Field tests on landfill covers for evaluation of performance of mineral cover systems

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Abstract: Cover systems consist of soil layers with different properties and different functions. They are exposed to the atmosphere and to vegetation. The water content of the soils varies with seasons and weather conditions. In winter, the degree of saturation of the soils increases, and in summer the water content is reduced while the matric suction increases. If the matric suction in the compacted clay layer exceeds a limiting value, desiccation cracks occur, and the sealing function is impeded. In order to examine the performance of mineral cover systems, two large scale test fields were installed with different thickness of the restoration profile. Preliminary results of these investigations were presented including data of water flow, matric suction and soil temperature. The role of the restoration profile for the water balance of the cover systems was focussed on.

Key words: landfill; cover system; field test

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垃圾填埋场覆盖层现场试验及特性评价

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摘 要：填埋场覆盖系统由不同的土层组成，它们具有不同的性质和功能。覆盖层直接与大气和植被接触，因此土的含水率随季节和天气条件不断变化。冬天，土的饱和度增加。夏天，土的含水率减少，同时土中吸力增加。如果土中吸力达到某个极限值，将出现干缩裂缝。这时，粘土阻隔层的密封功能将受到损害。为了研究粘土覆盖系统的长期性状，我们进行了两个大规模现场试验。本文介绍第一批现场试验结果，包括水流量、土中吸力和温度的变化规律。重点介绍保护层（营养层）厚度对覆盖系统水平衡的影响。

关键词：垃圾填埋场；覆盖系统；现场试验

0 Landfill cover systems

In order to prevent the migration of contaminants, leachate, gas, odours and dust from solid waste landfills, the waste body should be confined with a bottom liner and with a cover. The cover is not always compulsory. According to the European Landfill Directive[1], a sealing cover is required only in cases, where the supervising authorities come to the conclusion that the generation of leachate has to be prevented.

However, in Central Europe with a high population density and with a predominantly humid climate, it is appropriate to provide all solid waste landfills with covers after closure of the landfilling operation. Accordingly, the German Technical Regulations[2-5] request covers for all solid waste landfills. Their technical layout depends on the deposited waste material and thus on the type of landfill: DK 0 inert waste, DK I construction waste, DK II treated domestic waste, DK III hazardous waste (Fig. 1).

For the minimisation of leachate, landfill covers must contain a sealing layer that prevents precipitation water, rain and snow melt from getting into the deposited waste. The seal may consist of a “technically impervious” soil layer, of a geomembrane or of a composite liner, consisting of a mineral sealing layer and a geomembrane, as shown schematically in Fig. 1.

Since water will accumulate above the seal, but

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pore water pressures in the soil layers above the seal are not permitted, because they can initiate slope failures, it is necessary to drain the water above the seal by a drainage blanket. In landfill cover systems sometimes geosynthetic drainage mats are used. In most cases, as shown in Fig. 1, a permeable soil, gravel or coarse sand, serves as a drainage blanket.

In most situations, the cover shall facilitate growth of vegetation and landscaping to tie the landfill into the environment or to allow for some other use of the surface. For these functions a soil layer is needed, that provides support, water, air and nourishment for the plant roots. This layer is called the restoration profile. The restoration profile is commonly subdivided into a topsoil layer and a subsoil layer.

Landfills may contain waste material that undergoes chemical and/or biological degradation processes with time, associated with the production of gas. Unless the presence of landfill gas can definitely be excluded, a gas venting layer is needed below the seal. It may be necessary, to install a pipe system for gas collection.

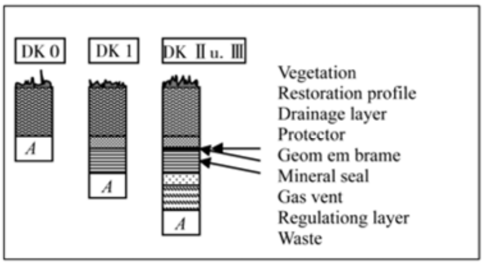

Fig. 1 Landfill cover systems for different types of landfills (German Regulations)

Last but not least, the waste has to be profiled and covered by a regulating layer before the construction of the cover system can be carried out.

In summary, the landfill cover consists of a series of layers, each of which serves a special function, and each of which has to meet certain requirements. All these layers interact mechanically and hydraulically. They have to be composed in such a way, that in combination they perform the functions of the cover system adequately.

1 Mineral seals

The key element of the landfill cover system is the sealing layer. When it contains or consists of a low permeability soil, its hydraulic conductivity shall be small, e.g., $k \leq 5 \cdot 10^{-9}$ m/s. The sealing performance shall not be impeded by mechanical, biological or physical actions such as differential settlements of the waste body with time, suction of plant roots or changes in water content due to elevated temperatures and/or thermal gradients. The latter may be caused by differences between air-temperature and the temperature inside the waste body that may be high due to exothermal chemical and/or biological processes.

Observations in some test fields and some exhumed mineral liners lead to the conclusion, that the sealing performance of compacted clay liners as well as of geosynthetic clay liners can be impeded by shrinkage cracks, if the water content of the clay decreases and the associated matric suction increases beyond a certain limiting value characterising the tensile strength of the cohesive soil[6-8].

An example of desiccation shrinkage cracks observed in a field trial for a cover of a landfill with high temperatures inside the waste body is shown on Fig. 2.

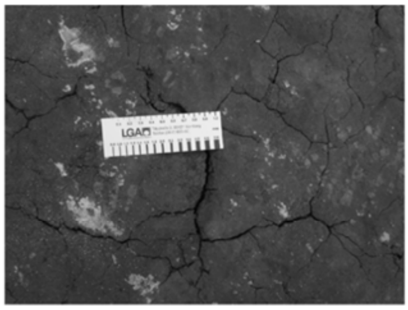

Fig. 2 Shrinkage cracks in a compacted clay liner, observed in a field trial for a cover system of a high temperature waste landfill

Since mineral liners are quite common in landfill cover systems and their proper functioning has to be relied upon for long term use, the problem of preventing desiccation and shrinkage cracks of clayey mineral liners has been paid much attention by geotechnical professionals in Germany during the past 10 years.

The physical phenomena which lead to shrinkage cracks have been studied by laboratory experiments on different soils. Theoretical approaches have been developed, and evidence of desiccation or of the successful prevention of desiccation has been obtained by a number of field trials[9].

This paper presents a field testing program, and intermediate results of ongoing research aimed at a better understanding of the performance of the restoration profile and at specifying its properties required for the

Table 1 Soil properties of the cover system

	Thickness/m	Soil	Grain parameter	γ_d/(g • cm^{-3})	W/%	W_1/%	W_p/%	I_p/%
Topsoil	0.2	SW	1261	1.6	20			
Subsoil	1.8(field 1) 1.3(field 2)	SW	1261	1.7	20			
Drain	0.3	GI	0019	1.8				
Comp, Clay	0.5	GI	3520	1.8	16	42	20	22

prevention of desiccation of the compacted clay liner within the cover system of a sanitary landfill under site specific conditions.

2 Field test

On the slope of a conventional domestic waste landfill, inclined at 14°, exposed towards the south, a 20 m long test field, subdivided into 2 test-areas (field 1 and field 2) of 13 m in width each, was constructed and instrumented. The profiles shown on Fig. 3 comprise the soil layers characterised by the properties given in Table 1. The two test-areas differ in the thickness of the subsoil layer of the restoration profile, which is 1.8 m in field 1 (thickness of the entire restoration profile of 2.0 m), and 1.3 m in field 2 (thickness of the entire restoration profile of 1.5 m).

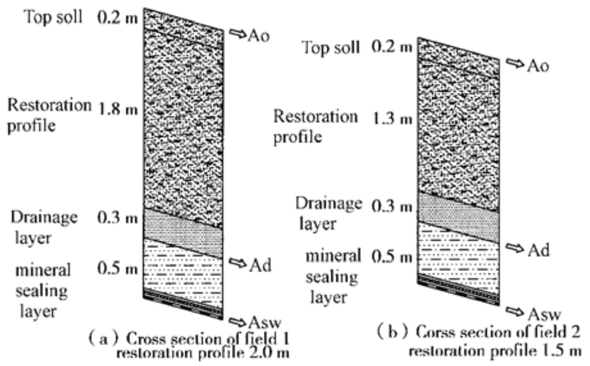

Fig. 3 Layout of test field sections

Field trials with the required minimum thickness of the entire restoration profile of 1.0 m according to present German Regulations[4] had been carried out at the site before, in field tests lasting from 1996 to 2001 and from 1998 to date[10].

The test field was equipped with device for data collection to monitor the following:

A_O Surface runoff

A_D Drainage flow in drainage blanket below restoration profile

A_{SW} Vertical seepage flow through compacted clay liner (intercepted by a geomembrane)

θ Volumetric water content of soil at different depths (FDR and TDR)

ψ Matric suction in soil at different depths (Tensiometers)

T Temperatures of soil at different depths

Additionally weather data (precipitation, air temperature) are collected.

The construction of the test field was completed in November 2001. In spring 2002, when the field measurements commenced, the vegetation started to grow. In summer 2002 the surface of the test field was well covered with plants.

The summer of 2003 was extraordinarily dry for Central European climatic conditions, and the vegetation suffered from drought. In 2004 the plants had recovered and the vegetation has reached its final maximal height of about 1 m.

3 Results of measurements

3.1 Precipitation, surface run-off, drainage flow and seepage through mineral liner

As an example of measured data, for the time period from May 2002 until March 2004, the accumulated precipitation and flows are plotted on Fig. 4 and 5 for fields 1 and 2. The scale of precipitation on the left side is 10 times the scale of flows on the right side of the plots. In Central Europe, commonly the precipitation is distributed rather evenly over the year, so the summation curve of rainfall would show an almost linear increase.

However, the year 2003 was very dry. With 520 mm, only 70 % of the long term average precipitation, which amounts to 750 mm, was recorded. Accordingly, the summation plot of precipitations, the fat black line, shows a flatter slope during summer 2003.

Among the measured flows, the discharge from the drainage layer A_D (light grey curve) has the greatest share. Drainage occurs only during winter months from November to March. During summer, the precipitation is partly consumed by evapotranspiration directly and partly stored in the soil layers of the restoration profile for later evapotranspiration.

The amount of drainage flow differs between fields 1 and 2. In field 1 with the greater thickness of the restoration profile (2 m) the drainage flow quantity, 70 mm in winter 2002/2003, is smaller than in field 2 with the smaller thickness of the restoration profile of 1.5 m, where the drainage flow was 133 mm.

Continued observations during subsequent years will have to demonstrate whether there is indeed a direct relationship between the thickness of the restoration profile and the drainage discharge A_D, as one would expect, or not. The evaluation of details on a daily basis revealed that the maximum drainage flow amounted to 10 mm/d. There is a time delay between events of extreme precipitation and the response of the drainage flow.

Substantial surface run-off A_O (dashed line) occurred only during the first year of observations when vegetation was still scarce. In the long run it plays no important role.

The vertical seepage through the mineral liner A_{SW} (fine solid curve) amounts to about one tenth of the drainage flow. Seepage through the mineral sealing layer occurred at the beginning of the measurements in early summer of 2002 during a wet period, further, from October 2002 to March 2003, and in winter 2003/2004. In the water balance of the landfill cover which is presented in Table 2, the seepage through the mineral liner amounts to 1.4 % to 1.8 % of the total precipitation. In some other test fields where desiccation of the mineral seals took place, the amount of seepage increased and the efficiency of the seals decreased with time[6,10]. In the present case, it is too early to draw conclusions with respect to the long term performance of the landfill cover system. It is possible that at least minor changes will occur during the next two or three years. However, it is worth noticing that during the first two years of the observation period 83 % to 86 % of the total precipitation went to evapotranspiration.

Table 2 Water balance of the test fields during the period May 2002 to March 2004

	Field 1		Field 2	
	mm	%of *N*	mm	% of *N*
Precipitation N	1308	100	1308	100
Evapotranspiration and storage	1127	86.1	1094	83.6
Surface run-off	18	1.4	24	1.8
Drainage flow	141	10.8	171	13.1
Seepage through mineral seal	22	1.7	19	1.4

3.2 Moisture content, matric suction and temperature

The moisture content of the soil layers was measured by FDR-sensors (frequency domain reflectometry) and by TDR-sensors (time-domain-reflectometry) at different depths below the ground surface.

In both methods the almost linear correlation between the square root of the apparent dielectric constant $\sqrt{\varepsilon}$ and the volumetric water content θ [m^3/m^3] of a soil is used for the determination of the moisture content by measuring the apparent dielectric constant ε [11].

The matric suction ψ (negative pore water pressure) was measured by tensiometers, and the temperature by electric thermocouples.

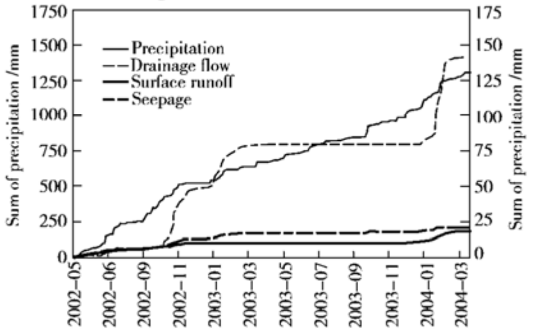

Fig. 4 Precipitation and measured flows of field 1 (thickness of restoration profile 2.0 m)

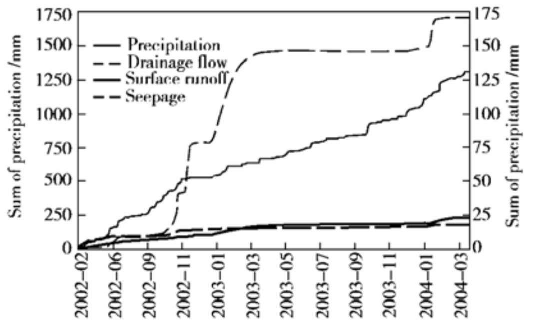

Fig. 5 Precipitation and measured flows of field 2 (thickness of restoration profile 1.5 m)

As an example, the variation of moisture content with time measured in field 1 with a 2.0 m thick restoration profile is plotted on Fig. 6.

The two upper fat lines represent the moisture content within the compacted clay liner; essentially they show no systematic changes during the measurement period. The restoration profile, however, shows significant variations of the volumetric water content.

The upper fat dashed line representing the moisture content at 1.8 m below ground surface, decreases from

May until September 2003, then it remains at $\theta = 0.25$ until Dec./Jan., to go up to $\theta = 0.35$ in winter 2003/2004.

The fine solid line, moisture content 0.2 m below ground surface, follows the seasonal cycle. Near the ground surface the moisture content starts at about $\theta = 0.35$, in summer 2003 it decreases until about $\theta = 0.2$, in winter 2002/2003 it goes back to $\theta = 0.35$, during the dry summer of 2003 it is gradually going down to about $\theta = 0.1$, and in autumn 2003 it reaches $\theta = 0.25$ again quite rapidly.

The light grey lines and the dotted line represent measurements of moisture content at depths between 1.8 m and 0.2 m. They indicate the variation of water content changes at different depths.

Tensiometers were installed in field 1 inside the restoration profile at 1.0 m, 1.4 m and 1.8 m depths, and inside the compacted clay liner at 2.4 m and at 2.6 m.

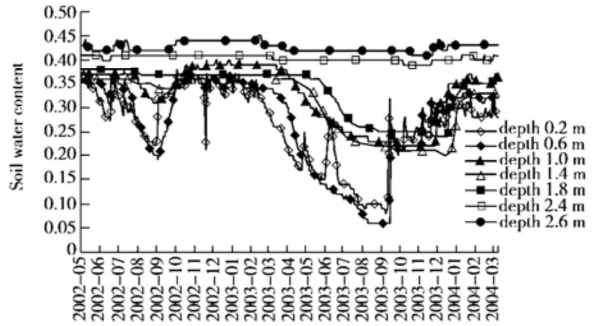

Fig. 6 Volumetric water content measured by FDR in field 1 (thickness of restoration profile 2.0 m)

The plot of measured matric suction is given on Fig. 7. The grey lines indicate that during the moist summer of 2002 at 1.4 m to 1.8 m depth the matric suction did not increase by more than about 50 hPa, whereas at 1.0 m depth, represented by the fine solid line (3), 700 hPa were reached and the tensiometer fell dry. During the dry summer of 2003, the fine solid line increases sharply already in April, the grey lines follow in May/June indicating desiccation of the entire restoration profile.

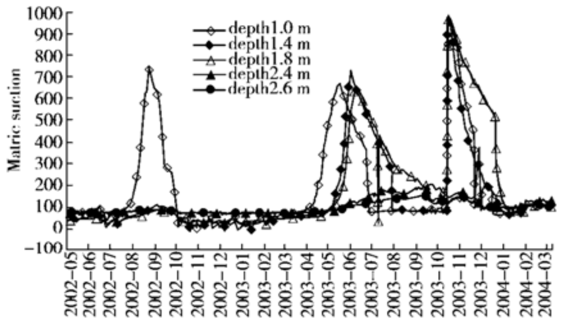

Fig. 7 Tensiometer measurements (matric suction) measured in field 1 (thickness of restoration profile 2.0 m)

The fat solid lines show a slight increase in matric suction of about 100 hPa during the dry summer months. This result indicates that while at depths between 1.4 m and 1.8 m the soil hardly loses any moisture during summers with average precipitation, in extremely dry years, water is extracted from the soil to depths as much as about 2 m.

The water content and matric suction curves of field 2 are not shown here. Due to the smaller field capacity available (water storage capacity) of about 225 mm of the restoration profile of field 2 (1.5 m thickness) as compared to the field capacity of about 400 mm in field 1 (2.0 m thickness), the effects of desiccation during summer months, particularly during the dry year 2003, are much more pronounced in field 2.

However, since the seepage quantity intercepted below the mineral seal in field 2 was as small as in field 1 where practically no decrease in water content of the compacted clay liner was observed, it may be justified to assume that no hydraulically effective shrinkage cracks have developed in the compacted clay liner of field 2 up to now.

On Fig. 8 the volumetric water content is plotted versus depth for selected dates when readings were taken. In February 2003 the volumetric water content in both profiles lies more or less between $\theta = 0.35$ to 0.4. Towards summer it deceases gradually across the entire restoration profile. In February 2004 the measured values are back to those of the year before in field 2 and lag behind somewhat in field 1. In field 1 the compacted clay liner (measurements at 2.4 m and at 2.6 m) experiences only a very slight change in water content, whereas in field 2 it is quite substantial, as can be deduced from the spread of the lines at the depth of the compacted clay liner (1.9 m to 2.1 m).

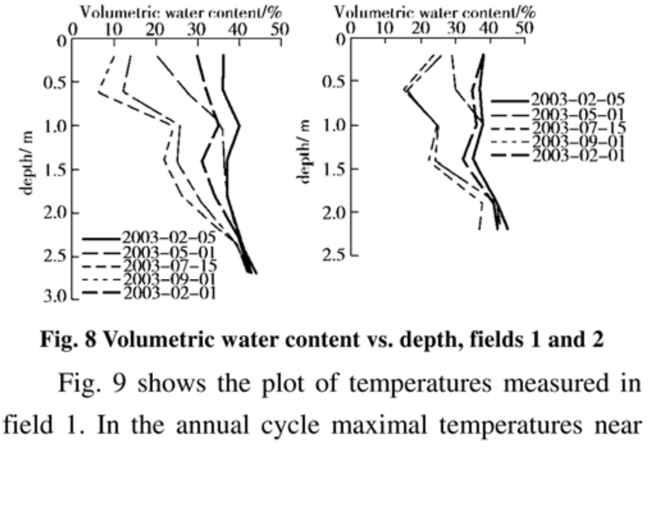

Fig. 8 Volumetric water content vs. depth, fields 1 and 2

Fig. 9 shows the plot of temperatures measured in field 1. In the annual cycle maximal temperatures near the ground surface (20 cm below) reach 25°C, minimal values are near 0°C. At 1.8 m below ground surface maximal temperatures are about 20°C, and minimal temperatures about 7°C. From February to April there is no pronounced thermal gradient, from May to August/September surface temperatures are higher than temperatures at depth. In August/September the thermal gradient changes sign, from then on until February temperatures near the surface are lower than at depth.

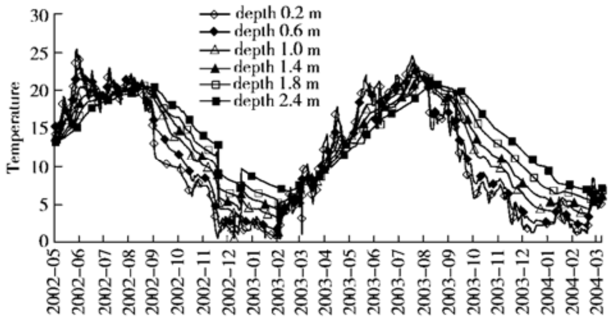

Fig. 9 Temperatures measured at field 1

4 Conclusions

The landfill cover system, consisting of a package of different mineral layers is exposed to the atmosphere. The moisture content and the matric suction of the soil layers undergo changes during the annual weather cycle. In summer evapotranspiration dominates, the water content of the soil layers is reduced, there is little to no drainage flow and no seepage through the mineral liner. In winter precipitation dominates, there is drainage flow and some seepage through the mineral sealing layer (about 10 % of the drainage flow). The amount of water passing through the restoration profile depends on the weather conditions and on the water storage capacity of the restoration profile. The thickness and the soil properties of the restoration profile also play a dominating role with regard to the degree and the depth of desiccation of the cover. In cover systems with compacted clay sealing layers the water storage capacity of the restoration profile should be sufficient to prevent desiccation of the compacted clay and in particular prevent the development of shrinkage cracks in the mineral seal. The differences in results measured at the two test fields demonstrate the influence of the thickness (2.0 m and 1.5 m) of the restoration profile on the water balance of the entire cover system.

The field measurements presented here for an observation period of about two years including one very dry summer indicate proper functioning of the tested cover systems up to now. However, the measurements have to be continued for at least two or three more years in order to facilitate predictions of long term performance.

Field trails of the type described in this paper are a powerful tool to study geotechnical systems with time- and temperature-dependent complex interactions of its members exposed to weather and climatic conditions. Neither small scale laboratory experiments nor pure analytical-theoretical methods can render the information obtained by a well-instrumented and carefully maintained field trial program. The data collected in field tests under well-documented boundary conditions provide valuable bases for the calibration of theoretical water balance models of landfill cover systems.

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