

## **ENVIRONMENTAL GEOTECHNICS OF LANDFILLS (WASTE DEPOSITS)**

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### **SUMMARY**

Landfill engineering (waste deposits) involves the entire field of geotechnical engineering in conjunction with interdisciplinary views. An appropriate pre-treatment of waste is crucial to avoid the passing-on of environmental impacts of today's landfills to future generations. Additionally, multi-barrier systems are recommended, especially in case of hazardous waste. For geotechnical stability analyses of waste deposits a compatibility investigation of the sometimes fundamentally different shear stress-strain behavior of waste and subsoil is recommended. Horizontal barriers commonly require composite liner systems, unless pretreated or mono-waste of low risk potential is deposited.

### **Key words**

Environmental geotechnics, landfill engineering, waste deposits, waste containment, landfill liner systems

## **MULTI-BARRIER SYSTEMS**

### **Interaction of barriers**

Disposal facilities of municipal/household waste, industrial waste and especially of hazardous waste should be designed and constructed according to the "multi-barrier system". This term originates in nuclear engineering and originally defines a security system consisting of several protective measures ("barriers" which act independently from each other). It was then taken over and extended in the waste disposal terminology (Stief, 1996) and has been widely used in Germany and Austria since.

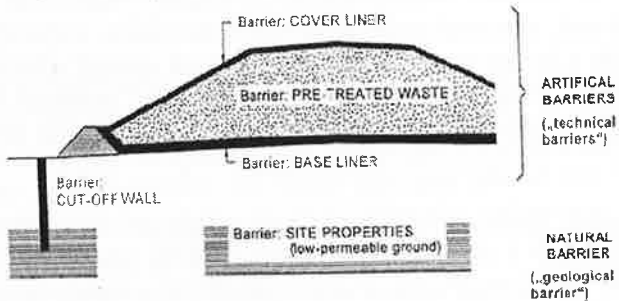
The multi-barrier concept comprises natural and man-made ("technical") barriers. In the case of waste deposits above ground, these barriers include (Fig. 1):

- Natural barrier ("geological" barrier), incorporating proper site characteristics from a geotechnical and hydrological point of view;

- Horizontal barrier (bottom liner and drainage system);
- Capping barrier (cover and/or liner and drainage system);
- Vertical barrier (cut-off walls) plus inner groundwater lowering – not obligatory.
- In a broader sense, “multi-barrier systems” also include the deposit and the waste itself. The pre-treatment of the waste and the operation technology of the disposal facility therefore play a significant role within the framework of a safe, well-managed deposit.

Consequently, the Austrian regulations contain rather stringent limit values for old and new waste deposits. This refers also to the quality of liner and drainage systems which could be improved

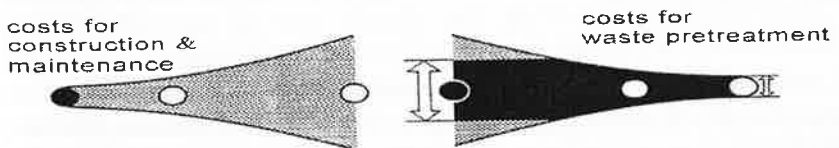
and adapted to the state of the art within a legal transition period.



*Figure 1 The multi-barrier system of a waste deposit*

### Natural versus technical barriers

The interaction of natural and artificial barriers determines the safety and the residual risk with regard to contaminant emissions from a waste deposit and should, therefore, play an essential role in siting. Sites which are only partly suitable, from a geological-hydrological point of view, can be significantly improved by appropriate construction measures, which is an important factor considering other evaluation criteria. A “technically neutral” evaluation, i.e. without specific consideration of technical, protective measures mostly leads to negative results, hence preventing the construction of needed disposal facilities. Subsequently, waste then continues, to a great part, to be “disposed off” in an unprofessional or even criminal way. Therefore, the environmental impact assessment or



*Figure 2 Interaction between the measures and costs for waste pre-treatment and a waste disposal facility.*

Schematic. Left point: clearly defined waste, mono-waste of low risk potential; Middle point: pre-treated waste; Right point: non-treated waste.

environmental compatibility analysis of a certain waste disposal site should always weigh the effects of the two possibilities: a so-called “zero-solution” in the entire region (with insufficient waste management) and an engineered waste disposal facility.

Referring to the natural (geological) barrier, different expert opinions do exist, and consequently also diverging national or even regional regulations. The discrepancy is mostly based on different “philosophies” of geologists (who want to rely only on nature) and geotechnical engineers (who also rely on the capacity of modern technologies). A highly engineered fill of clay or stabilised soil, executed under strict site supervision, certainly provides a sub-grade with a higher barrier effect than natural ground which always exhibits heterogeneity, discontinuities, etc. Consequently, Austrian regulations allow in case of insufficient geological barriers a substitution with multi-layered clay fills.

The required thickness of a “geological barrier” or its technical substitute varies between 1 m to 7 m depending on its permeability, on the waste properties, on the liner system of the landfill (e.g. single or double composite liner system), and on national regulations. Austrian governmental regulations also consider the permittivity  $\psi = k/d$  of the ground which permits the following variation of the horizontal barrier properties:

- thickness  $d \geq 5\text{ m}$  with  $k \leq 10^{-7} \text{ m/s}$
- or  $d \geq 3\text{ m}$  with  $k \leq 10^{-8} \text{ m/s}$  ( $d \geq 1\text{ m}$  with  $k \leq 10^{-9} \text{ m/s}$  only in exceptional cases)

Thinner barriers are not permissible, at least not for natural subsoil which always exhibits a scatter of parameters which is locally uncertain, even if it is described as a so-called homogeneous ground. But modifications are possible depending on the mineral composition of the barrier which also has a strong influence on the efficiency of the natural or artificial barrier.

### Design considerations

The costs for construction, operation, maintenance, and aftercare of a waste disposal facility decrease with the degree of waste pre-treatment. The less the waste has been pre-treated, the higher are the security requirements for the

facility as well as for the multi-barrier system in its entirety. Moreover, pre-treatment commonly reduces the contaminating life-span of the waste. Depositing waste which is not pre-treated means passing on the environmental impact of that facility to future generations. This refers not only to hazardous waste but also to municipal waste. The arrow in Fig. 2 symbolises the limit of the possible pre-treatment, depending on the current state-of-the-art technique. Accordingly, inert material disposal facilities, for instance, do generally not need any bottom liners while high-security facilities (for hazardous waste) need multiple-barrier liners, have to be controllable at all times, and must be repairable in such a way that, even in the case of failure, there is no relevant environmental impact.

Furthermore, a division of the waste in sections and compartments has to be assured, in order to avoid a blending of the waste which might favour critical synergistic effects.

All types of disposal facilities should preferably be designed and constructed in such a way that the waste can be retrieved, if needed, as it could, in the future, represent valuable secondary raw material. This recommendation postulated by the author already 25 years ago has gained full actuality meanwhile. Landfill mining (also "urban mining") refers not only to municipal household waste (MHW) but also to residual waste from waste incineration. Ashes or slags resp. from sewer sludge, for instance, contain 15 to 20% phosphate. This may be used to recover phosphorus, mainly required for fertilizers. This phosphorus can even be better absorbed by plants than natural phosphorus from conventional mines. Valuable secondary new materials from MHW are mainly Fe, Al, Cu, Zn, and even brass and high-grade steel.

A proper design of a new waste deposit or of an encapsulated contaminated medium (waste and/or soil, abandoned industrial buildings etc.) should further be made in such a way that the service life of the containment system exceeds the contaminating life-span of the waste deposit, etc. It has to meet requirements for no or negligible environmental impact for a x-year post closure period. In many countries interest is only focused on a 30-year period, whilst others have regulations requiring negligible impact for 100 to 500 years post-closure or even in perpetuity.

Regulations which require "no impact" are emotionally desirable but involve practical difficulties or can simply not be fulfilled. Furthermore, the environmental impact that can actually occur is controlled by the detection limits used in the chemical analysis of the groundwater. Therefore, "no impact" regulations may place unrealistic restrictions on the design of facilities, whereas "negligible impact" regulations are practicable.

“Negligible” should be quantified on the basis of considerations of background chemistry, the chemical species, and the potential aesthetic and healthrelated implications of an increase in concentration in the groundwater (Rowe et al. 1995).

The contaminating life-span of a landfill depends on the mass and thickness of the waste, the leachate strength, the infiltration through the cover, and the contaminant transport pathway. Even if properly designed, specified, and constructed, the service life of many of the key components of a landfill barrier system will probably not exceed a 100 to 200-year post-closure period. Consequently, the pre-treatment of hazardous and municipal waste will be unavoidable in the long-term even in those countries where waste is hitherto simply landfilled without barriers.

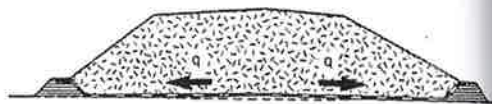
Politicians are adopting a “greener” image – at least in the industrialised world. They are enacting stricter and more voluminous legislation; and they are changing priorities in waste management policy, away from “low costs” towards “environmentally sustainable”. Therefore, waste

pre-treatment and engineered waste deposits accept to gain increasing international applica

Pit landfill



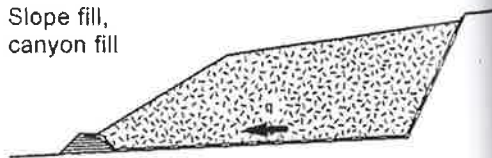
Waste pile



Surface impoundment



Slope fill,  
canyon fill



## STABILITY OF LANDFILLS

“Landfill stability” in the widest sense comprises geotechnical, physical, chemical and hydrological aspects. Accordingly, a landfill may be considered „stable” when its contents do no longer pose (significant) risks to human health or the environment. However, widely/internationally accepted definitions of „landfill stability” and „final storage quality” are not available.

Therefore, the following chapter focuses only on the geotechnical stability of landfills.

Waste disposal facilities may be conventional landfills (Fig. 3), structural containments, or deposits in underground spacings.

Conventional pit-landfills can be best “hidden” in the landscape but require extensive drainage/pumping to remove the leachate. A natural drainage is not possible there which results in a higher risk in case of defects in the drainage or barrier system. Leaks in a (conventional) bottom liner system or leakages from there may be localised in sectors, but not at the exact point. A repair of the bottom liner is basically only possible after waste removal. Consequently, landfilling of excavation pits creates in many cases the contaminated sites of the future. Therefore, in Austrian regulations only waste piles and slope/or canyon fills are permitted for new facilities. A natural drainage of the bottom and capping liner systems must be available in order to minimise operation costs, long-term risks and maintenance or aftercare, respectively. As a compromise, a partial filling of larger excavation pits can be tolerated if the deposit exhibits the form of a slope fill, or if pit fills are situated near the crown of slopes where a natural drainage of leachate is possible.

Legal exceptions from this regulation are the adaptation of old facilities to the present state-of-the-art and deposits where practically no leachate arrives at the bottom liner/drainage system – both exceptions in combination with high quality natural and technical barriers.

Figure 4 gives an overview of several geotechnical aspects which have to be considered for the design, construction, operation, and aftercare of a waste deposit. The main problems with regard to geomechanics are large differential settlements in the base of the waste deposit and slope stability. Consequently, several national regulations basically exclude weak soils or unstable slopes as possible sites for waste disposal facilities – which may be too stringent. On the other hand, they recommend “standard”-values for calculatory waste parameters, assuming stress-strain compatibility – which in

most cases does not

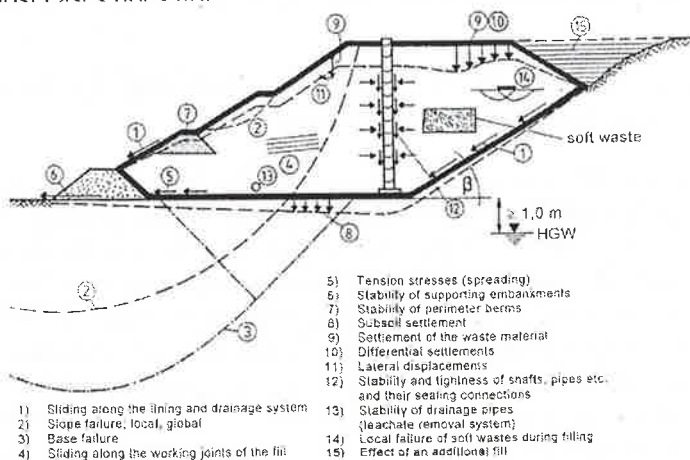


Figure 4 Stability and deformation of a waste fill to be considered for design

Slope stability analyses have to take into account that municipal solid waste and soil have completely different shear stress-strain properties – especially if the subsoil consists of stiff clays or silts with a low residual shear strength,  $\Phi_r$ , as indicated in Fig. 5. Municipal household waste requires large shear deformations until the entire shear strength is mobilised. Unlike stiff soils, MHW does not exhibit a clear fracture. Therefore, the friction angle is a fictitious value, symbolised by  $\Phi^*$ . In contrary, the soil reaches its peak strength,  $\Phi_{\max}$ , already at relatively small deformations, and further movements cause a decrease to  $\Phi_r$ . A similar discrepancy refers to the cohesion: Large shear deformations in the soil reduce the cohesion from  $c$  to finally  $c_r = 0$ , whereas they still mobilise an increasing fictitious cohesion,  $c^*$ , in the municipal waste. Consequently, slope stability analyses of waste deposits have to consider the compatibility of waste and subsoil deformations, especially in case of slope fills (Fig. 6). For slope stability and ground analyses the following shear criterion has proved suitable:

- municipal waste:  $\Phi_{\text{calc}} < \Phi^*_{\max}$ ,  $c_{\text{calc}} < c^*_{\max}$ ;
- subsoil (clay barrier):  $\Phi_r < \Phi_{\text{calc}} < \Phi_{\max}$   $c_{\text{calc}} \geq c_r = 0$

The different shear stress-strain behaviour of municipal waste and subsoil (or clay liners) influences not only the safety factor but also the shape and location of the most critical slide surface. Fig. 7 shows the total shear resistance  $\sum \tau_i \cdot l_i$  along the slide surfaces a, b, c of Fig. 6, and it illustrates a dominating influence of the subsoil's parameters which is usual in case of a very low residual shear strength of cohesive ground.



Especially critical is a progressive slope failure starting from the toe zone of a landfill, e.g. in a locally overstressed zone of low (residual) shear strength. Fig. 8 illustrates the progressive propagating of the failure towards the crown, whereby the shear stress-strain behaviour in the points A, B, C differs significantly: In A large shear deformations may have led already to the residual value  $\Phi_r$ , whilst B has just reached its maximum resistance, and C has mobilised only a small part of its full shear resistance.

In case of landfills with steep slopes and/or subsoil with high shear strength, slope failures usually start on the crown of the waste deposit. Horizontal tensile stresses in the upper zone cause vertical cracks there, thus mobilising to a high degree the shear strength of the waste.

The consequences for slope stability analyses, risk assessment and design are:

- Low-permeable ground which is advantageous for waste disposal sites exhibits in many cases a low residual shear strength and the tendency to progressive failure. Therefore, a detailed investigation of the shear parameters is essential, especially the determination of  $\Phi_r$ .

The shear properties of municipal waste cannot be described by “constants” or standardised parameters, and they are therefore not well suited for being included in regulations. Stability analyses should be based at first on a deformation assessment and allowable deformations

respectively.

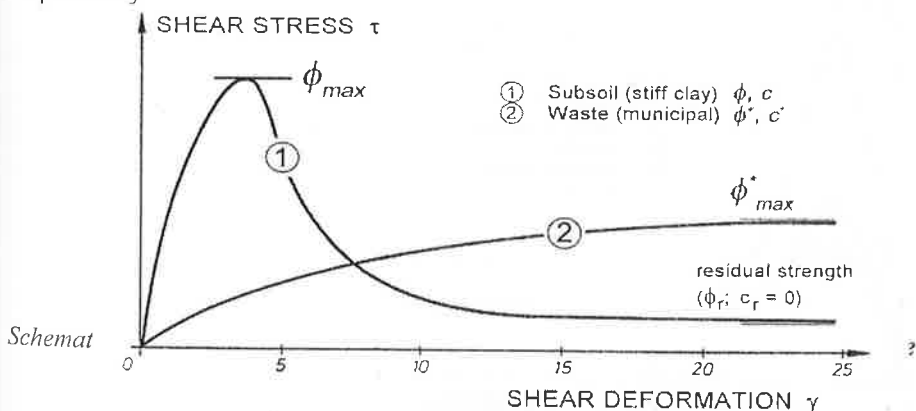


Figure 5 Shear strength – strain diagrams for municipal waste and stiff clayey soil



## BOTTOM LINER SYSTEMS

The bottom liner usually represents the most important technical component of the multiplebarrier system. Therefore, it should consist at least of two different sealing materials to achieve a high, durable, and multi-efficient barrier effect against contaminant migration. This is achieved by composite liner systems. So-called mono systems, consisting only of one material (e.g. geosynthetics or recycling products) should be limited to waste deposits with a low risk potential.

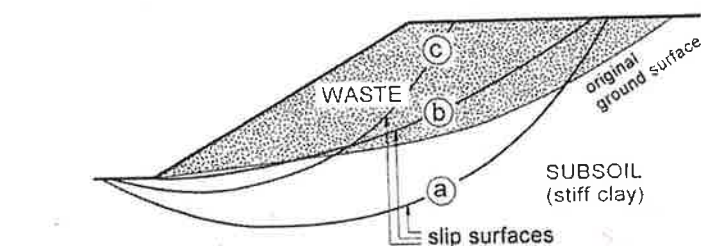


Figure 6 Slope failure investigation of a slope fill (municipal waste) and the chosen (any) slip surfaces a, b, and c assumed as examples with relevant slip surfaces running through the waste

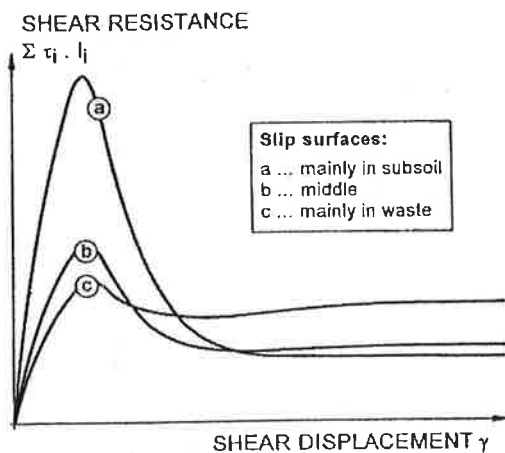


Figure 7 Shear resistance along the slip surfaces a, b and c in Fig. 6, based on the  $\tau - \gamma$  - diagrams of Fig. 5.

Composite liner systems may consist of clayey soils ("mineral liners") and/or geosynthetics, asphalt, recycling material, chemically improved soil, metals, etc. Most regulations for municipal solid waste and for hazardous waste prescribe composite liner systems based on clay liners and geosynthetics, also incorporating a proper drainage (leachate collection and removal) system – e.g. Figure 9. But the possibility of alternatives should be kept open to encourage further developments.

To evaluate novel systems, a number of criteria are required (the following order is not weighted):

- Permeability (by convection, diffusion),
- Resistance (mechanical, physical, chemical, biological),
- Long-term behaviour, durability,
- Cracking and self-healing properties,
- Stress-strain behaviour,
- Friction, adhesion,
- Compatibility of the single elements,
- Overall structure of the entire barrier-drainage system,
- Workability during construction and duration of construction,
- Sensitivity towards weather during the construction period,
- Quality control and assurance,
- Repairability in the case of failure,
- Thickness of the structure regarding increase or decrease of the deposit volume,
- Environmental impact during the production of the barrier and drainage materials,
- Availability of the raw materials for the liner and drainage system, and their future resources,
- Public acceptance.

Innovative systems should exhibit at least the same efficiency as conventional systems, hence, a technical equivalency must be proved. To evaluate this, risk analyses are necessary, also including the properties of the waste and the subsoil, whereby the durability of the components plays an essential role.

Table 1 Assumption for a risk analysis evaluating the base liner of a waste deposit.

Phase	Period (years)	Efficiency of the barrier				
		Subsoil/subgrade		Liner and drainage system:		
		geological barrier	technical barrier	clay liner, mineral liner	geosyn- thetics	drainage systems
Operation (filling of waste)	0 - 25	++	++	++	++	++
Operation and/or aftercare	25 - 50	++	++	++	++	++ + 1)
Aftercare	50 - 100	++	++	++	++ + 1)	+
Final state 2)	100 -	++	++	++ (4 + 1)	++ (1)	(- + 0)

Table 1 contains some assumptions referring to clayey and geosynthetic liners. The values actually depend very much on the usage, the structure, the materials, and the installation quality of the liner and drainage system. For instance, geomembranes placed between clay liners, will probably still be intact.

Even after 100 to 200 years. Mono-systems consisting only of geosynthetics make a thinner structure possible but, on the other hand, exhibit a shorter life-time than composite systems.

An optimum resistance to pollutant migration is provided if the mineral liner is firmly covered by a geomembrane (without a geotextile between). The physical interaction of this reduces diffusion. Figure 9 shows a standard liner and drainage system which is common for municipal and pre-treated hazardous wastes in most industrialised countries. The thickness of the mineral liner varies relatively widely in the individual national regulations.

Composite liner and drainage systems with a primary and secondary leachate collection and removal system have proved suitable in the case of waste with a high risk

a low natural barrier

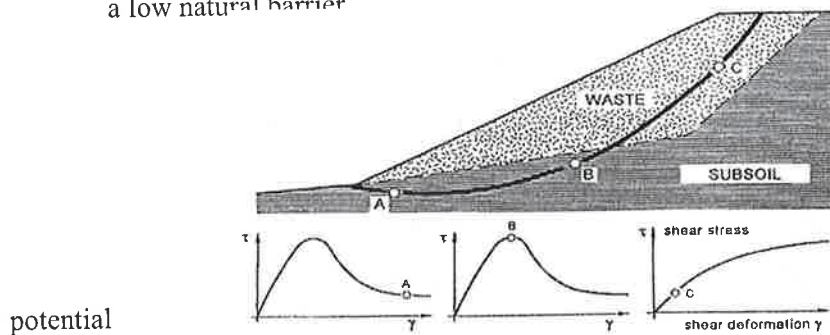


Figure 8 Shear strength-strain diagrams: different mobilisation of the shear waste and subsoil

## CAPPING

Most national regulations prescribe a rather “non-permeable” capping of the waste deposit after closure. Figure 10 illustrates typical designs which reflect widely used standards. However, placing of such liners immediately after finishing waste filling increases the risk of long-term environmental impact because the contamination life-span increases with decreasing infiltration into the landfill.

Furthermore, greater differential settlements of not pre-treated municipal waste inevitably cause local leaks. Both factors worsen with increasing height of the landfill and with decreasing degree of waste pre-treatment. From this point of view, a temporary semi-permeable cover of the landfill is of advantage. Geosynthetic clay liners have also proved suitable as an alternative to multi-layered liner systems because they are rather flexible and easy to remove.

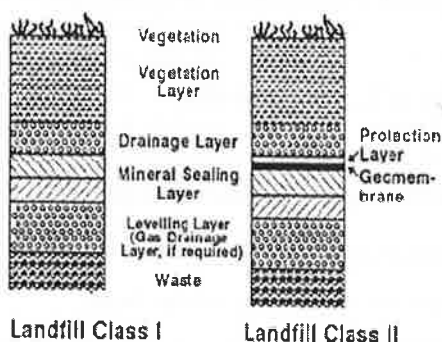


Figure 10 Capping liner and drainage system according to German regulation “TA Siedlungsabfall”.

Class1 = excavation material and debris; Class2 = household waste

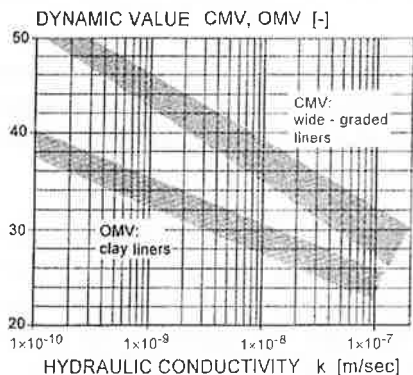


Figure 11 In-situ permeability control of mineral liners

(uniform clay to wide-graded clay-gravel mixtures) by means of roller-integrated continuous compaction

control (CCC). Examples of correlation between the dynamic compaction values, CMV or OMV, and the hydraulic conductivity coefficient,  $k$ .

The quality assurance of the capping comprises proper control of materials, site supervision and especially long-term monitoring. The latter should be combined with a hydrologic evaluation of the landfill performance, taking into account the annual precipitation and the possible infiltration into the capping. This methodology also makes an additional quality assurance of the bottom liner and drainage system possible. The local correlation between precipitation and infiltration into the surfacenear humus/soil must be known; it depends not only on the soil characteristics but also on the surface roughness and inclination, and on the plants. Finally, the landfill cover should consider emission mitigation or utilisation of landfill gas.

## MINERAL LINERS (CLAY LINERS)

Essential for the quality of a mineral liner are the following factors:

- grain size distribution;
- mineral composition (especially of the fines);
- homogeneity of the fill material;
- water content during compaction;
- degree of compaction;
- post-treatment.

Hydraulic conductivity, pollutant adsorption capacity, diffusion characteristics, stress-strain behaviour, cracking (shrinkage), self-healing properties, and chemical resistance are in the end the result of the above parameters.

Frequently there is uncertainty about the chemical properties of wastes and the effects of microorganisms, synergism, and long-term reactions. In such cases, especially as multiple-barrier against hazardous waste, the bottom liner should incorporate different clay minerals. This may be achieved by mixing bentonites, illite, kaolinite, chlorite, etc. as one optimised additive or by placing a multi-layer system with different additives.

The following clay minerals are recommended for such "multi-mineral clay liners": Highly activated sodium-bentonite in the bottom layer, calcium-bentonite for the protection of the sodiumbentonite mixture, illite or kaolinite for the next soil layer, and partially organophilic bentonite in the top layer. The four-layer clay mineral chlorite has proved to be relatively stable against chemical attack and may also be used in multi-layer soil lining systems (Brandl, 1992).

Commonly, a hydraulic conductivity of  $k \leq 10^{-9}$  m/s is required on construction sites for bottom liners. In many cases natural clays and clayey silts do not achieve this value, and homogeneous mixing with clay powder is difficult (due to crumbling etc). Moreover, too fine soils may shrink and permit pollutant migration through fissures.

Most guidelines and regulations recommend/prescribe clay or clayey silt for mineral liners. But comprehensive laboratory investigations and site experience have shown that wide-grained gravel, improved with a small percentage of fines, provides the highest liner quality. Mixing with bentonite or other clay powders is easy due to the coarse grains which have a kneading and milling effect. The best results are those for a grain size distribution which approximates to the Fuller curve which is well known from concrete technology. Control tests on numerous construction sites provided values of  $k \leq 10^{-11}$  m/s to  $10^{-10}$  m/s for (silty) sandy gravel mixtures with 3–5% sodium bentonite or 5–8 % kaolinitic clay powder.

An improved, wide-graded sealing material provides further advantages over clays:

- Mostly easier available from adjacent sites for mixed-in-place or mixed-in-plants.
- Easier to homogenize and to compact during construction.
- More stable under different weather conditions during construction work.
- Less tendency to shrinking.
- More stable when not yet covered by waste.
- A very low porosity and, consequently, a high resistance to aggressive leachate and to diffusion migration of pollutants.
- Higher stiffness and shear strength.

The compaction degree has proved to be the most suitable parameter for site control and quality assurance. It should therefore be an essential part of regulations together with the hydraulic conductivity (which requires additional laboratory testing).

So far, compaction control has been carried out mainly by spot checking. This involves a certain residual risk, and in order to avoid this, the roller-integrated Continuous Compaction Control (CCC) was developed.

The dynamic compaction values have to be calibrated on the basis of conventional tests, e.g. compaction degree ( $D_{Pr}$ ) or density  $\rho$ , or deformation modulus  $E_v$ . Meanwhile, correlations with the hydraulic conductivity have also been developed (Fig. 11). The main advantages of this control method are the following:

- Continuous control of the entire area.
- Results are already available during the compaction process, hence no hindering or delay of the construction work.
- Optimisation of the compaction work, including prevention of local over-compaction (which causes near-surface re-loosening of the layer).
- Full documentation of the entire area.

Because of these advantages CCC has been included in Austrian regulations on mineral liners for about 15 years already. Experience in Austria has shown that CCC increases the quality of compacted mineral liners significantly. Theoretical and practical details are given in Brandl & Adam (1997).



## CONCLUSIONS

Environmental geotechnics refers not only to the siting, design, construction, operation, aftercare, monitoring, etc. of (new) waste disposal facilities but also to contaminated land evaluation and remediation.

An “absolute” site cleaning in a strict physical/chemical sense is practically not possible. Costeffective measures achieve an efficiency of about 70 to 80 (90) %. Cleaning of more than 90 (95) % commonly leads to an excessive increase of costs. From a pragmatic point of view, it therefore should be preferred to remediate more sites on a lower level than to spend the available money on just one site – whereby the question “how clean is clean” still remains.

Concerning the design and operation of new landfills, it should be emphasized that a “100% barrier efficiency” cannot be achieved, even with highly engineered waste disposal facilities, unless the waste exhibits a very low risk potential or is properly pre-treated. Hence, waste separation (already during collection) and pre-treatment should have priority over complicated containment concepts.

Accordingly, waste may be deposited in Austria only if the total organic carbon (TOC) is 5% at the maximum (or the lower caloric value LCV  $\leq 6000$  kJ/kg). This regulation has been in use for 15 years already; its legal transition period ended on 31. December 2008.

With regard to the design of new waste disposal facilities, reasonable regulations are to be favoured, which require negligible impact for a prescribed period of time. This aftercare period should be at least 30 years after closure of the landfill, depending on the results of monitoring (landfill gas, leachate, settlements, slope stability, etc.).

The EU landfill directive (Council Directive 1999/31/EC) stipulates in article 10 that landfill operators must ensure financial security for landfill closure and aftercare measures for a period of at least 30 years. This time-span is also often interpreted as the “active aftercare phase” for a landfill site, including gas extraction and treatment, leachate collection and disposal. However, from a scientific and technical point of view, the real aftercare period will most probably last longer in order to achieve environmentally harmless emissions – particularly regarding leachate quality (Huber-Humer, 2007).

With respect to environmental protection, it would not be understandable to be satisfied with shorter periods to pass the impact of not properly designed or operated waste disposal facilities on to future generations. On the other hand,

excessive regulations requiring negligible or even no impact in perpetuity would represent unrealistic restrictions and might, therefore, cause delay in the construction of urgently needed new facilities. The term “negligible effect” on the groundwater and air should be quantified on the basis of chemistry, biology, and health-related implications.

## REFERENCES

- [1] Brandl, H. (1992). Mineral liners for hazardous waste containment. *Geotechnique* 42, No. 1: 57-65.
- [2] Brandl, H. (1994). Vertical barriers for municipal and hazardous waste containment. In *Developments in Geotechn. Engineering*. Balasubramaniam et al. (eds). Rotterdam: Balkema
- [3] Brandl, H. (1995). Stability of Waste Deposits. *Proc. 10th Danube-European Conference of ISSMGE, Romania*: 1043-1056.
- [4] Brandl, H. & P.K.Robertson (1996). Geoenvironmental site investigation, specification and characterization. *Proc. 2nd International Congress on Environmental Geotechnics, Osaka*: 1345-1375. Rotterdam: Balkema.
- [5] Brandl, H. & D. Adam (1997). Sophisticated continuous compaction control of soils and granular materials. *XIVth Int. Conference on Soil Mech. and Found. Eng.*, Hamburg. Rotterdam: Balkema.
- [6] Fellner, J. et al. (2007). In-situ Treatment Methods Capable to Achieve Final Storage Quality? In *Waste matters, 2nd BOKU Waste Conference, Vienna*, P. Lechner (ed.)
- [7] Huber-Humer M. (2007). Dwindling Landfill – Gas Relevance and Aftercare Approaches. In *Waste matters, 2nd BOKU Waste Conference, Vienna*, P. Lechner (ed.)
- [8] Rowe, R.K. & R.M.Quigley & J.R. Booker (1995). *Clayey Barrier Systems for Waste Disposal Facilities*. London: E & FN spon.
- Stief, K. (1996). *Multibarrierenkonzept als Grundlage von Planung, Bau, Betrieb und Nachsorge von Deponien*. Müll u. Abfall, H.1, Berlin