LONG-TERM EFFICIENCY OF GCLS WITH REGARD TO NATURAL DRYING AND WETTING CYCLES

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Abstract: Geosynthetic clay liners (GCLs) are widely used in landfill engineering and dam construction for sealing applications. GCLs are mostly made by needle-punching of two nonwoven geosynthetics filled with powder or granulate bentonite. The bentonite used in GCLs is special clay (approx. 75 to 90 % of its weight is montmorillonite) with very high swelling capacity, high ion exchange capacity and very low hydraulic conductivity. Evaluation of laboratory tests and numerous excavation results have shown that GCLs as well as compacted clay liners (CCLs) can be affected by desiccation. But during wetting periods the available swelling potential of GCLs, together with a counter pressure activated by the geosynthetic structure and the overburden can close cracks in the bentonite filling. This "healing effect" can be expected, if sufficient water and surcharge load are available.

To prove this GCL behaviour under field conditions a special lysimeter set-up was designed and built in 1998. The lysimeters were integrated in a hill shaped soil body with a height of about 3 m. As parts of landfill sealing systems the GCLs were covered in the lysimeters with drainage gravel or geosynthetic drainage layers (GDLs) on which a layer of soil for recultivation purposes was placed. Collected data of the lysimeter tests include temperature, humidity, precipitation and drainage water discharge above the GCLs and permeation water discharge through the GCLs. All data are measured automatically every 10 minutes. Supervising of data collection and scientific data interpretation have been carried out by the Institute of Soil Mechanics and Foundation Engineering of the University of Hannover right from the beginning in 1998.

The results show a significantly different behaviour of the GCL-liner systems investigated in these lysimeters between (dry) summer and (wet) winter periods for more than 9 years. After drying periods with decreasing liner effectiveness the system regenerates in wet periods very well every year, if the type and the thickness of the cover soil above the GCL is matching certain conditions.

Keywords: GCL, lysimeter, landfill cover system, permeation in dry and wet periods, reversible material behaviour

INTRODUCTION

In landfill engineering conventional components of liner systems e.g. mineral drainage layers or compacted clay liners, are replaced more and more by geosynthetics. Geosynthetic products for such purposes must feature at least the same degree of functionality and efficiency as the mineral components and in addition they should have advantages in installation and costs.

It has been proven by many researchers that bentonite encapsulated between geotextile components can form an excellent liner component. Such bentonite mats for landfill covers are mainly investigated in laboratory tests to determine the permeability coefficient. These tests cannot cover the complex permeation behaviour of GCLs exposed to climate conditions in situ.

Cover systems of waste deposits featuring needle-punched bentonite mats have been excavated in Germany. X-ray investigations have documented that needle-punched bentonite mats display cracks when the water content is dropping below a critical value.

Tests to measure the permeation rates through GCLs under boundary conditions in situ comparable to landfill covers are described by Henken-Mellies et al. (2002), Wolsfeld (2005) and Melchior et al. (2006).

Such field tests have been performed mainly to demonstrate the sealing capacity of GCLs and were not especially worked out to investigate the effects of wetting and drying cycles caused by seasonal humidity changes due to our climate conditions.

The water holding capacity of recultivation layers designed according to German state-of-the-art in landfill-engineering, the evaporation and the water taken by vegetation in the growing season lead to periods in which no drainage takes place. This means, that no water is permeating through the recultivation layer into the drainage layer and furthermore evaporation can generate a reduction in water content of the bentonite within the GCL. Consequently water suction stresses in the pores of the bentonite can lead to cracks in the layer. Due to such changes of temperature and water content, GCLs show an instationary permeation behaviour. We have to regard increasing permeation during dessication (Reuter, 2006). The sealing efficiency of GCLs in landfill covers is depending on its water content and may be reversible. To investigate this behaviour in a long-term, six lysimeters were built and filled with different cover systems including GCLs with granular or powder filling.

LYSIMETER SET-UP

The lysimeter method is appropriate to model a section of a cover system with soils in a bigger scale and to study the water movement. The lysimeters were constructed in autumn 1998 in a similar way as described by Maile (1997). This design has shown its general ability as an approved system. The lysimeters were surrounded with soil to meet in situ temperature and rainfall conditions better than with a free standing lysimeter type.

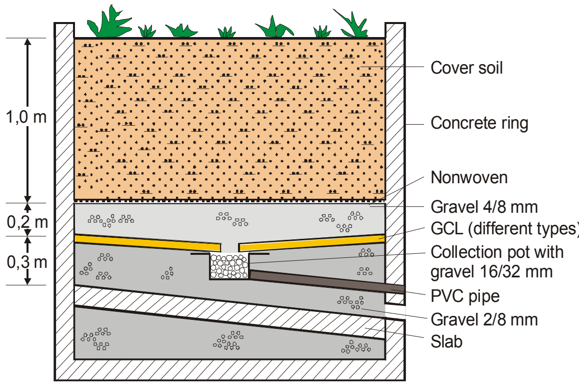


Figure 1. General layout of a lysimeter test set-up

The lysimeters were built in a hill shaped soil body (Figure 2) with a height of about three meters containing also equipment for measuring the water discharge above and below the GCL (Figure 4). The concrete rings have a diameter of 2 m. The entire area of the lysimeter as well as the bottom slab was seal-coated. The connection between the slab and the ring wall was additionally reinforced with a woven geosynthetic to prevent tearing of the coating. The bottom slab was constructed with an inclination towards the edge to guide the permeating water to the measuring system. Prior to the filling of clean gravel on top of the concrete slab a PVC pipe and a stainless steel collection pot were installed. To avoid movements during the filling with gravel the pipe system was fixed. The stainless steel pot was coated inside. To prevent clogging of the collection system, a needlepunched nonwoven was placed on the bottom of the collection pot, which has been filled with 16/32 mm gravel.

Figure 2. Vegetation on the lysimeters in the beginning of 2002 (left) and after two years (right)

The installed needle-punched GCLs were pre-cut with a diameter of 2 meters and a 5 cm diameter hole in the middle so that water from above the GCLs can flow into the collection pot and from there to the measuring equipment. To allow water flow towards the middle, where the drainage collection pot is located the GCL was installed with an inclination. To avoid side wall leakage a 1.5 mm thick PVC strip (10 cm) overlapped the GCL and was fixed 20 cm above the GCL to the concrete ring. An overlapping stainless steel sheet was fixed on the PVC strip and additionally sealed on the top.

For the lysimeters 1 to 3 the filling was selected to model a landfill capping (Figure 3). The lysimeters 3 to 6 have a different filling which is mainly modelling sealing systems for groundwater protection below roads. The cover soil thickness and therefore the overburden load are small. In this paper these lysimeters will only be discussed for comparison purposes in chapter 4.

The GCLs in lysimeters 1 to 3 were covered with 20 cm of 4/8 mm gravel. Soil for recultivation, which will be described later, was placed above in a thickness of about 1 m and separated by a needlepunched PP nonwoven with a mass per unit area of 300 g/m². Some soil-mechanical classification values of the cover material are indicated in Figure 3. The top level of the cover soil was some centimeters below the edge of the concrete rings to keep water from intensive rainfall in the system. Grass and similar crops are growing in the recultivation soil to match natural evapotranspiration conditions of landfill covers.

Within the first three years, root growth in the cover soil layer was leading to an increasing volume such that the lysimeter soil surface level was raising considerably. To prevent rain water to run out off the system, the upper edge of the concrete rings should be 5 cm above the soil surface. Therefore vegetation was removed in July 2002 to reestablish the set-up. Furthermore the cover soil of lysimeter 1 was replaced by sand which was installed without compaction and is therefore showing a quite good permeation of water. The coefficient of water permeability of this sand was investigated by laboratory tests and was found to be about 10^{-3} m/s. Compared to the original condition, the retention capacity of the cover soil now is considerably lower thus expecting a higher water discharge on the GCL in lysimeter 1 due to drainage. The data and parameters of the different fillings of the lysimeters 1 to 3 are given in Figure 3.

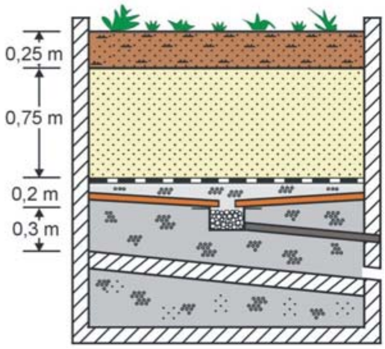
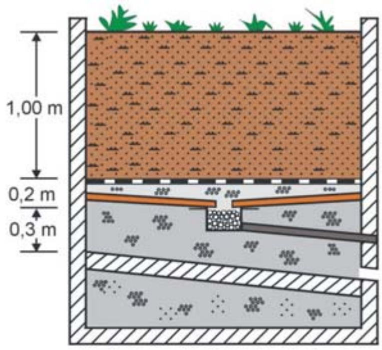
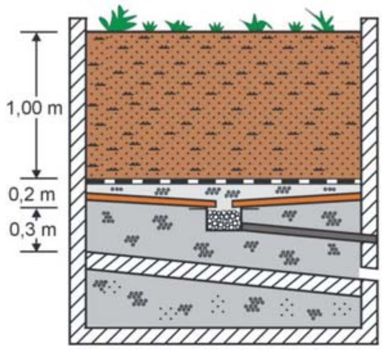
Lysimeter 1:	**Lysimeter 2:**	**Lysimeter 3:**
		
Cover soil: sand Permeability: ~ 10^{-3} m/s Dry Density: ~ 1.3 g/cm³ drainage layer: gravel GCL: NSP 4900-1, ca. 4670 g/m² powder-bentonite-filling [until July 2002 the cover soil was equal to lysimeter 3]	Cover soil: silty sand Permeability: ~ 10^{-6} m/s Dry Density: ~ 1.5 g/cm³ drainage layer: gravel GCL: BFG 5000, ca. 5000 g/m² powder-bentonite-filling, bentonite-impregnated non-woven [until July 2002 the density of the cover soil was equal to lysimeter 3]	Cover soil: silty sand Permeability: ~ 10^{-7} m/s Dry Density: ~ 1.7 g/cm³ drainage layer: gravel GCL: NSP 4900-3, ca. 4500 g/m² granulated bentonite-filling

Figure 3. Lysimeter fillings

The cover soil of lysimeter 2 has also been removed in July 2002, cleaned from large roots and reinstalled without compaction thus providing a lower density of the layer. Accordingly, a higher quantity of drainage water is to be expected. In lysimeter 3, only vegetation and roots near the surface have been removed. Grass is growing on the top of all lysimeters and on the surrounding soil body (Figure 2 (right)).

For monitoring temperature and water content of the cover soil and of the bentonite in the GCLs new sensor systems have been installed e. g. to measure the dielectric coefficient of the GCL layer. This system should be tested and calibrated within the frame of the programme. But these measurement systems have not reached a status to deliver data of practical value.

Figure 4. Meteorological station (left), measuring room (middle,) tipping bucket to measure water discharge (right)

MEASUREMENT RESULTS

Data of the rainfall, temperature, drainage water discharge above the GCLs and permeation water through the GCLs have been evaluated. Relevant water balance parameters of a lysimeter and a landfill capping system which are needed for the data-analysis are given in Figure 5.

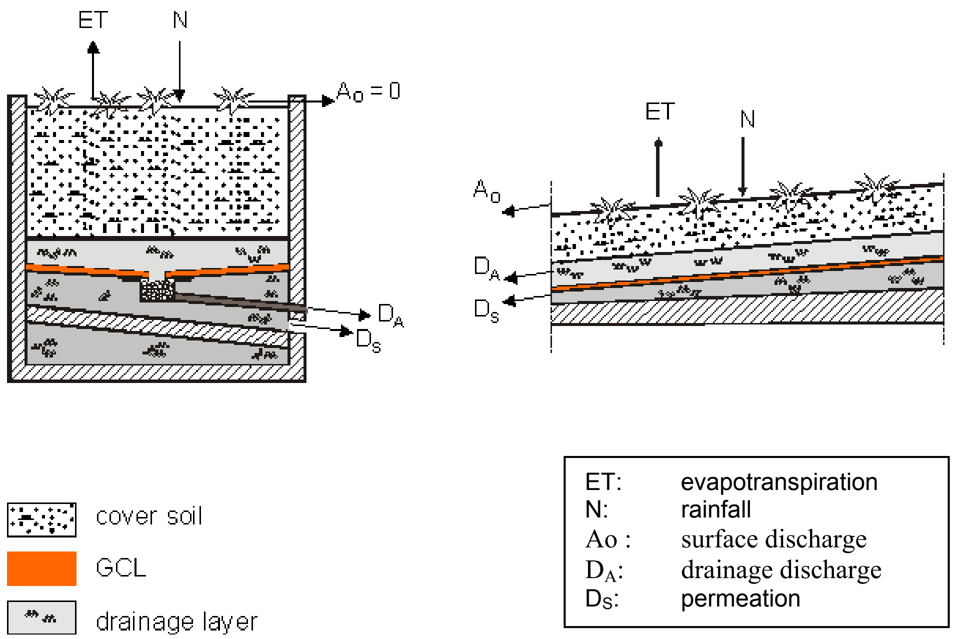


Figure 5. Water balance parameters for a lysimeter (left) and for a landfill cover system (right)

Accumulated data of rainfall, drainage water discharge above the GCL and of water permeating through the different GCLs of lysimeter 1 to 3 during the measuring period from 1999 to 2007 are presented in Figure 6. The time of the exchange of the cover soil is marked in the charts to facilitate data interpretation.

The rainfall shows a quite constant distribution over the year, which is typical for the humid climate in Central Europe.

The discharge of the drainage water is concentrated in the winter-period between November and April. In the summer-half-year there is nearly no drainage discharge due to a higher evapotranspiration and related effects. Therefore even heavy rainfall is not remarkable in the drainage-discharge-plot in summer-periods as the plants absorb and evapotranspirate most of the water.

The discharge of the permeation water is not directly related to the drainage discharges. Permeation of the GCLs increases mainly in the first half year and decreases in the second half year, generally in a similar manner for all the three lysimeters. Lysimeter 3 shows no significant decrease of permeation in the summer periods.

Shortly after July 2002 there was a significant increase of the drainage discharge of the lysimeters which was partly caused by the cutting of the plants and mainly -in case of lysimeter 1 and 2- by the higher hydraulic conductivity of the cover soil.

The GCL in lysimeter 2 shows a special permeation behaviour. Since summer of 2003 there was no permeating water collected. To rule out the possibility of system defects and measuring mistakes, the water-discharge pipes have been inspected. These investigations made sure that the equipment of the lysimeter-system is intact. In February 2007, a remarkable amount of permeation water discharge was collected again. This may be taken as an additional indicator, that the measuring system of lysimeter 2 was always working and that actually no water was permeating through this special GCL of the type BFG 5000 with bentonite-impregnated non-woven on top (Figure 3) for about three years.

The following table shows the summarized data of the lysimeters 1, 2 and 3 for the whole investigation period.

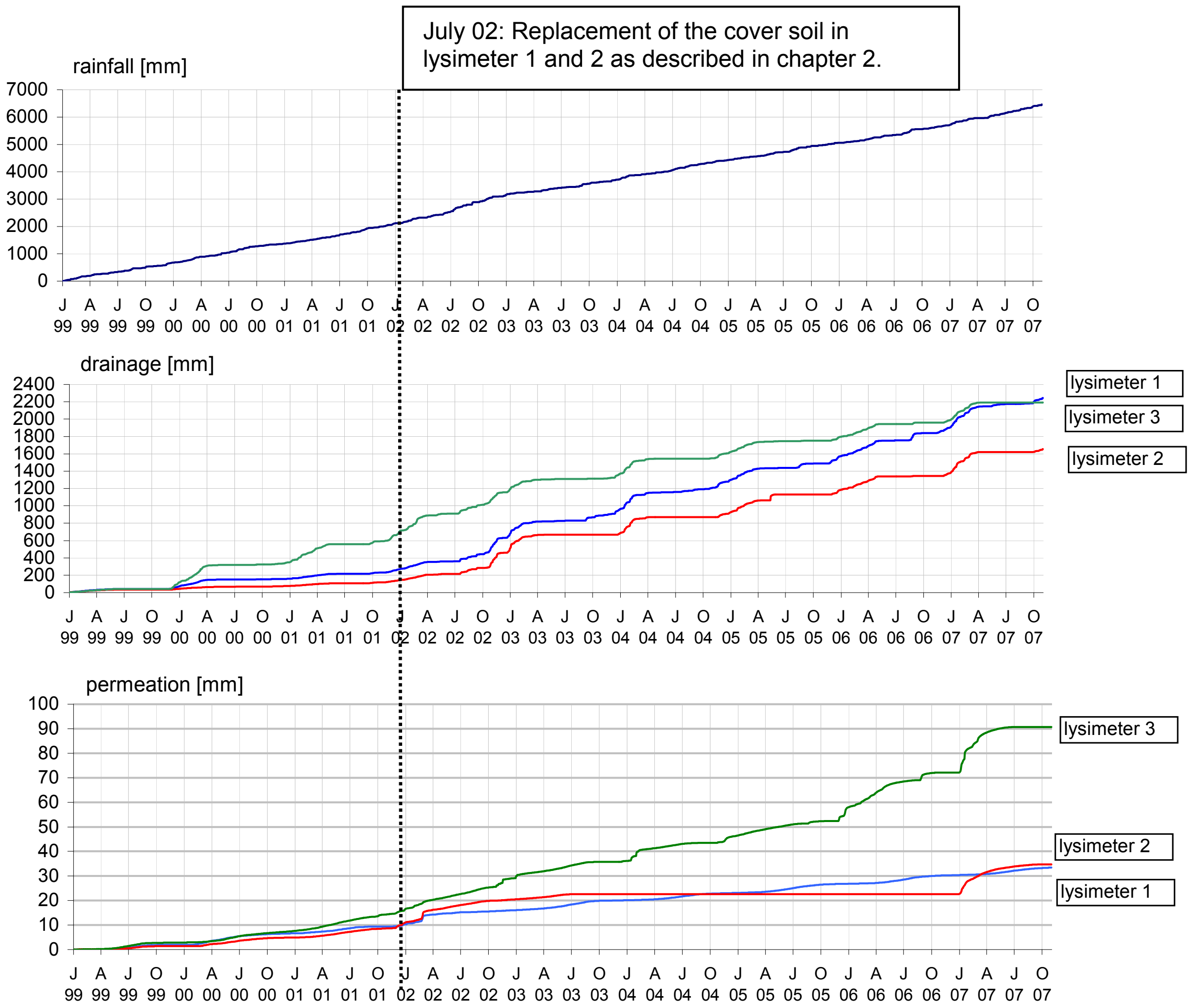


Figure 6. Accumulated data of the lysimeters 1 to 3 for the period from 1999 to 2007

Table 1.Summarized data for a period of about nine years

	Rainfall [mm]	Drainage		Permeation	
		[mm]	% of rainfall	[mm]	% of rainfall
Lysimeter 1	6461	2245	35	33	0.5
Lysimeter 2		1655	25	35	0.5
Lysimeter 3		2192	34	91	1.4

The portion of the rainfall that permeated through the GCLs during nine years is about 0.5 and 1.4 % only.

Figure 7 shows the effect of the cover-soil changing more significantly. As already described above, the cover soil in lysimeter 1 was changed from a silty sand with a higher density to a sand with a permeability coefficient of aproximately 10^{-3} m/s. As a result of this, the amount of drainage water is increasing and more water is reaching the GCL in summer periods. This effect is obviously leading to decreasing permeation. Further interpretation of this phenomenon will be given in chapter 5.

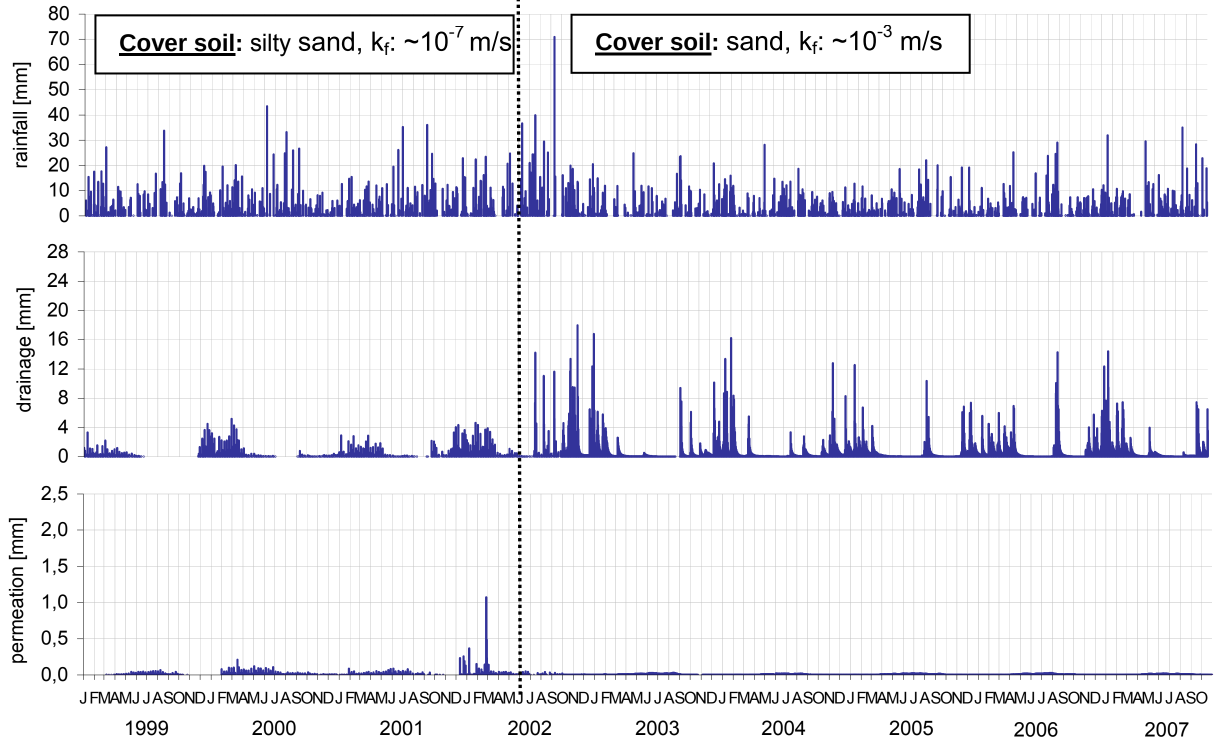


Figure 7. Rainfall, drainage and permeation for lysimeter 1 between January 1999 and October 2007 (daily datas)

LINER SYSTEMS WITH THIN COVER SOIL LAYERS

In summer 2001 three additional lysimeters (no. 4, 5 and 6) with cover soil layers of only 0,65 to 0,85 m in thickness above the GCL were started up. The GCL-type installed in these lysimeters is a NSP 4900-1, with powder bentonite filling of ca. 4670 g/m² as also used in lysimeter 1. The cover soil material is the same as in lysimeter 3. The drainage layer is a thin geosynthetic element and therefore quite different to the gravel layers in lysimeter 1, 2 and 3, which are about 0.2 m thick. Consequently the surcharge load and insofar the counter pressure in case of swelling effects is much lower in lysimeter 4, 5 and 6 compared to the others. Some information about the effect of cover soil thickness on the permeability of GCLs under humid climate conditions may be drawn from Figure 8, which shows the permeation in the summer periods of lysimeter 1 to 3 (left) and of lysimeter 4 to 6 (right).

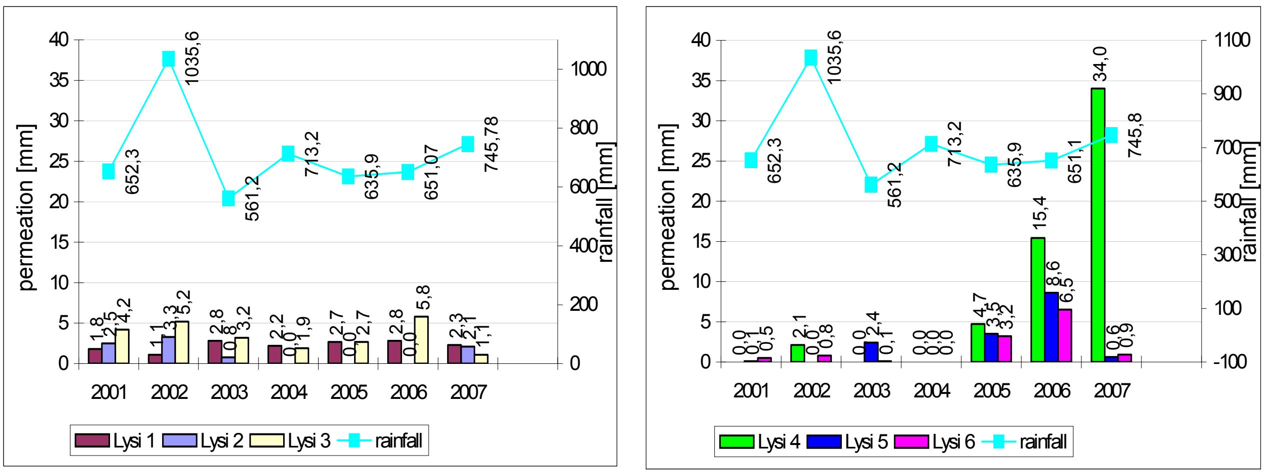


Figure 8. Permeation during half year periods in summer of lysimeter 1to 3 and lysimeter 4 to 6

Obviously, the development of permeability of GCLs during several years exposed to humid climate conditions under soil covers of less than 1 m in thickness (lysimeters 4 to 6) and of thicker cover layers is different. GCL-permeability remains nearly constant in lysimeter 1, 2 and 3 with thicker cover layers, whereas GCL-permeability is increasing after some years considerably in lysimeter 4, 5 and 6 with thinner covers.

EFFICIENCY OF THE GCLS

The GCL-efficiency η_{GCL} can be defined as the drainage discharge related to the amount of all water that reach the GCL (drainage plus permeation discharge) in selected seasonal time periods (Figure 9, right). The efficiency η_{System} of the whole sealing system is defined and calculated by reducing the rainfall rates of selected time periods by the permeation rates and relating them to the amount of rainfall rates (Figure 9, left). It is useful to indicate such efficiency values in percent. The system-efficiency is a useful parameter for comparing different capping or cover systems.

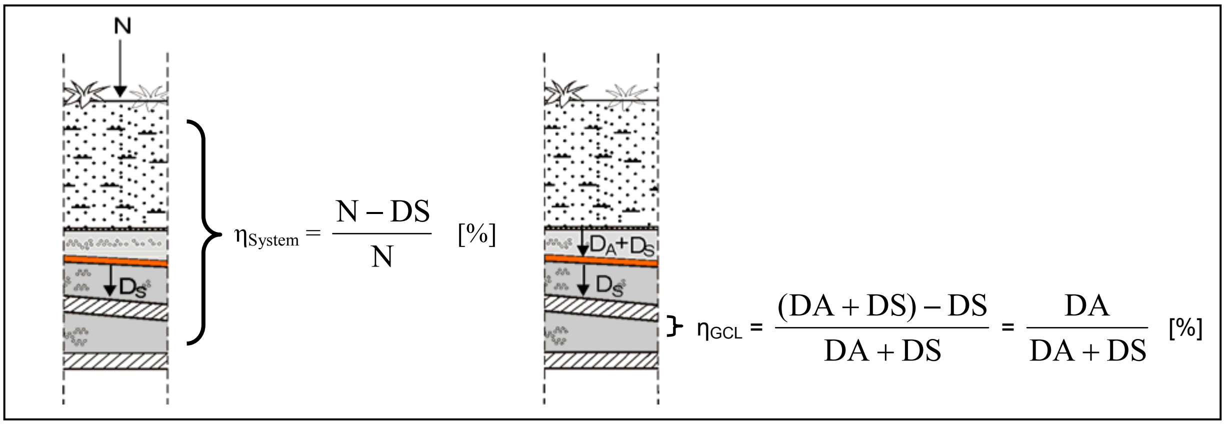


Figure 9. Required water quantities and definitions for the efficiency η_{GCL} of the GCL (right) and of the whole sealing system η_{System} (left)

Representative efficiency data of the landfill cover system installed in lysimeter 3 are shown in Figure 10 . This lysimeter was chosen for efficiency documentation because it is in operation since the beginning of our investigations under unchanged conditions, which were specified above. Similar results have been obtained for lysimeters 1 and 2.

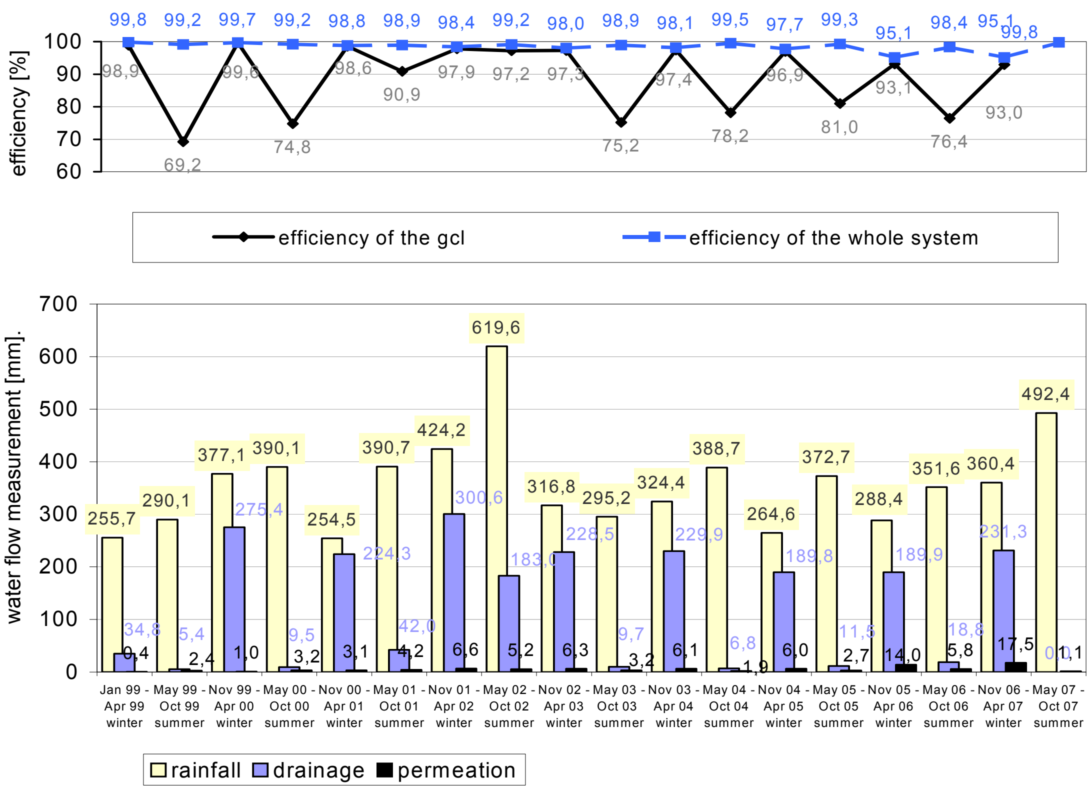


Figure 10. Sealing efficiency for lysimeter 3 during winter and summer half-year periods

Figure 10 shows the GCL-efficiency (black line) and the efficiency of the whole system (blue line) which were calculated by summarizing data for hydrological half year periods. The efficiency of the GCL in each summer is significantly reduced. In the winter periods, the efficiency of the GCL increases approx. to the level of the previous winter. This is a result of lower evapotranspiration and a higher drainage water discharge so that more water is available for the GCL. In winter periods as well as in summer periods, the efficiency of the whole system was found to be nearly constant for all lysimeters 1 to 3 mainly at a level of 98 to more than 99 %. The characteristic of this graph, as well as the seasonal variation of the efficiency values together with the effects due to the cover soil described above, lead to the conclusion that the efficiency of a needle-punched bentonite mat is closely related to the water supply and cover conditions. After a period with reduced water content and increasing permeability, a GCL under a thick layer of cover soil is able to regenerate to its full sealing efficiency.

A similar effect was found in laboratory tests by Egloffstein (2000) and in lysimeter irrigation tests by Maile (1997). The lysimeter field studies in Lemförde, Germany, show this ability of needle-punched bentonite-mats under conditions of humid climate in Europe in a long term investigation.

CONCLUSIONS

The following conclusions and consequences for landfill engineering can be drawn from our investigations of cover systems with GCLs installed in lysimeters and exposed to climate conditions in Germany:

- Large scale testing in lysimeters under in-situ conditions is an effective and economic way to prove the long-term permeation behaviour of cover systems with GCLs.
- High-quality-GCLs, filled with 4,500 to 5,500 g/m^2 of powder or granulate bentonite covered by soil layers of more than one meter in thickness and exposed to humid climate conditions in Germany show a very high sealing efficiency. During nine years of investigation, only 0.5 to 1.4 % of the rainfall permeated through the GCLs.
- A replacement of silty cover soil with a water permeability of 10^{-7} m/s by sand with a water permeability of about 10^{-3} m/s leads to a decrease of permeation, due to a more steady water supply and therefore less desiccation of the GCL during the summer periods.
- The sealing efficiency of the GCLs depends on the amount of drainage water, which supplies the bentonite with water. After a temporary increase of permeation due to lower water content GCLs regained full sealing efficiency in the following winter period; this may be called reversible material behaviour or self-healing capacity.
- GCL-sealing systems with a thin cover and a small overburden load show a decrease in sealing efficiency after some years. Lower overburden and therefore small counter pressures against swelling pressure obviously leads to an increas in permeability and to a reduced self-healing capacity.
- For landfill engineering, the positive effects of sufficient and steady drainage water supply above the GCL on their sealing capacity must be taken into consideration, when recultivation and drainage layers on GCL-liners have to be designed. The thickness of the overburden depends on the climate conditions and layers should be at least more than one meter in thickness for landfill covers in our area. The type of cover soil and their density should be selected in such a way that a steady wet "local climate" in the soil pores above the GCL is provided.

REFERENCES

Blümel, W. et al. (2003): Investigations on water permeability and balance in landfill capping systems. Two Rivers conference 2003, Canada.

Egloffstein, T. (2000): Der Einfluss des Ionenaustausches auf die Dichtungswirkung von Bentonitmatten in Oberflächenabdichtungen von Deponien. Schriftenreihe der Fakultät für Bio- und Geowissenschaften der Universität Karlsruhe (TH), Band 3. Karlsruhe/Germany.

Henken-Mellies, W.U. et al. (2002): Long-term field test of clay geosynthetic barrier in a landfill cover system, Proceedings of the International Symposium IS Nuremberg. Nuremberg, Germany.

Maile, A. (1997): Leistungsfähigkeit von Oberflächenabdichtungssystemen zur Verminderung von Sickerwasser und Schadstoffemissionen bei Landschaftskörpern. Studienreihe Abfall NOW, Vol. 15. Stuttgart/Germany.

Melchior, S. et al. (2006): Zwischenergebnisse der Versuchsfelder der MEAB zu alternativen Oberflächenabdichtungssystemen auf der Deponie Deetz. In: Henken-Mellies, U. (Hrsg.): 17. Nürnberger Deponieseminar 2006. Abdichtung, Stilllegung und Nachsorge von Deponien. Veröffentlichungen des LGA-Grundbauinstituts, Nürnberg, Heft 85, S. 105-128.

Reuter, E. (2006): Long-term measuring of sealing effects and water balance of bentonite mats - Experiences of seven years of lysimeter measuring. Überlegungen zum Eignungsnachweis von Komponenten in Oberflächenabdichtungssystemen für Altdeponien. Deponieworkshop Zittau-Liberec 2006.

Wolsfeld, N. (2005): Bodenphysikalische Eignung mineralischer Oberflächenabdichtungssysteme für Monodeponien der Stahlindustrie. Schriftenreihe des Instituts für Bodenkunde und Waldernährungslehre der Albert-Ludwigs-Universität Freiburg i.Br. Heft 43 Freiburger Bodenkundliche Abhandlungen.