in Figure 3.

Figure 3 Test-pit showing a section of the test field with vegetation, top soil (dark), subsoil (light grey) and drainage geocomposite (white)

The main objective of measurements is the precise determination of the relevant water fluxes (see Figure 1):

- surface runoff (Q_S),
- drainage flow (Q_D),
- seepage flow through the GCL (Q_L).

The water fluxes are continuously measured at high precision in a measuring container. In addition soil moisture measurements by FDRprobes are carried out in the restoration profile. The relevant meteorological data (precipitation, temperature, relative humidity etc.) are measured in a meteorological station nearby. Readings of all measuring devices are taken automatically with the data stored on a PC. All data are transferred the LGA-Geotechnical Institute via GSM.

Figure 2 shows the test field under construction, where the GCL is just put into place in the large scale lysimeter. Figure 4 shows the water collection and measuring devices inside the measuring container. Figure 5 gives an impression of the test field with thick grass vegetation.

Figure 4 View inside the container for water flow measurements and data collection

Figure 5 View of the test field in Summer of 2000

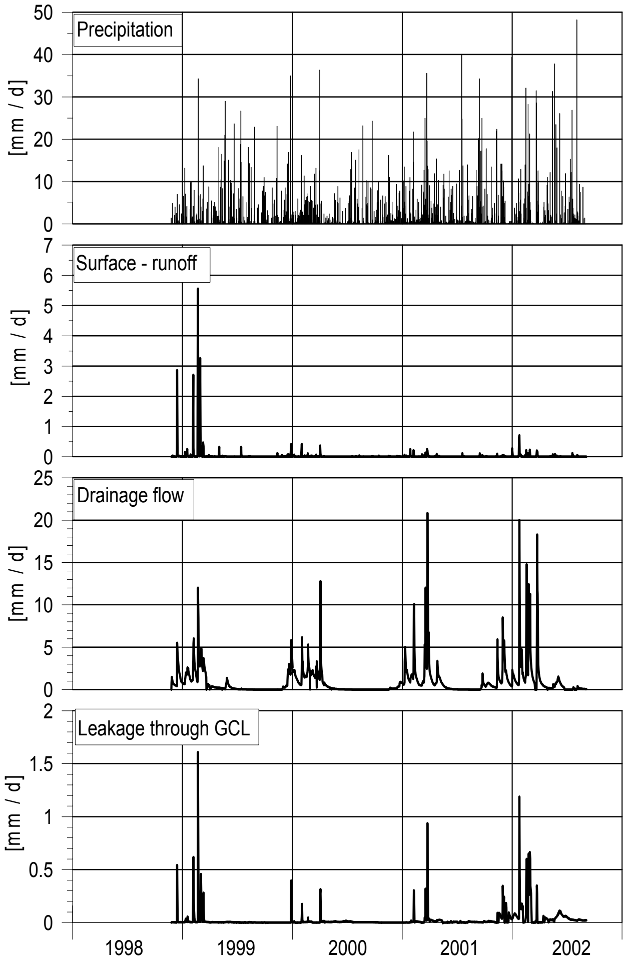


Figure 6 Results of test field measurements: daily values of precipitation, surface runoff, drainage flow and leakage through GCL from 1998 to 2002

3 RESULTS

3.1 *Precipitation and surface runoff*

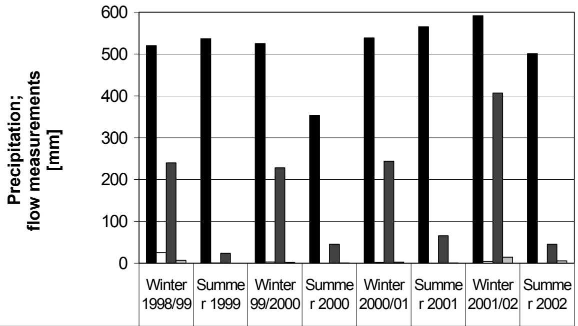
Measurements in the test field started in November 1998. The results of the precipitation and discharge measurements are shown in Figure 6 as daily values in mm/d. The precipitation shows a pattern typical for cool temperate, humid conditions, which prevail in Bavaria. At the location of the landfill, average annual precipitation is about 750 mm. During the observation period precipitation was about 20% higher. Precipitation is almost evenly distributed over the years, without prominent wet or dry seasons. Peak daily precipitation reaches 40 mm.

Noteworthy surface runoff occurred only in the first winter season, while the vegetation on the recultivation layer was still sparse. After this initial period only minimal surface runoff is recorded, which is restricted to a few events in winter times.

3.2 *Drainage flow*

Drainage flow shows a systematic pattern of seasonal variability: Substantial drainage flow is recorded in winter, during the months of October through March. During the summer half year from April to September there is only little drainage flow. In summer, even heavy rainfall associated to thunder storms does not result in drainage flow. The maximum daily drainage flow which occurred during the observation period was 21 mm/d in the generally wet month of March 2001. Daily values of > 5 mm/d occur a couple of times each winter. Peaks in drainage flow occur simultaneous to precipitation events. Following a flow event drainage flow rapidly decreases again to values below 1 mm/d. Drainage flow is recorded by high resolution measurements. The drainage flow reached a maximum short-time value of 3.1 l/(s x ha).

Figure 7 gives the results of the precipitation and flow measurements as semi-annual sums. During the winter half-year (October to March) the sum of drainage flow is in the range of 200 - 400 mm. In the time from April to September ("Summer" in Figure 7) the sum of drainage flow is only 20 - 60 mm. During this time evapotranspiration is the dominant element of the water balance.



	Winter 1998/99	Summer 1999	Winter 99/2000	Summer 2000	Winter 2000/01	Summer 2001	Winter 2001/02	Summer 2002
Precipitation	520	537	525	354	538	565	592	501
Surface runoff	25	1	3	0	2	1	4	1
Drainage flow	240	24	228	46	244	66	407	46
Leakage through GCL	7	0	2	1	3	1	15	6

Figure 7 Results of measurements in the test field: Precipitation and flow measurements given as semi-annual sums (in mm)

3.3 *Leakage flow*

Leakage flow through the GCL is shown in the lowermost graph of Figure 7. Note that the y-axis of this graph is expanded, compared to the other y-axes. Leakage flow occurs only on a few days during the observation period. It is not, as might be expected, proportional to the drainage flow, but it is restricted to a few events per year. Noticeable leakage flow only occurs, when the drainage flow exceeds 5 mm/d. Then the leakage flow reaches daily values of 0.2 to 1.6 mm/d. On the following day it drops to nearly zero again.

Figure 8 shows a plot of precipitation (bold line) and leakage through GCL (thin line) as cumulative sums during the observation period. While the plot of precipitation shows a steadily increasing line, the plot of cumulative leakage through the GCL shows a stepwise increasing line. Leakage takes place mainly during winter, which is represented by the rising parts of the cumulative leakage curve. The plateaus of the curve during summer indicate, that there is no leakage in this time.

Precipitation and leakage in Figure 8 are plotted on their respective y-axes in the ratio of 100 : 1. The curve of cumulative leakage runs below the curve of precipitation during most of the observation period, indicating that leakage amounts to less than 1% of precipitation.

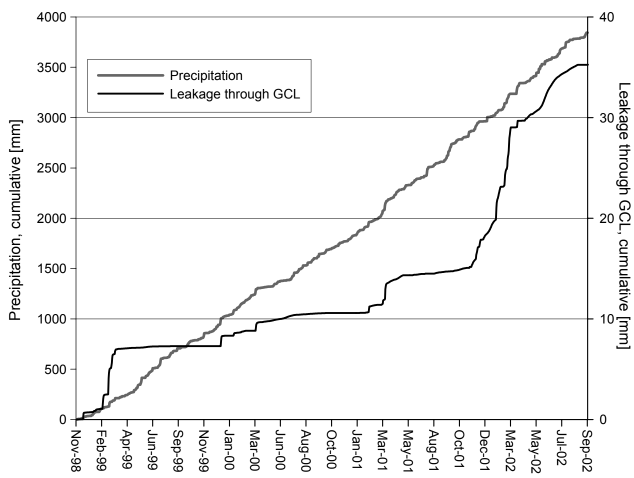


Figure 8 Results of test field measurements, drawn as cumulative curves: Precipitation (left y-axis) and leakage through GCL (right y-axis). Note the 100-fold expansion of the right y-axis

3.4 *Soil moisture measurements*

Four FDR-probes are installed in the restoration profile for continuous monitoring of the soil water content. After proper calibration FDR-probes measure the volumetric water content of the soil. The FDR-probes are installed in a vertical measuring profile within the test field at 0.2 m spacing between 0.2 m and 0.8 m depth.

The results of the measurements of volumetric soil water content by means of the FDR-probes is shown in Figure 9. All 4 FDR-probes display the same overall pattern of higher water content in winter and lower water content in summer. Water content in the topsoil fluctuates between 15 Vol.-% in summer and 30-35 Vol.-% in winter. In the subsoil, which is low in fine fraction, water content varies between 10-14 Vol.-% in summer and 15-20 Vol.-% in winter.

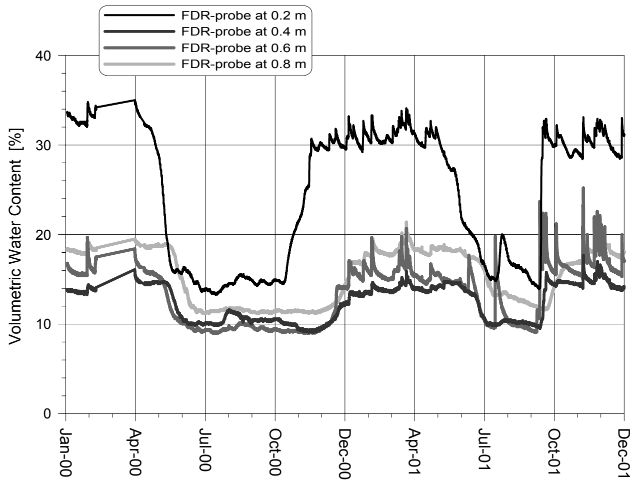


Figure 9 Results of soil moisture measurements by FDR-probes in the restoration profile

3.5 *Moisture measurements within the GCL*

In order to gain a better understanding of the long-term processes within the GCL, it is of special interest to monitor the water content of the bentonite-filling of the GCL. Continuous measurements of soil water content can be made by the FDR method (as described above) or by the time-domain-reflectometry (TDR)-method.

In-situ-measurements within the bentonite layer of a GCL are difficult due to the low thickness of the material. Miniature TDR-probes of the type IMKO P2M were tested in the laboratory with GCL specimens and gave reproduceable, semiquantitative results.

Subsequently, two miniature TDR-probes were installed in the GCL of the test-field. They are situated near the center of the test field with a spacing of 0.5 m between them. As there was no experience with this kind of in-situ-measurements before, the TDR-probes were placed close together, in order to check the reliablilty of the data.

Due to the extremely low thickness of the bentonite layer, it is possible that the measuring volume around the rods of the TDR-probes reaches into the adjacent material of different water content. Therefore in Figure 10 the mV-readings of the output-signal of the TDR-probes is given rather than the calculated water contents using the tentative laboratory calibration. Low mV-readings represent low water content, higher readings represent higher water content.

The results of the TDR-probe measurements within the GCL are shown in Figure 10. The readings of the TDR-probes give continuous information about the moisture conditions of the bentonite of the GCL within the lysimeter test-field.

The most remarkable feature of the graphs in Figure 10 is, that the water content of the bentonite does not remain constant. Instead, there are obviously considerable changes in water content of the bentonite in the course of the year. There is a pattern of higher water contents in spring and early summer and lower water contents during the rest of the year, which is repeated in consecutive years.

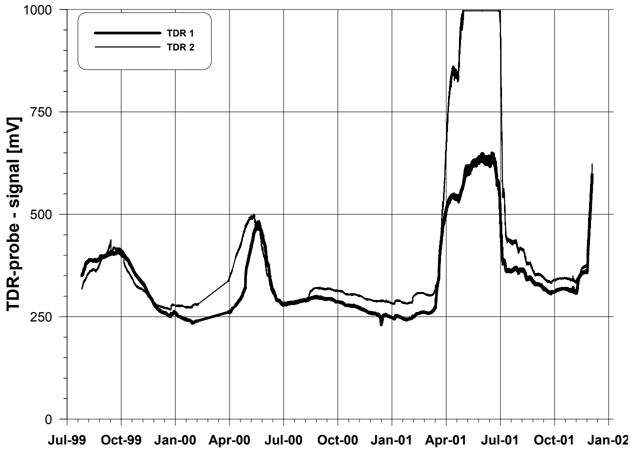


Figure 10 Results of moisture measurements of the GCL using miniature TDR-probes

4 DISCUSSION

4.1 *Water balance of the restoration layer*

The observations made in the test field give insights into the water balance of a landfill cover system with a GCL as sealing layer. Under middle-European climatic conditions the water balance at most locations shows distinct seasonal differences: During summer months evapotranspiration exceeds the amount of rainfall. In addition soil water is extracted and evapotranspirated. During winter season precipitation is higher than evapotranspiration. The soil water reservoir is replenished. When the field capacity of the soil is reached, additional precipitation percolates down into deeper layers. This process, which in natural soils leads to groundwater recharge, has repeatedly been observed in lysimeter test fields on landfills as drainage flow and seepage flow (Henken-Mellies et al., 2001; Barth & Wohnlich, 2003; Breh & Hötzl, 2000; Siegmund et al., 2001).

During the months from April to September (indicated as "Summer" in Figure 7) the water balance is dominated by evapotranspiration, which during these months exceeds precipitation for average locations in Germany. Hence there is only little discharge during the summer half of the year. Exceptions from this rule are connected to extreme weather conditions, such as the cool and wet autumnal conditions starting in mid-September of 1998 or the extremely wet summer of 2002. During the winter half of the year (October to March) evapotranspiration is low. Precipitation during this time of the year first leads to replenishment of the soil water reservoir and then to substantial discharge.

The layers above the GCL have important functions with respect to the water balance: The restoration layer has the task to keep desiccation stress away from the GCL in summer time. Soil water extraction due to evapotranspiration should not reach down to the base of the restoration zone. In the test field the 1 m thick restoration layer does not sufficiently fulfill this task: The FDR-measurements in different depths of the restoration layer indicate, that the soil reaches a low and constant water content in summer and autumn. This low water content can be interpreted as the permanent wilting point of the soil.

4.2 *Performance of the GCL*

Leakage flow through the GCL is in the order of a few millimeters per year or 0.3% to 1% of the precipitation. In the first winter after construction of the test field leakage flow was somewhat higher; since then it remains as low as 0.3% of the annual precipitation. During the extraordinarily wet year of 2001/2002 leakage reached 1.9% of precipitation.

The process of leakage through the GCL is obviously not a low and constant flow, but a sporadic flow, which is triggered by high drainage flow (see Figure 2). It can be assumed that during times of high drainage flow (> 5 mm/d) a hydraulic head builds up temporarily in the drainage layer, which then causes leakage flow. During most of the time the drainage layer effectively keeps the hydraulic head at about zero, and consequently no leakage flow occurs.

The desiccation of the restoration profile obviously also affects the GCL: The in-situ-TDR-probes detected annual changes in moisture content of the bentonite layer.

The leakage flow through the GCL in the test field reported here is in the same range as in test fields elsewhere: Siegmund et al. (2001) made long-term observations at a test field in Thuringia. In the profile of the test field they placed a sandy buffering layer between the drainage layer and the GCL, in order to reduce the risk of desiccation of the GCL. Here leakage flow occurred on numerous days during winter season with flow on individual days ranging from 0.05 to 0.25 mm/d.

Blümel et al. (2002) report on lysimeter measurements at Lemfoerde in northwest-Germany. Lysimeters with a diameter of about 2 m were filled with different GCL and a restoration profile of not more than 1 m in thickness. During the 3-years measurement period the average leakage rate was found to be 3 - 5 mm/yr, which is about 0.5% of the precipitation during the observation period.

5 CONCLUSION

The performance of a drainage geocomposite and a Ca-GCL within the surface cover system of a landfill has been observed in the lysimeter-test field on the landfill at Aurach, Bavaria.

The water balance of the 4-years monitoring period shows, that evaporation accounts for 2/3 of the water output. 30% of the water input drain off laterally in the drainage geocomposite, and only 0.9% seep through the Ca-GCL. These results show, that the landfill capping system including a heavy Ca-GCL fulfills its task to minimize the leakage of water into the landfill body.

The measurements within the lysimeter test-field are being continued in order to gain more information about the long-term behaviour of the Ca-GCL in the surface capping system.

The results emphasize the importance of a properly designed landfill cover system including a sufficiently thick restoration layer in order to regulate the water balance of the surface cover system. The results of the in-situ-moisture measurements within the restoration profile show, that during most summers the extraction of soil moisture reaches down to the base of the 1.0 m thick restoration layer. For the climatic and vegetational conditions given at the test-site the restoration layer of 1.0 m thickness is obviously not sufficient to keep desiccation stress away from the underlying GCL.

The thickness of the top soil cover of surface sealing systems should not be designed just to satisfy the minimum requirements given in the EC-landfill directive ("top soil cover > 1 m") but should be designed taking into account the conditions at each individual site.

6 ACKNOWLEDGEMENTS

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