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25 Years of Experience with a Lysimeter System with Geosynthetic Clay Liners

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Abstract. Since 1999, a lysimeter facility with 6 test areas has been installed in a hillshaped soilbody in northern Germany, in which long-term tests with geosynthetic clay liners are carried out. Inside of the hill is a measuring room which contains the devices for measuring the precipitation, the amount of drainage water above the GCLs and the amount of permeation water passing through the GCLs every 10 minutes since 25 years. Based on this data, the Long-Term behaviour was investigated under various boundary conditions and the efficiency of the Geosynthetic Clay Liners under different boundary conditions was analysed. Different types of geosynthetic clay liners were investigated and it was considered under different overload-situations. The paper provides an overview of the general test set up and the most important findings on long-term permeability, influences from dry-wet and freeze-thaw cycles, and other findings from 25 years of testing the lysimeter system.

1 Introduction

Developments in landfill construction and infrastructure projects show that conventional components of standard sealing systems, such as mineral drainage layers or compacted clay liners, are increasingly being replaced by geosynthetic materials. The geosynthetic product should have at least the same functionality and efficiency as the mineral components in standard systems. In addition, it must have advantages in terms of economy and processing.

Tests to measure the permeation rates through geosynthetic clay liners (GCLs) under in situ boundary conditions comparable to landfill covers are described e.g. in [1, 2, 3].

Most of these and similar field tests were conducted to demonstrate the sealing efficiency of GCLs. They were not specifically designed to investigate the effects of drying and rehydration cycles caused by seasonal moisture fluctuations or to compare different filling materials.

In order to investigate the long-term sealing behavior of GCLs, six lysimeters were built in Lemfoerde [4, 5, 6], Germany, and equipped with different cover systems to gain further insights into the performance of GCLs. GCLs with granular and powdered sodium bentonite filling have been investigated since 1998. In 2002 and 2010/2011, the surface layers above

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the GCLs were rebuilt to determine the influence of water permeability and storage capacity of the cover soil on the effectiveness of the GCLs.

This paper therefore summarizes one of the longest known studies on the functioning of GCLs, which has now been ongoing for more than 25 years and will give some of the findings.

2 Lysimeter set-up

Only a "closed" section of soil and liner system can be modelled using a lysimeter. For the evaluation of lysimeter tests, a simplified water balance equation is given below as equation (1), in which interception and surface runoff are not taken into account:

$$N - ET - (DS + DA) - \Delta S = 0 \qquad (1)$$

In this equation: N: Precipitation, ET: Evapotranspiration, DA: Drainage water collection, DS: Permeation through the GCL, S: Water storage capacity

Six lysimeters (lysimeters 1 to 6) were installed inside a mound-shaped soil body (2 m diameter, 3.0 m height) in 1998 in order to reduce any side effects, e.g. due to temperature fluctuations.

Fig. 1: Impressions from the construction of the lysimeters

Inside each mound was a so-called measuring room, which contained devices for measuring precipitation, the amount of drainage water above the GCLs and the amount of permeation water through the GCLs. Lysimeters 1 to 3 were installed in 1998; their GCLs have not been replaced to date. Lysimeters 4 to 6 were also installed in 1998; their GCLs were replaced in 2010/2011.

Fig. 2 schematically shows the characteristic data and cross-sections of the systems, in particular the different soil covers over the GCLs since 2010/2011.

The drainage layers of lysimeters 1 to 3 consisted of gravel, while a geosynthetic drainage layer was used in lysimeters 4 and 5. Lysimeter 6 had no drainage layer. The GCLs in lysimeters 1, 2, 4 and 6 contained sodium bentonite in powder form, while the GCLs in lysimeters 3 and 5 contained sodium bentonite in granular form.

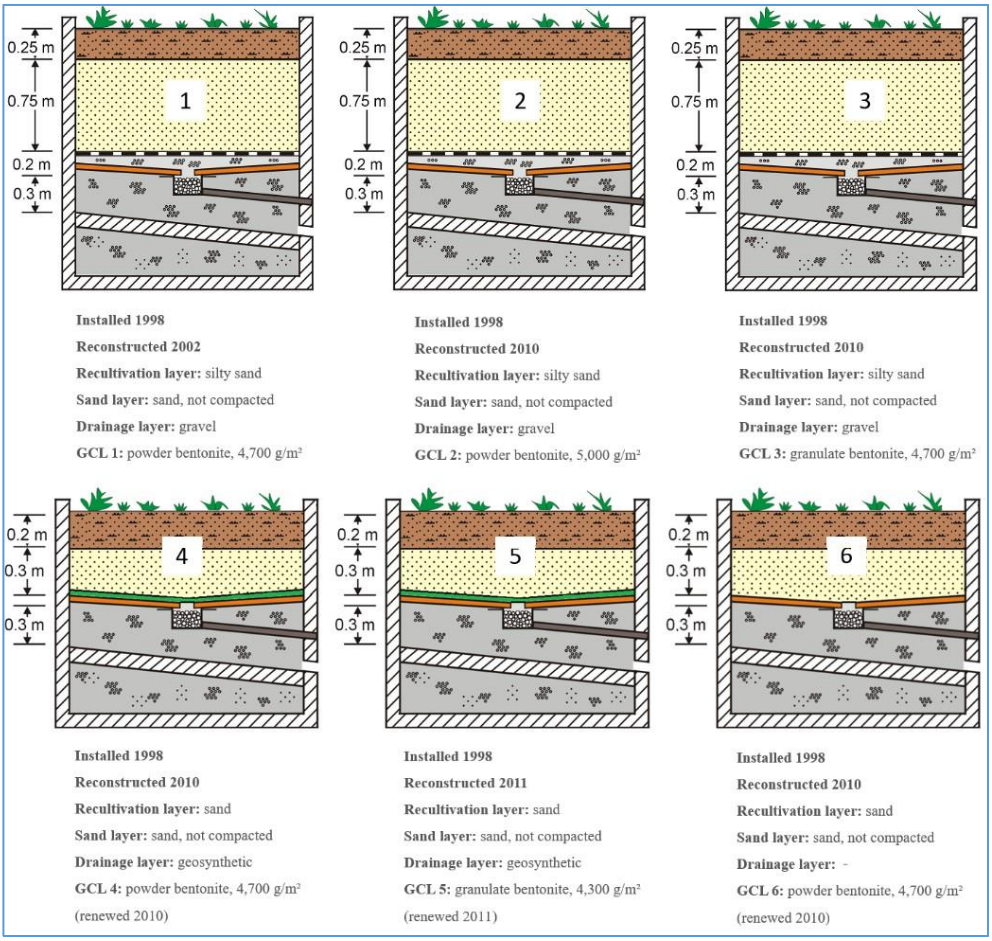


Fig. 2: Cross-sections and characterization of lysimeters 1 to 6.

Within each lysimeter, the amount of precipitation (N), drainage water (DS), and permeation (DA) were measured daily and described in the following chapters. With the exception of one example, the following analyses refer to lysimeters 1-3 as this is the construction method that was predominantly used and these were operated with the same products over the entire 25 years.

3 Results

3.1 General results

Fig. 3 shows the accumulated values of precipitation (N), drainage water (DA) and permeation water (DS) during the entire operation of the lysimeter in the current setup.

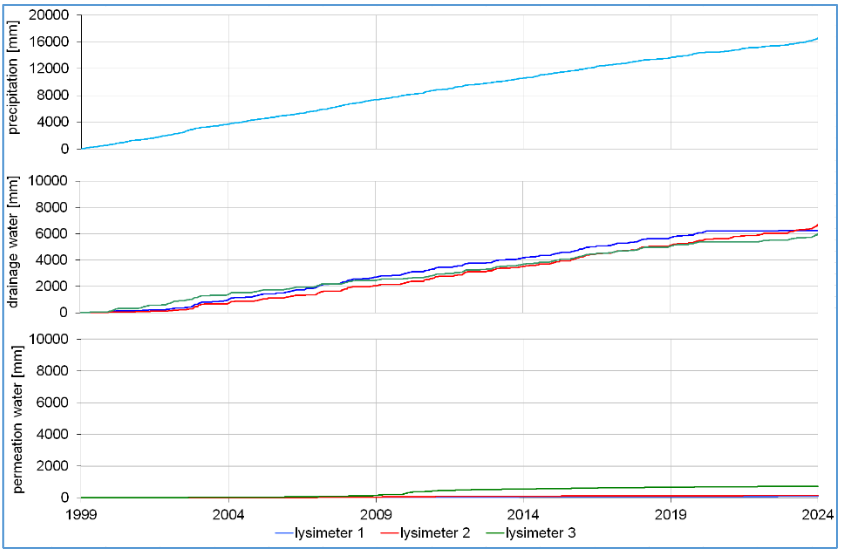


Fig. 3: Accumulated data of precipitation (N), drainage water (DA) and permeation water (DS), lysimeter 1-3.

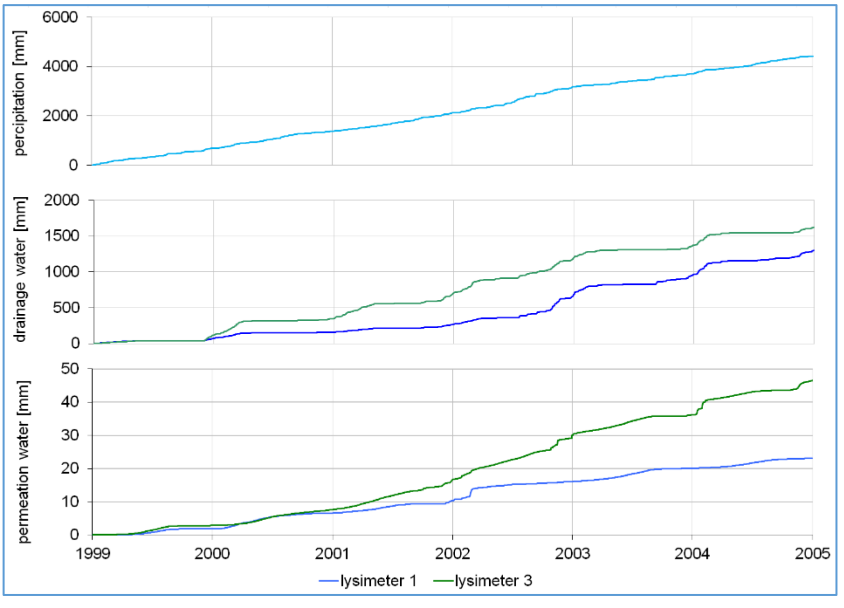


Fig. 4: Accumulated data of precipitation (N), drainage water (DA) and permeation water (DS), lysimeter 1 and 3 for the first 5 years.

Fig. 4 shows the accumulated values in a larger scale for the first 5 years also for precipitation, runoff over the barrier (drainage) and permeation through GCLs 1, 2and 3. The permeation curves show the typical behaviour of a GCL with the initial ion exchange and the associated slight increase in permeation through the GCL after nearly one year. There are slight differences depending on the type of bentonite (powder – blue / red line or granules – green line).

Fig. 5 shows an example of the daily results of precipitation, runoff over the barrier (drainage) and permeation through the GCL in lysimeter 1 for the years 2011 - 2021 (11 years), after the reconstruction in which the GCL was provided with a new sand cover. While the GCL in lysimeter 1 remained unchanged, the permeation values showed a clear decrease since the introduction of the sand cover in comparison to the first years (see Fig. 4). By replacing the cohesive, silty topsoil with the sand cover, the GCL can absorb water more quickly, which leads to an increase in the moisture content of the bentonite in the GCL. A higher absorption capacity of the topsoil layer reduces the moisture content of the bentonite in the GCL. A higher moisture content is not maintained because less water penetrates through the topsoil. In addition, the water stored in the topsoil is released back into the air (upwards) and not into the bentonite when the humidity is low. Reduction of water content was evaluated by different samples taken from the Lysimeters and can vary depending on soil on top and period of the year. This is also recognized by exhumations at Landfill site since the mid of the 90ths where values found from less tan 50% up to 100% and sometimes more.

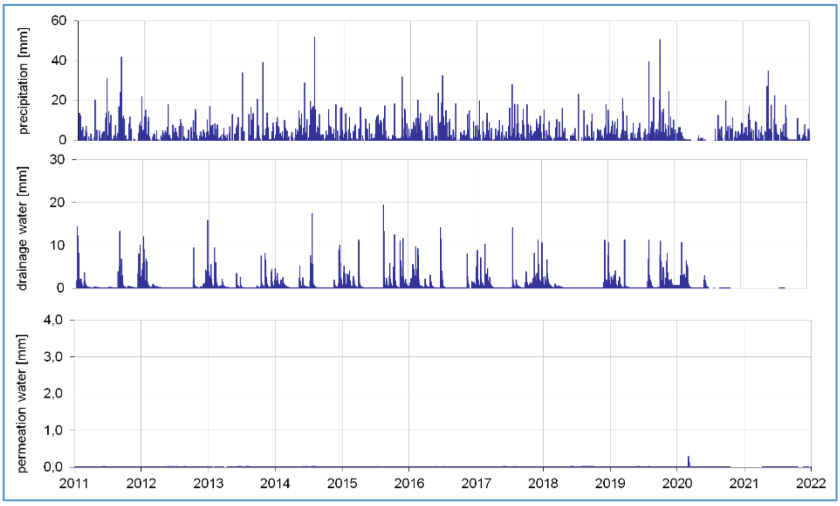


Fig. 5: Daily amounts of precipitation (N), drainage water (DA) and permeation water (DS) in lysimeter 1 for a period of 10 years after reconstruction of the cultivation layer.

Fig. 6 shows an example of the daily results of precipitation, runoff over the barrier (drainage) and permeation through the GCL in lysimeter 3 for the years 2011 - 2021 (11 years), after the reconstruction, during which the GCL was provided with a new sand cover.

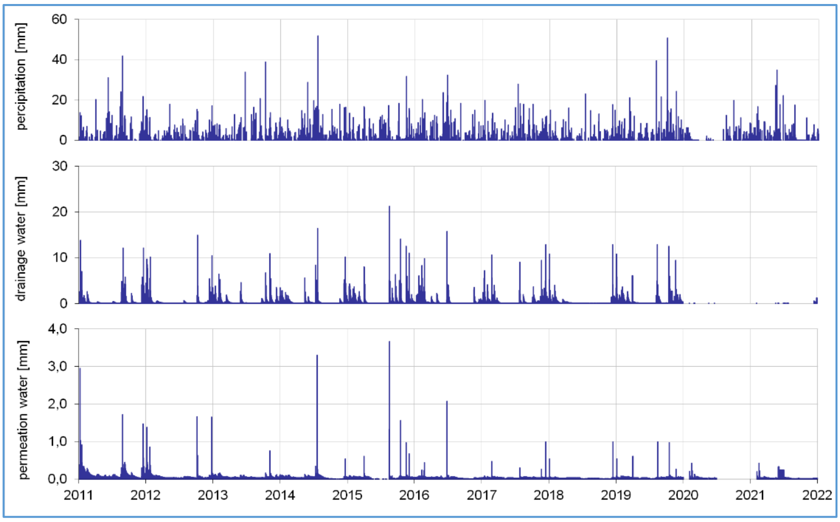


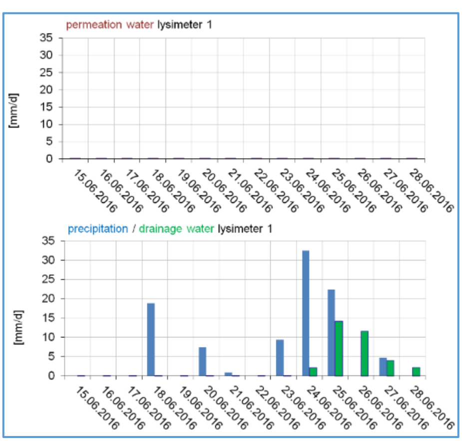
Fig. 6: Daily amounts of precipitation (N), drainage water (DA) and permeation water (DS) in lysimeter 3 for a period of 10 years after reconstruction of the cultivation layer.

Compared to lysimeter 1 (see Fig. 5), the change in permeation here is basically similar, but the permeation after rain events is higher than for the product in lysimeter 1. This indicates a higher initial permeation - a slower closing process of cracks during swelling. Irrespective of this, the long-term permeation after remoistening will be comparable.

3.2 Drying and rehydration of geosynthetic clay liners in the lysimeters

Depending on the superstructure above the GCL different system efficiencies are determined.

A comparison with the same cover but different GCL is shown in Fig.s 8 and 9, in which rain events and the onset of drainage as well as the onset of permeation after the rain events in June 2016 are shown with high resolution. Here, the permeation values for lysimeter 1 are significantly lower than for lysimeter 3, which in this comparison is due to the different structure and the different speed of swelling of the bentonite after rewetting.



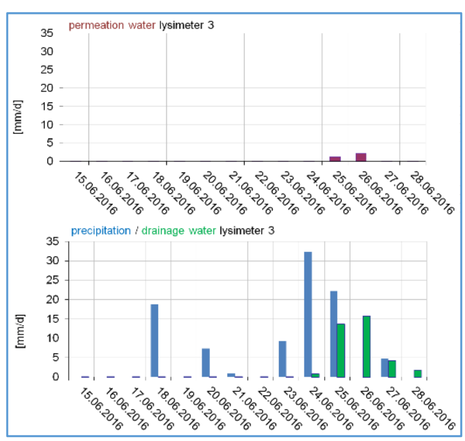


Fig. 7: Lysimeter 1, 15th to 28th June 2016 **Fig. 8:** Lysimeter 3, 15th to 28th June 2016

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An evaluation for the same month with the same type of cover, but lower cover height as in Figs. 7 and 8, is shown in Figs. 9 and 10.

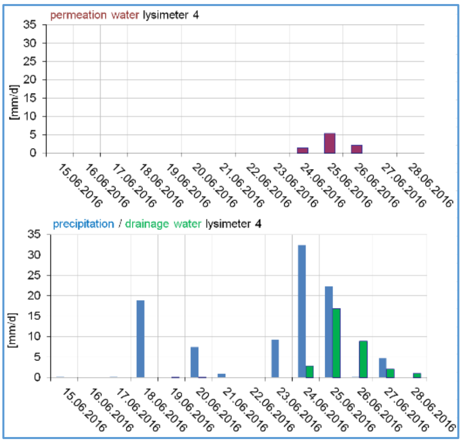


Fig. 9: Lysimeter 4, 15th to 28th June 2016

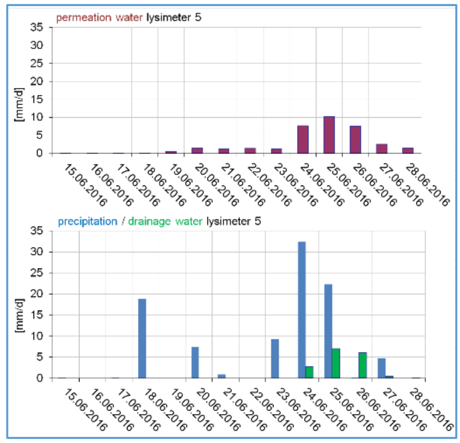


Fig. 10: Lysimeter 5, 15th to 28th June 2016

The cover height is roughly halved in these lysimeters (4 and 5) compared to the example in Figs. 7 and 8. The products are nearly comparable to the products from lysimeters 1 and 3.

The comparison from Fig 9 and 7, as well as 8 to 10, show the impact of the cover height above the GCL. The comparison from Fig. 7 to 8 as well as 9 to 10 shows the impact of the structure of the bentonite with similar bentonite amounts.

3.3 Efficiency of the installed systems

An evaluation for the system installed in the lysimeters with the entire system η_{system}, the so-called system efficiency. System efficiency is defined here as the efficiency of all surface layers, including the geosynthetic clay liner, meaning that of the entire system. It is calculated by the precipitation values reduced by the permeation and relating them to the total values of the precipitation as shown below in equation (2). It is useful to provide the values in percent. This system effectiveness provides a helpful characteristic value for comparison evaluations of the sealing effectiveness of various sealing systems and other surface sealing structures.

$$\eta_{system} = \frac{N}{N-DS} \; [\%] \qquad (2)$$

The abbreviations are explained in (1).

All 3 lysimeters (1-3) fulfilled, on a different level, the requirements from Germany for mineral sealing in a capping in Germany of less than 20 mm/year permeation.

While the system efficiency decreased in the summer half-years due to very low water drainage amounts, a very good sealing effect was achieved again in each winter half-year. This indicates an increase in the water supply of the GCL will also have an increased sealing effect.

An influence on the effectiveness of the system could be determined by a significantly lower coverage. Long dry phases have a greater influence on initial permeabilities, which in turn can be positively influenced by the choice of cover type.

4 Decision-tool

As previously demonstrated, the lysimeter has provided valuable insights and confirmed how factors such as overload, cover type, and periods of moisture or precipitation events influence sealing effectiveness. Additionally, various studies on long-term effectiveness following ion exchange have clearly highlighted the impact of bentonite mass per unit area in the GCL [7] on sealing performance. These studies [8] also identify which properties are critical for evaluation and which are less significant. These findings, along with others, have driven the development of a decision-tool at Naue: the so called Bentogram (Fig. 11)

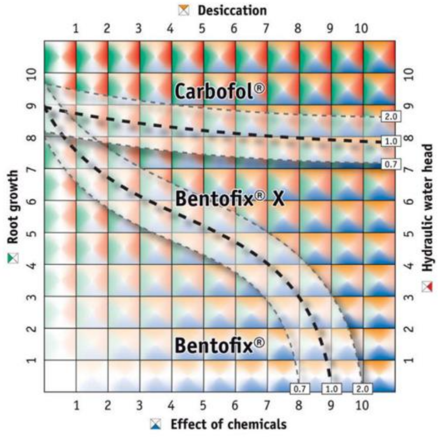


Fig. 11: Decision-tool

Depending on the site-specific conditions - such as the risk of water head, chemical impact, desiccation, root growth, or other factors (where higher values indicate greater risk) - this tool facilitates the selection of the most appropriate sealing system. Options include a geosynthetic clay liner, a multicomponent geosynthetic clay liner), or a geomembrane. The overload aspect is covered by the desiccation factor.

Safety levels are determined based on the parameters of a GCL and the construction on site. For example, with a bentonite weight of 4,000 g/m² (dry), a safety level of 1 is achieved. Increasing the bentonite weight to 5,000 g/m² /(dry) raises the safety level to 1.2, while reducing it to 3,000 g/m² (dry) lowers the safety level to 0.7. Fig. 12 gives for a capping sealing a range of safety levels as recommendation for the key impacts water head, chemical impact, desiccation, and root growth.

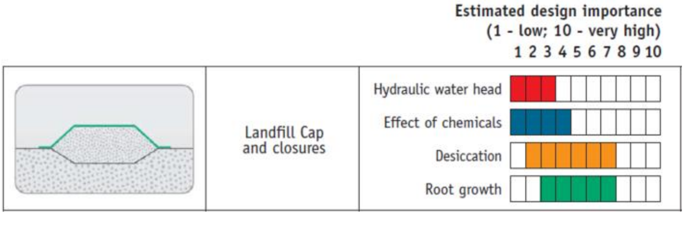
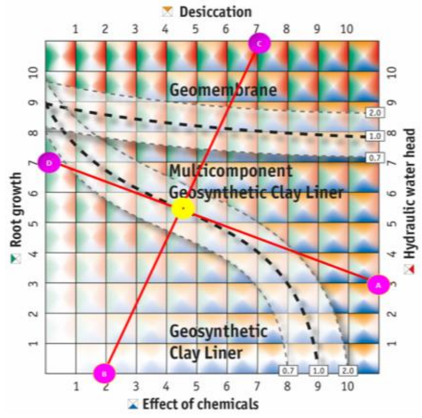


Fig. 12: Recommendations for the risk evaluation (low – high) per application, for e.g. in a Landfill cap

Fig.s 13 and 14 provide exemplary evaluations for capping sealings under varying conditions. Fig. 13 represents a scenario with a low soil cover, which corresponds to a higher risk of desiccation and increased stress due to root growth. In contrast, Fig. 14 illustrates a situation with greater soil cover, resulting in a lower risk of desiccation and reduced stress from root growth. Both evaluations consider key risks: water head (A), chemical impact (B), desiccation (C), and root growth (D).

Fig. 13 recommends selecting either a geosynthetic clay liner (GCL) when the safety level of product and given site condtions is 2 or higher or, preferably, a multicomponent geosynthetic clay liner when the safety level is below 2. Conversely, Fig. 14 suggests a geosynthetic clay liner as the suitable choice.



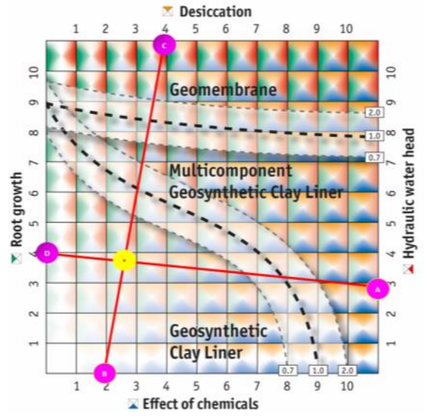


Fig. 13 (left) and 14 (right): Decision-tool showing recommendations for using multicomponent geosynthetic clay liners (left) or geosynthetic clay liners (right).

The main difference with Fig. 13 is the lower cover height, which favours drought stress of the system during longer dry phases and also brings more influence from the planting/roots. The potential influence of both is significantly reduced by increasing the cover (Fig. 14).

5 Summary and conclusions

Lysimeters are normally used to measure parameters of the soil water balance In the described test situation / test setup which have been operated continuously for more than 25 years in Lemfoerde, Germany, the data from six lysimeters with different soil layers, different cover heights and different GCLs were analysed to determine influences on the efficiency of the GCLs under field conditions.

The lysimeters were set up to demonstrate the sealing capability of the GCLs and to investigate the effects of drying and rehydration cycles caused by seasonal moisture fluctuations. The following conclusions and consequences can be drawn from these investigations of sealing systems with GCLs installed in lysimeters and exposed to climatic conditions in Germany since 1998:

- Large-scale tests in lysimeters under in-situ conditions are an effective and economical way to demonstrate the long-term permeation behaviour of cover systems with GCLs.
- High-quality GCLs filled with 4,700 g/m² to 5,000 g/m² sodium bentonite (dry) and covered with soil layers more than one metre thick, which are exposed to the humid climate conditions in northern Germany, showed a very high sealing efficiency over more than 25 years of testing.

- Replacing the silty topsoil with a water permeability of 10-7 m/s with sand with a water permeability of around 10-3 m/s led to a reduction in permeation due to a more even water supply and thus to less drying out of the GCLs during the summer periods.
- The sealing efficiency of the GCLs depends on the amount of drainage water that supplies the bentonite with water. After a temporary increase in permeation due to the lower water content, the GCLs regained their full sealing efficiency in the following winter period; this can be described as reversible material behaviour or self-healing capacity.

Not every GCL achieves the same system efficiency regardless of the type and quantity of bentonite and regardless of the environmental conditions. The findings from test fields, laboratory tests and the lysimeters led to the development of the Decision-tool, which can help the user in the selection of sealing elements to be used, but also in the selection of covering soils and soil thicknesses.

This provides the designer and user with a tool that summarises the findings and knowledge from more than 30 years of using GCLs and also gives recommendations on which type of barrier should be used.

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