REQUIREMENTS FOR GEOSYNTHETIC DRAINAGE SYSTEMS IN LANDFILL CAPS – EXPERIENCE GAINED FROM EXCAVATIONS AND TEST SITES

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Abstract: Geosynthetic drains in landfill covers save natural gravel sources in areas without natural raw material, the construction volume is dramatically lower, so that less soil movement is necessary and more waste could be placed in the landfill. Additionally the over all costs are lower with geosynthetic solutions. The question is the geosynthetic long-term performance und durability. The German Federal Institute for Materials Research and Testing (BAM) has established a testing guideline for suitability proof of geosynthetic or geocomposite drain elements (GCD) for final landfill capping systems that is unique in its kind. The BAM guideline uses a uniform procedure for determining long-term water flow capacity and the internal shear strength representing durability for more than 100 years. Input data for the determination of the long-term drainage performance is also creep behaviour developed under compressive and shear stresses. However, the extrapolation of creep curves is only then permissible when it can be shown that aging over the period being extrapolated does not invoke any relevant changes in the material due to aging. Design requirement relating to hydraulic and structural stability of capping systems in slopes also depend on the bedding situation of the drainage elements being considered and fulfilled. The paper describes the design method for the required proofs of long-term hydraulic functionality including the filtration performance regarding the vegetation layer. Additionally, this paper deals with realised projects under consideration of different slope angles and cover soil thicknesses for underlining the examined BAM requirements.

Keywords: Drainage, landfill capping, design method, resistance, capping system, geocomposites drainage materials

INTRODUCTION

Geosynthetic drainage systems (GDS) have been in use for many years as long-term drainage for precipitation and artesian water in landfills, construction work, tunnel and bridge abutments, areas where GDS has replaced conventional mineral drainage materials like gravel or sand, thereby protecting natural resources and the environment.

For example, just one truck is required to transport a quantity of GDS that would be required for draining an area of approximately 3,500 m² of a landfill capping system. As a contrast, approx. 65 trucks would be required to transport a mineral drainage layer (30 cm of gravel) to performance the same area of 3,500 m². Technical recommendations relating design approaches and calculation methods due to drainage capacity and filtration efficiency have already been anchored in a variety of guidelines and technical bulletins such as:

- Use of Geotextiles in Hydraulic Engineering, DVWK (German Association for Water Management and Soil and Water Engineering), guideline No. 221,1992
- Guideline on the Employment of Geotextiles and Geogrids in Road Construction Earthworks, Issued 1994, FGSV (Research Society for Highway Administration and Traffic Engineering)
- Drainage of areas with Earth-contact Areas and Backfilling of Constructions, WAS7, BMV (Federal Ministry for Traffic) 1996
- Recommendation E2-20 GDA (1997/2003): Drainage Layers in Surface Sealing Systems
- BAM Guidelines regarding geosynthetic drain elements for landfill cappings: Long-term water flow capacity and long-term shear strength: Verification of Suitability for landfills, Federal Institution for Material Research and Testing, BAM, 2003

Further information regarding design and execution can be found in a variety of publications. Today, the use of GDS as drain elements for landfill cappings is state-of-the-art. The following article will describe the present state of experience taking into consideration field excavations and lysimeter tests as well as design requirements in comparison.

EXPERIENCE GAINED FROM EXCAVATIONS AND A TEST SITE

In 1999, NAUE, in cooperation with tBU (Institut für textile Bau- und Umwelttechnik GmbH) and the Technical University of Munich (Prüfamt für Grundbau, Bodenmechanik und Felsmechanik) carried out 6 excavations in different landfills (Figure 1) where GDS had been installed. Further, during the course of the Bay Forrest Research Project F58F 1991, a large-scale lysimeter unit was set up at the landfill in Kienberg where a variety of drainage layers had been installed. Investigations on GDS in landfill caps were carried out by the tBU (Institut für textile Bau- und Umwelttechnik GmbH) and by the Technical University, Munich (Prüfamt für Grundbau, Bodenmechanik und Felsmechanik). The GDS had been subjected to stress and strain in service for a duration of 2 to 12 years.

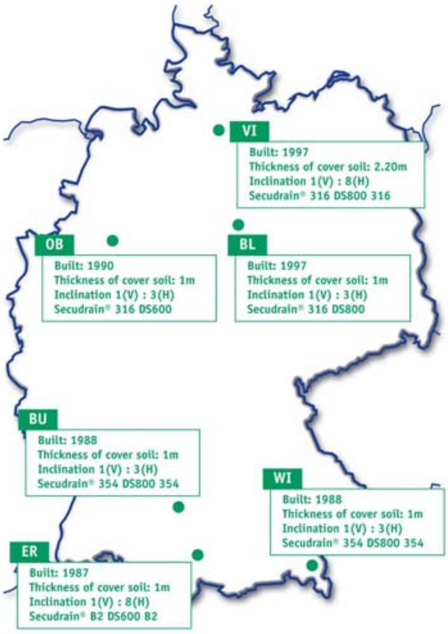


Figure 1. Locations and site specific conditions of excavated landfill caps with GDS

The aim of the excavations was to confirm long-term laboratory investigations and compare these with in situ results. Furthermore, various safety/reduction factors (E2-20GDA, 1997) considered to reduce laboratory values ($Q_{i,Lab}$) for the water drainage capacity were checked and the long-term water drainage capacity ($Q_{i,longterm}$) was then re-evaluated. Finally, an overall impression of the excavated GDS, which had been in service for many years, was evaluated. In addition, in-situ measurements were made of the drainage core thicknesses in order to compare the long-term reduction in thickness in practice with laboratory investigations. All of the cases involved a GDS type Secudrain® DS comprising a three dimensional monofilament drainage core, with needle-punched separation and filtration non-woven geotextiles on both sides.

In order to determine long-term drainage capacity of a GDS, it is required to have information on the expected long-term thickness of the product used. Previous creep tests allowed the conclusion that a long-term drainage core thickness of 5-6 mm for the investigated GDS would be expected. During excavations, the in-situ thickness of installed GDS was measured on a few measuring points in undisturbed areas. Surprisingly, all thickness measurements of the explored GDS types were in the range of 6-9 mm, thus several millimeters more than the results of laboratory creep tests. As it has been proven that creep rate decreases under stress in time, after five to ten years of in-situ stress and strain any significant changes in thickness compared with the documented excavation time periods are no longer to be expected. The results of the excavations show that the laboratory values lie on the safe side and can be used to measure the water drainage capacity in the end situation.

The GDS samples that were excavated were also subject to long-term stress and strain in a pressure creep test under 20 kN/m² in order to supplement the knowledge gained so far and to investigate future creep behavior of the samples, which, in some cases, had already been 12 years in service. The long-term pressure creep tests and extrapolated long-term prognoses show that even after several years of pre-stress, no difference could be recognized between samples that were as good as new and those that had been subjected to stress and strain over many years. In lab tests, the drainage capacity was determined at hydraulic gradients of $i = 1.0$ and $i = 0.1$. In all cases, the results lay higher than the values that had been expected after dimensioning.

In addition to the drainage capacity, the filter properties of the separation and filtration geotextile that keep the drainage core free of soil sediments in the long-term are also significant factors. For this purpose, the geotextile used (needle-punched nonwoven) must allow passage of rainwater pressure-free into the drainage core, whereby the geotextile must retain the soil without any clogging with fine particles, which would decrease the permeability to a value that is lower than the permeability of the soil. The long-term permeability of the nonwoven is achieved – as per current regulations – when the permeability of the factory-new nonwoven reduced by a factor of 50 - 100 more permeable than the soil to be filtered. It could be proved by means of the excavated samples that permeability had only been decreased by a factor 3 - 8 (in one case a factor of 23) (refer to Table 1). This shows that the prescribed reductions fall distinctly short of the filter regulations for non-wovens. Figures 2 and 3 show REM pictures of non-wovens in excavated and factory-new condition (Müller-Rochholz 2000, 2001).

Table 1: Hydraulic properties of filter geotextiles

Excavations	BL	OB	ER	BU	WI	VI
Water permeability (20 kPa) k_v [10^{-4} m/s] - original / with soil "clogging"	23 / 3.1	23 / 1.0	40 / 7.7	61 / 2.0	61 / 9.2	23 / 5.8
Actual factor of decrease	7.4	23	5.4	3.1	6.6	3.9
Soil fines in cover non-woven [g/m²]	521	39	483	672	1021	136

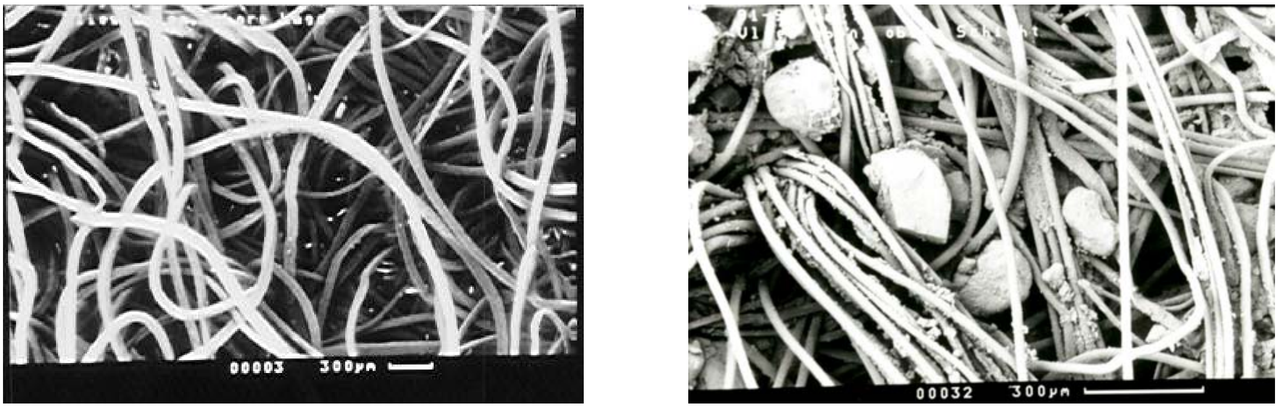


Figure 2. REM of nonwoven for excavated GDS from landfill BU (left) and landfill VI (right)

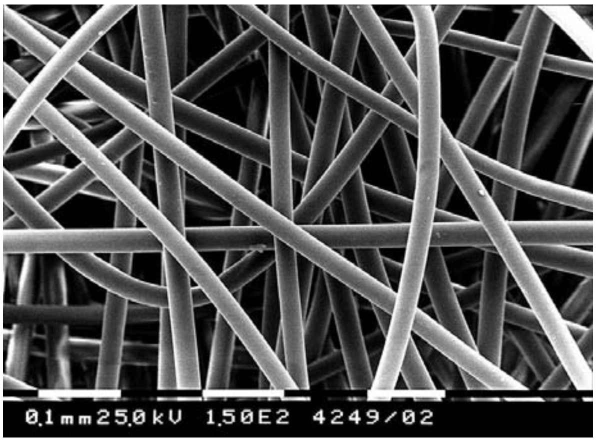


Figure 3. REM of factory-new filter nonwoven

During a German research project carried out between 1998 and 2003 by Bay-Forrest a variety of issues were addressed, including the question of the efficiency of geosynthetic drainage systems in landfill sealing systems. The planning of test sites and execution of observations were in the hands of the Dr.-Ing. Steffen Ingenieur-Gesellschaft mbH in Essen and the Prüfamt für Grundbau, Bodenmechanik und Felsmechanik of the Technical University Munich.

In 1992, the landfill Kienberg was capped; however, for economic reasons at that time, without the integration of any metrological equipment. During the above-mentioned research project, this was installed later in 1998; at the same time samples were excavated in order to determine the current condition and any changes in the GDS. A series of observations were then conducted from 1998 to 2000. Up to 2002, a further series of observations were only carried out in a reduced form, due to financial issues. It was determined that precipitation was able to infiltrate completely as the vegetation layer on the landfill Kienberg was highly permeable.

One of the most outstanding facts to emerge from the series of observations carried out on the landfill Kienberg is that even the most heavy discharges of water such as those experienced during the flooding in Bavaria at Whitsun 1999 (rainfall between May 20, 1999 and May 22 1999 was 61.4 mm) into the drainage layer no significant differences compared to mineral drainage layers were determined. This can be seen in the example of measurements made during the Whitsun flooding (Figure 4). The recorded measurements show almost identical drainage capacities in both the mineral and the geosynthetic drainage layers (GDS).

Furthermore, the Dr.-Ing. Steffen Ingenieurgesellschaft mbH was commissioned by the Technical University in Munich to investigate the filter and drainage efficiency on the Kienberg landfill. The results from two test sites were compared with each other. The geosynthetic drainage mat in the test section I consisted of a three-dimensional 600 g/m² drainage collection core covered on both sides with a 300 g/m² needle-punched filtration nonwoven geotextile. A 30 cm thick gravel drainage layer (gravel 8/32 mm with $k = 1\ 10^{-2}$ m/s) was installed in test site IV, which was covered with a needle-punched nonwoven (300 g/m²) geotextile filtration layer between the gravel drainage and the vegetation layer.

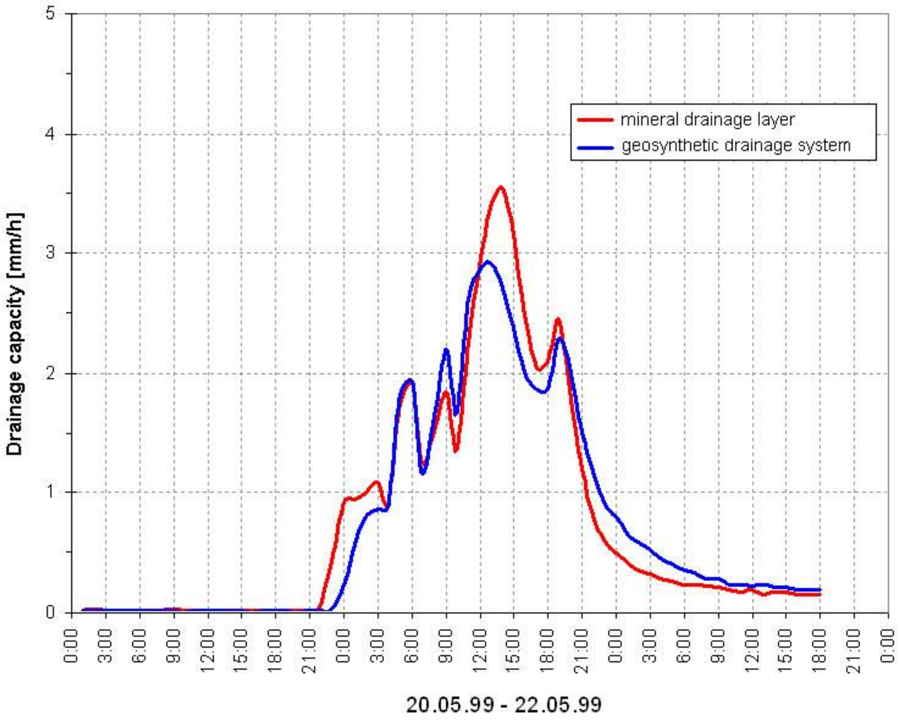


Figure 4. Water-flow capacity, measured on site for geosynthetic drainage layer (GDS) compared with mineral drainage layer (Bavaria, landfill Kienberg, Whitsun 1999)

Table 2. Peak rainfall and capacity utilization

	Secudrain® GTD	gravel drainage layer 8/32 mm
11. – 12.05.1999 23.7 mm precipitation	13.8 %	58.6 %
20. – 22.05.1999 61.4 mm precipitation	15.5 %	37.5 %
22. – 25.07.1999 16.8 mm precipitation	1.4 %	6.0 %
17. – 23.05.2000 25.5 mm precipitation	0.5 %	7.2 %
27.05.2000 16.7 mm precipitation	0.5 %	3.2 %
11. – 19.07.2000 46.2 mm precipitation	27.8 %	31.7 %
20. – 23.09.2000 46.2 mm precipitation	17.6 %	23.4 %
01. – 09.10.2000 37.7 mm precipitation	19.0 %	25.6 %

The report of the results shows that the GDS in comparison to the 30 cm gravel drainage is not only equivalent but also far more efficient (Table 2). It turned out that the tested GDS exhibited a very high reserve capacity that far exceeds the design value given by E2-20 GDA recommendation, even during extremely short-term hydraulic loading. The following measured data were captured continuously over a period of 2 years in both test sites:

DIMENSIONING – HISTORY, LONG-TERM IMPACT AND PRINCIPLES

Up to the middle of the Nineties, the water drainage capacity of a GDS in the laboratory was considered only from the aspect of stress and strain and without any concern to long-term reduction in thickness due to creep behavior in relation to the cover soil thickness and its confining stresses combined with reduced water drainage capacity. A blanket decrease in water drainage capacity was to integrate the impact of creep.

Already back in 1991, more strict recommendations (Saathoff 1999 and E2-20 2003) were made to re-address the fact that drainage capacity is significantly influenced by the long-term thickness of GDS under stress and strain and that long-term creep tests are required to simulate pressure and shear compression stress (for inclined surfaces) as a function over time. This would allow long-term water drainage capacity to be correctly assessed.

Assessments made by BAM (2003) regarding the suitability of drainage elements for surface sealing in landfills takes into intensive consideration long-term creep behavior and additionally the direct impact of the confining elements in the test equipment on the drainage element for the determination of the water drainage capacity. This issue is addressed in more detail in Müller (2005), BAM (2004 and BAM (2003). The type of confining elements around the GDS is only rudimentarily considered in E2-20 (1997) and in E2-20 (2003) via a blanket reduction factor.

In BAM (2003) the extraordinarily long service life of drainage layers (drainage elements, GDS) of more than 100 years as is required under the Landfill Regulations, is processed textually beyond the previously mentioned regulations in order to assess the suitability of a drainage element for landfill surface sealing purposes. Thus, the requirements made on GDS and its long-term water drainage capacity beyond existing standards, are taken into consideration.

The aim of structural design is to prove that GDS in the long-term features sufficient water drainage capacity QA [l/m*s] to drain away the amount of water ingress QE [l/m*s] from the drainage taking into consideration all of the project-relevant conditions (load, length of flow, inclination etc.) without exceeding the drainage capacity of the drainage core. Relevant aspects of the structural design can be:

- Examination in flat areas (e.g. planes): long-term thickness determined in the laboratory by means of creep tests ≥ 104 hours simulating compressive stress
- Examination for slopes: long-term thickness determined in the laboratory by means of creep tests ≥ 104 hours simulating combined shear and compressive stresses under different loads (extrapolated thickness after 106 hours equivalent to 114 years).
- Long-term water drainage capacity depending on the type of GDS confining elements in the planned landfill cap (laboratory test: hard/hard with rigid plates, hard/soft or soft/soft; e.g. hard for stable subbase with or without geomembrane, soft for cover soil placed over the GDS). Figure 5 shows the procedure as per BAM (2004) and Müller (2005).
- Determination of drainage spacing is based on an object-relevant water balance analysis (e.g. HELP analysis) or according to E2-20 GDA (1997) and E2-20 (2003).
- Reduction factors for material resistance (drainage element properties) and component safety coefficients for the installed product (e.g. roots, biological or chemical influences, installation uncertainties).

According to experience, the critical condition for the drainage capacity is under low gradients (e.g. flat plateau areas). In slopes (e.g. where 1(V) : n(H) is approx 1:3), the long-term thickness is lower than on a plateau area due to the additional shear stress from the confining stress but the higher hydraulic gradient leads to a comparatively higher rated value than for the drainage capacity.

Hydraulic load in drainage systems caused by infiltrating rainwater are site-dependent. Seen from a project-specific aspect, it always makes good sense to use water balance analyses (e.g. HELP analyses) to determine project-specific drainage requirements. In E2-20 (2003), the input design value for the infiltrated drainage water is given as 25 mm/d as a maximum value or as 10 mm/d and an additional safety coefficient of FSSY = 2.0 for the design value. In E2-20 (2003), the input design value for the amount of infiltrated water of 10 mm/d is proposed for pre-dimensioning for cover soils with good water-retaining properties (cohesive soils) and sufficient thickness.

Current procedures for assessing the long-term water flow capacity under differing bedding situations of a GDS for landfill caps in accordance with BAM (2003) are shown in Figure 5 (refer to Müller, 2005). The basic design approach is shown in Figure 6.

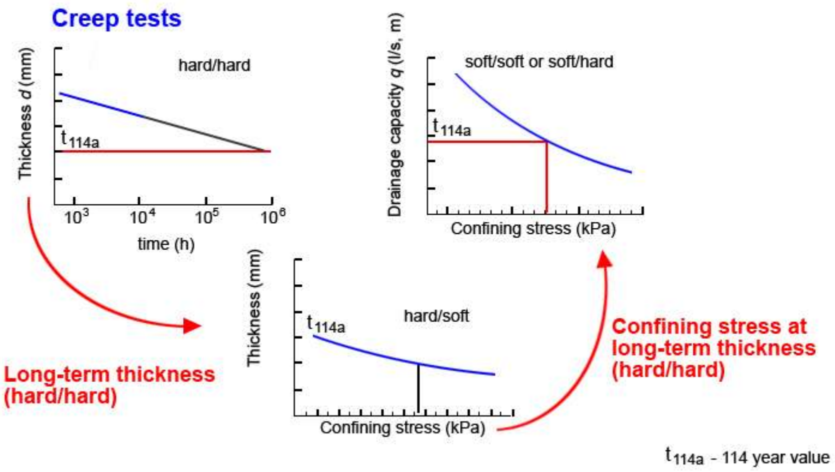


Figure 5. Long-term water drainage capacity under different bedding situations (Müller, 2005)

Material resitance GDS $\geq$ **Influence on GDS**

$$\frac{q_{LZ}}{\gamma_{R,1}\cdot\gamma_{R,2}\cdot\gamma_{R,3}\cdots} \geq (\gamma_{S,1}\cdot\gamma_{S,2}\cdot\gamma_{S,3}\cdots)\cdot q_{design}$$

q_{LZ} = long-term drainage capacity
dependent on: thickness (creep)
confining stress
inclination
bedding

q_{design} = amount of in-flow (l/m*s)
= drainage capacity (l/m²*s) x length of drainage (m)

γ_R = Reduction factors
including: creep extrapolation, connections, overlaps

γ_S = partial safety factors
including: root penetration
clogging
degradation
settlement

⇨ Determination by BAM for approval for landfill caps

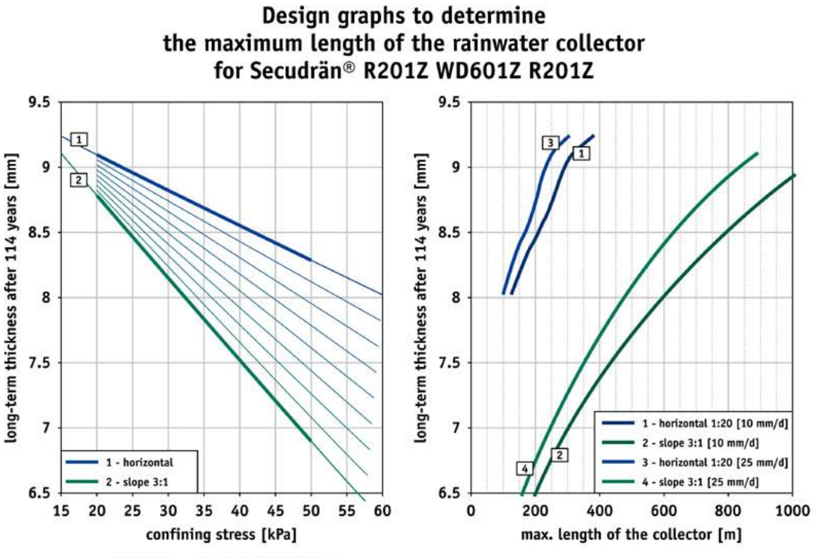
⇨ Determination based on site specific values, excavation experience or recommendations (e.g. E2-20)

Figure 6. Design principles for long-term water flow capacity in landfill cappings according to the procedure in BAM (2004) and Müller (2005)

In each individual case, accurate examination of the hydraulic capacity with project-relevant boundary conditions (drainage length, gradient, inflow area, banquettes, confining stress, bedding, vegetation, precipitation zone etc.) is required.

In BAM (2004) and Müller (2005) it is stated that ageing effects and thus the material creep effects must in principle not be considered by means of reduction factors. It is recommended that they are determined in accurate laboratory creep tests that provide fundamental long-term conclusions about the tested material. The uncertainty of these investigations may be estimated with the reduction factor, which means that the material resistance is definable.

On the impact side (Figure 6), the input design value of seepage water discharge can be reasonably estimated. In comparison, it is more difficult to estimate the component safety coefficient on the impact side as it may be controlled and impacted by the planning and execution of the construction project. The varying parameters of different recommendations are stated in BAM (2004) and Müller (2005) and the federal German facility BAM did not carry out an assessment of its own. Further geosynthetic consultants, such as "BBG Bauberatung Geokunststoffe" have good experience in estimating the component safety coefficient using conclusions gained from field tests and excavations. Figure 7 shows a dimensioning alignment chart for the drainage element Secudrain® R201Z WD601Z R201Z, with the BAM approval recommendation.



Explanation:
- applies to bedding hard/soft
- reduction q_{LZ} over creep tests and bedding hard/hard, % reduction on hard/soft (refer also to section 9.2, BAM report file no. IV.32/1317/04)
- contains acc. to NAUE/BBG: $FS_{IN} = 1.25$; $FS_{CR} = 1.0$; $FS_{CC} = 1.05$; $FS_{CB} = 1.3$; $\Pi\ FS = 1.7$
- contains acc. to GDA recommendation E2-20 (1997) at 10 mm/d $FS_{FY} = 2.0$; bei 25 mm/d $FS_{FY} = 1.0$

Figure 7. Example of a dimensioning alignment chart for Secudrain® as per BAM (2004)

SEEPAGE WATER DISCHARGE / PRECIPITATION

Since 1998, a lysimeter unit has been in operation on the premises of NAUE GmbH & Co. KG in Lemfoerde (North Germany) scientifically monitored by the Institut für Grundbau, Bodenmechanik und Energiewasserbau at the University of Hanover, and Dr. E. Reuter (IWA Minden) and Dr. N. Markwardt (pedotec GmbH Berlin). The aim of this project is to observe the long-term function of geosynthetic clay liners (GCL) under a variety of installation conditions and changing climatic conditions (Müller-Kirchenbauer *et al.* 2008).

Since the fall of 2002, a newly installed measuring unit has allowed continuous capture of drainage run-offs above the sealing and percolation through the sealing in a 10-minute resolution. It is thus possible to link water flow through the cover soil (∑ drainage run-off and permeation) to respective events of precipitation and to illustrate the dependency of drainage capacity on the type and thickness of the vegetation layer. Seasonal impacts can likewise be well illustrated. In Table 3, the type and thickness of the top soil from 4 different lysimeters are shown. The lysimeter indicates natural vegetation that is cut back twice a year (in Spring and Fall) to about 5 cm. In Table 4 are the total values per half-year, the peak daily values per lysimeter as well as the percentage relationship between drainage spacing and precipitation, divided up into the winter half-year 2003/2004 and the summer half-year 2004.

Table 3. Lysimeter set-up

	Lysimeter A	Lysimeter B	Lysimeter C	Lysimeter D
Thickness of covering layer	1 m	1 m	0.8 m	0.6 m
Type of cover soil	Top soil approx. 20 cm, Sand, approx. 80 cm	Top soil	Top soil	Top soil
k-vale of soil	Top layer: 10^{-7} m/s Sand: 10^{-3} – 10^{-4} m/s	10^{-7} m/s	10^{-7} m/s	10^{-7} m/s

Table 4. Precipitation/Infiltrated drainage quantity for lysimeters A to D

		Infiltrated drainage quantity			
	Precipitation	Lysimeter A	Lysimeter B	Lysimeter C	Lysimeter D
Winter half-year 2003 – 2004					
Max. daily value	20.8 mm	16.2 mm	17 mm	16.7 mm	17.9 mm
Total	324.4 mm	266.6 mm	202.7 mm	262.8 mm	266.2 mm
Ratio: infiltrated drainage quantity / precipitation	-	*82 %*	*63 %*	*81 %*	*82 %*
Summer half-year 2004					
Max. daily value	28.2 mm	3.35 mm	0 mm	0 mm	1.66 mm
Total	388.7 mm	55.2 mm	0 mm	0 mm	8.64 mm
Ratio: infiltrated drainage quantity / precipitation	-	*14 %*	*0 %*	*0 %*	*2 %*

Figures 8 and 9 show precipitation and measured seepage water discharge of the lysimeters, separated into winter half-year 2003/2004 and summer half-year 2004 (daily values). The documented findings clearly show the differences in the quantity of seepage water discharge, which is infiltrated through the cover soil. On the one hand, the dependency on the thickness of the top soil (lysimeters B/C/D) is shown, on the other hand, the type of top soil (A/B). The vegetation layer (100 cm) with a lower retaining capacity (lysimeter A, 80 cm sand) reacts distinctly more rapidly and intensely to precipitation than all the other lysimeters; even when the thickness of the vegetation layer with high retaining properties is only 60 cm. Furthermore, it becomes apparent that the seepage water discharge is higher than in the same vegetation layer (lysimeter B/C/D). In the winter, half-year precipitation is naturally stronger and the vegetation layer displays a distinctly higher degree of water saturation than in the summer half-year (differences of about 16-18 mm/day). The peak value as design input value according to the recommendations GDA E2-20 with 25mm/day was not observed.

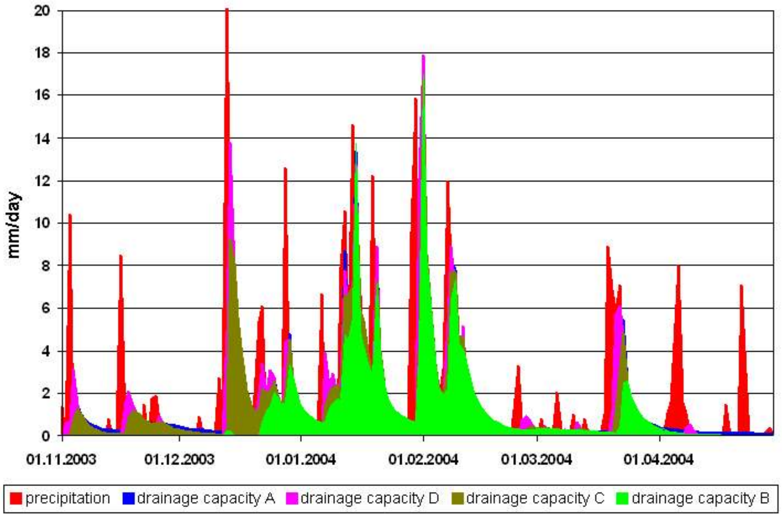


Figure 8. Precipitation and drainage spacing winter half-year 2003-2004 (daily value)

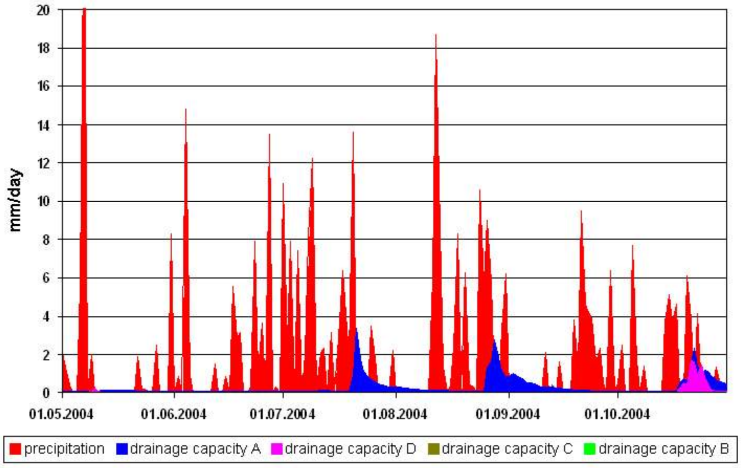


Figure 9. Precipitation and seepage water discharge summer half-year 2003-2004 (daily value)

SUMMARY

In the design and its calculations it is required to prove that geosynthetic drainage elements achieve adequate long-term site specific drainage capacities, fulfill filter effectiveness criteria and are suitable for steep slope applications if applicable; all considering site-specific conditions.

The excavations on GDS in landfill caps, some of which were installed 12 years ago, showed excellent filtration efficiencies (good soil retention and acceptable water permeability values) of needle-punched filter nonwoven geotextiles as cover geotextile and therefore a high drainage capacity of the GDS drainage core, due to no soil passage into the drainage core.

With the publication and acceptance of the BAM guidelines for geosynthetic drainage layers (GDS) in landfill caps an accepted material testing procedure is available. It requires design relevant testing, such as determination of the creep behavior under compressive and shear stresses, long-term internal shear strength of the GDS and material ageing in landfill environments. The design with geosynthetic drainage layers in landfill caps that follow the procedure of the BAM guidelines leads to an excellent drainage functionality for service lives of at least 100 years.

It is to be expected that the design input value of seepage water discharge of 25mm/d per E2-20 GDA (1997) gives a safety reserve as findings from the lysimeters and HELP analyses conclude lower drainage spacing.

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