

Cracks Due to Desiccation in Cover Lining Systems Phenomena and Design Strategy

K. J. Witt

*Professor, Department of Civil Engineering, Geotechnical Engineering,
Bauhaus-University Weimar, Coudraystr. 11c, D-99423 Weimar, Germany*

R. M. Zeh

Research Assistant & PhD-Student, Geotechnical Engineering, Bauhaus-University Weimar

Abstract

Capping systems with mineral liners - compacted clay liners CCL as well as clay geosynthetic barriers GBR-C - are often applied as a standard cover for landfills with small or medium hazardous waste. During dry periods, the clay liners can show a suction-induced dewatering due to seasonal fluctuation of the restoration layer's soil moisture. In addition, the roots of the vegetation can deepen and penetrate into the mineral liner. If an ultimate suction is exceeded in the clay liner, irreversible cracks will occur and will reduce the sealing effect dramatically. The stress and deformation under which tensile cracks initially occur are imposed by the moisture change of the adjacent layers and on the allowable suction of the mineral material related on its soil-physical properties and the stress conditions. Knowing this limits of effect and resistance a mineral layer can be designed with an engineering approach. The paper briefly shows the different impacts and some design principles to reduce the probability of desiccation cracks in cover systems with mineral liners.

Introduction

Compacted cohesive soils with low hydraulic conductivity (silt, clay) are used as an exclusive mineral liner or as a part of a composite liner (compacted clay and flexible membrane liner). The liner has to reduce the advective infiltration of water into the waste body and to prevent gas outlet into the environment. Further required characteristics of the liners and the total lining system are described in the European regulations and its national documents (EU-LANDFILL DIRECTIVE, 1999, DEPV,2002).

In spite of several research projects such as AUGUST et al. (1998), BAYFORREST (2002) some problems dealing with cover lining systems are not solved definitively. In addition, no consistent design strategy have become accepted during the last two decades. Important durability problems of mineral liners are related to small loads, restraint deformations and the periodic changes of the moisture in the entire system. Regarding the long-term function of the cover lining system, the desiccation risk of mineral liners is of central relevancy because desiccation will cause cracks in the mineral liner anyway, sooner or later. The result will be an exceedingly increase in permeability and therefore the loss of usability of the cover.

In this paper, some fundamentals and an approach to design long term impervious lining systems are presented. Furthermore, supporting 'geotechnical tools' such as laboratory tests (e. g. tensile strength or shrinkage test) or numerical simulation (e. g. water balance) to characterize limit state conditions are briefly described.

Results from site observations and excavations

A number of excavations (e. g. overview in RAMKE et al., 2002) showed that mineral liners in cover lining system of landfills have often reduced or lost their sealing characteristics during a few years by micro and macro cracks or single tubes, respectively. The reasons often couldn't be identified exactly. Therefore, the different processes and phenomena in cover lining systems should be analysed to get a better understanding. The central impact to a multi-layer soil system is the seasonal varying inter correlated soil moisture in each layer. All layers normally are unsaturated. Therefore, the suction profile varies by the changing water contents and the soil moisture is influenced mutually due to the suction gradients. From soil physics it is well known, that every change in suction will force a change in volume, shrinkage or swelling (Fig. 1). During the winter season (less vegetation), the soil system in-

creases the moisture in the layers. While the suction decreases there is an advective flow towards the waste body. During summer, high suction values in the restoration layer are obtained and the water moves under an upward directed gradient. Therefore, the moisture in the clay liner decreases. These effects are supported and superposed by root growing which could dewater the top of the clay liner if the restoration layer is too dry and too thin, respectively, related to the climatic impact. Contrary to these seasonal effects there is a transport of water vapour towards the lower temperature that can be neglected under real circumstances. Using standard dimensions for capping systems all over Europe, desiccation wouldn't be a problem in the Northern countries but in the central and especially in the Southern regions, where strong dry periods during summer are usual. Another adverse effect can arise independent of the location of the landfill, if fresh-air circulation in the drainage induces vapour transport.

As a result of a German workshop dealing with desiccation processes in cover lining systems, RAMKE et al. (2002) have summarized all known experiences about cracking and root penetration in clay liners of capping systems of landfills. Further knowledge from lysimeters and excavations are represented in ZEH & WITT (2002b). ROESLER & BENSON (2002) published results of in-situ studies dealing with cover lining systems in different climatic zones in US. Besides, desiccation in some clay liners were observed, too. All these studies definitely show the risk that mineral liners could be cracked or root-penetrated within a cycle of a few years. But even a pre-crack state with not visible micro cracks can increase exceedingly the liner's permeability. Furthermore, two main problems due to cracking in mineral liners could be derived from all results (also cf. WITT & ZEH, 2004):

- i) Direct root penetration into the surface or the total mineral liner in case of a too thin or dried restoration layer related to the climatic exposition.
- ii) Cracking in mineral liners by dewatering due to high suction values in adjacent layers (drainage or compensation layer). Reasons could be a capillary rise to the dried restoration layer or convective vapour transport into a ventilated drainage.

In-situ and laboratory tests show, that the critical suction in a mineral liner (crack initiation) depends on a couple of soil-mechanical and soil-physical parameters like content of minerals, plasticity, soil structure, degree of compaction, initial moisture, overburden load etc. From empirical studies we learn, that the critical suction varies in the range of 25 to 60 kPa for soils used for CCL (USCS classification groups ML – CL). Bentonites (clay geosynthetic barriers) or polymeric improved soils might show higher limits of suction (SIEGMUND et al., 2001, SCHANZ et al., 2004).

Limit State Conditions

For any soil dewatering results in an increase of the matrix potential (suction) corresponding to the specific soil water characteristic curve (SWCC). Especially in cohesive soils as used for CCLs, this increase in suction leads to a reduction of void ratio and therefore to a certain shrinkage. The amount of volumetric strain depends on the structure and the strength of the soil. Nevertheless, any change in water content of a mineral clay liner causes a certain volumetric strain as illustrated in figure 1. But changes in water content of the CCL are obligatory if the moisture and the suction of the adjacent layers vary in turn of time. In a CCL or GBR-C this volumetric distortion due to internal suction starts primarily verti-

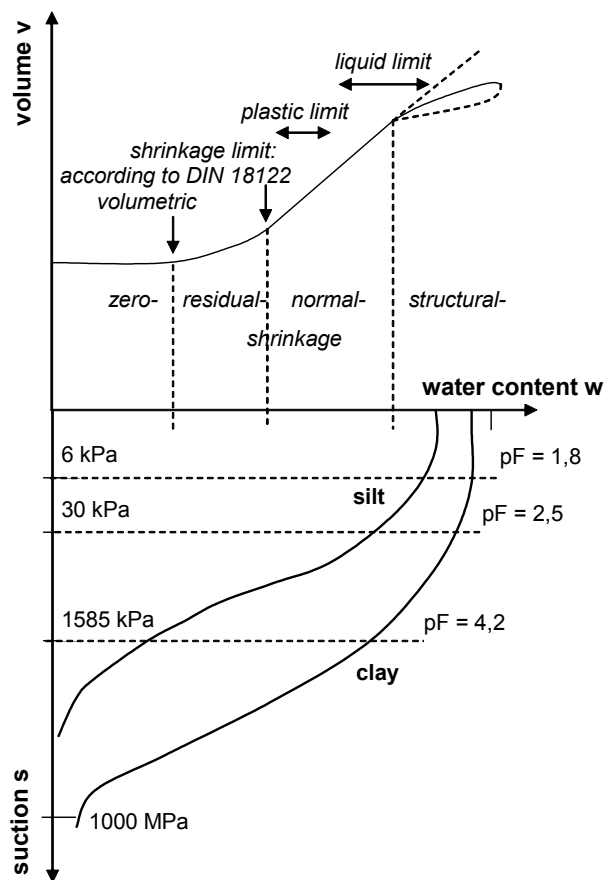


Fig. 1: moisture – volume - suction relationship of a cohesive soil

cal in the direction of the initial mayor principal stress. But if we consider total stresses including the superimposed suction, we can draw up easily, that there must be a lateral strain additionally if the total stress exceeds the prior lateral stress in rest. A crack occurs, if the total stress is greater than the ultimate tensile strength of the soil that will be influenced by cohesion, aging, (sometimes cementation) and capillary forces. Therefore, a crack is nothing else as a local collapse of the soil structure.

The actual suction Ψ_{act} within a profile of a mineral liner results from the interaction of the initial clay with the adjacent soil layers, which soil-water-conditions are strongly influenced by the vegetation and the history of climatic impact. The ultimate matrix potential Ψ_{ult} is a soil specific parameter of the compacted clay that might depend at least on a couple of soil mechanical parameters and boundary conditions:

$$\Psi_{ult} = f(\sigma_o, t_{max}, E^*, \nu, C_{Mat}, A_{Crack}) \quad (1)$$

with

$$\sigma_o = \sum \gamma_i \cdot d_i : \text{cover load}$$

$$t_{max} = f(\sigma_o, c, \phi, \psi) : \text{tensile strength}$$

$$E^* = \text{Young's modulus (tensile strength to strain)}$$

$$\nu = \text{Poisson's ratio}$$

$$C_{Mat} = f(\text{clay content, } \rho_{initial}, \text{energy}_{initial}, \text{structure}) : \text{soil characteristics}$$

$$A_{Crack} = f(\text{number of cracks, max. accepted crack depth, crack length}) : \text{normalised crack number.}$$

The estimation of the tensile strength in special laboratory tests yield to a well-defined relationship of suction (water content) changes and the tensile strength respectively E-modulus, (cf. HEIBROCK ET AL., (2003), ZEH & WITT, 2005). A combination of the water balance programmes with stress approaches and the tensile strength test results can be used as an upper boundary crack prediction for cover lining systems. But the relationship within an actual soil layer is far too complex to be analysed by a simple model that leads to a suitable design criteria using common soil mechanical parameters. During deformation process, coupled mechanisms may be acting in different parts of an element of a mineral liner. Over the finite depth of the clay liner the relative importance of the different parameters causing collapse may change as the dewatering and deformation process continues. Nonetheless, an overall limit state equation can be obtained providing a basis for a simple design approach.

Following eq. 1 a crack will occur, if the actual matrix potential exceeds an ultimate value

$$\Psi_{act} \geq \Psi_{ult} \quad (2)$$

This may also be expressed in terms of moisture. Initial cracks will occur if the actual water content falls under an ultimate value:

$$w_{act} \leq w_{ult} \quad (3)$$

In both equations partial safety factors can be introduced to get an engineering design criteria comparing impact and resistance.

The probable adverse actual value of suction ψ_{act} respectively water content w_{act} can be estimated by numerical simulations of the balance of water during long term periods as described in ZEH & WITT (2002a). The available water balance programmes like HELP or BOWAHALD run accurate enough to predict the future moisture conditions for probable adverse climatic impacts. Sophisticated mathematical models as used for coupled heat, moisture, air flow and deformation problems in unsaturated porous media (THOMAS & SANSOM, 1995, ZHOU & ROWE, 2005) allow a better analysis and understanding of the time dependent phenomena, but they are not sufficiently applicable for a quantitative prediction due to a gap of the relevant parameters. A more fundamental strategy following the observation method starts with an empirical estimation of probable adverse effects coupled with the continues measurements of the suction in a test field as described by SIEGMUND et al. (2001).

To estimate the ultimate value of suction ψ_{ult} respectively the water content w_{ult} there are two approaches, a conservative empirically based assumption (combined with observation) or the direct experimental determination of the ultimate values with dry-wet-cycle test, simulating the entire process of desiccation under real stress conditions. Fig. 2 shows the scheme of the test device in a rigid wall

permeameter. The soil sample is fixed inside a cell between permeable support plates which are loaded by the axial pressure stamp. In the upper part of the cell water can be applied to measure the primary permeability. After dewatering the cell dry air can be floated to dry down the soil specimen slowly. The axial pressure is kept constant, the axial deformation from shrinkage can be observed. The suction within the soil can be measured with micro-tensiometers continuously. The drawdown of the water content can also be obtained by continuous weighting the entire equipment. During drying a small sub-atmospherical air pressure is applied in the space below the sample. This air trap indicates even a small increase in air permeability of the soil specimen and therefore the initiation of cracks. To identify the development and structure of the cracks X-ray pictures of the sample can be made at different sages of desiccation.

With this simple and reproducible test, the ultimate suction and water content can be determined for any stress condition and history of dewatering. The technique is well established for testing GBR-C (KÖDITZ ET AL., 2004) but also suitable to investigate the limits of thin silt and clay layers.

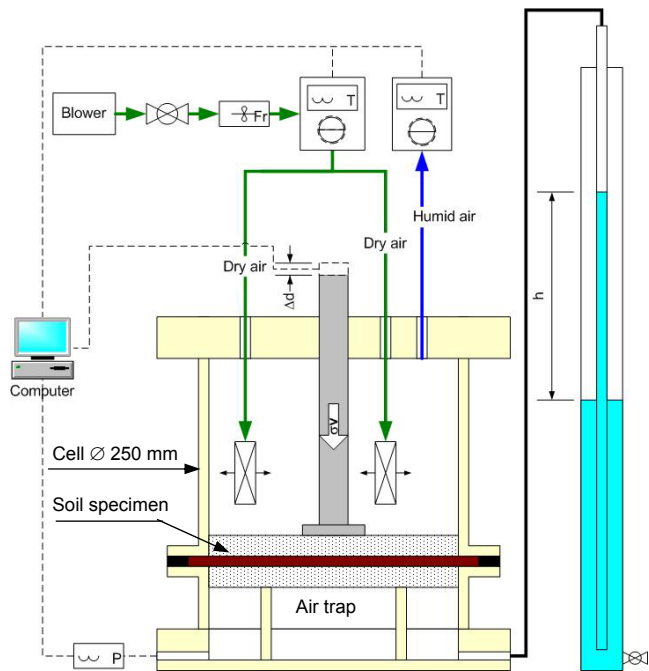


Fig. 2: Schematic setup of a rigid wall desiccation test

Design Principles

Landfill covers with composite liners, as prescribed in the EU directive for hazardous waste landfills, are sufficiently resistant against desiccation of the mineral component. A flexible membrane upon the mineral liner is the most adequate measure against root penetration. But even exclusive mineral system, as used in most of the alternatives, can be constructed desiccation resistive, if the material of the

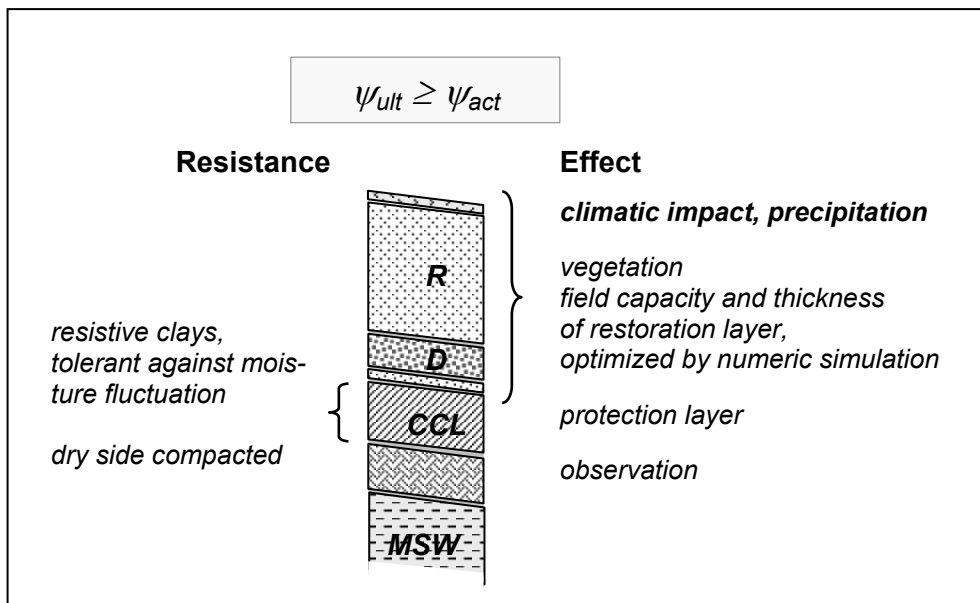


Fig. 3: Design strategy and tools to influence effects and resistance

liner and the thickness of the restoration layer meets the requirements of the specific site conditions. The scheme of design and the tools to influence impact and resistance are illustrated in Fig. 3. The design of a cover system must be focused on both, the allowable ultimate suction of the mineral liner and the most adverse one as a result of the climatic circumstances and the water balance of the entire cover.

The ultimate resistance, i. e. tensile strength respectively crack initiating suction, depends on the physical properties of the material, the build in conditions and the overburden pressure. Soils with a low capacity of shrinkage are silts and clays with a low and medium plasticity, while high plasticity soils are less suitable for a CCL due to the high shrinkage potential. In addition the tolerance against fluctuation of moisture of a cohesive soil can be improved by compaction at dry side of the proctor optimum.

A more powerful tool is to restrict the imposed suction within the liner during the probable adverse climatic impact by designing an adequate system related to the site conditions. The most important factor will be the thickness, property, and porosity (density) of the restoration layer, that should work as a water-storage during the climatic changes of the seasons. For example, a slightly compacted restoration soil with a thickness of 1.5 m and an effective field capacity of about 200 mm/m is able to work as a water storage sufficiently at a humid location with an annual precipitation of > 1,000 mm. Therefore no desiccation problems and no root penetration will come up under such circumstances. But in a semiarid area with < 400 mm annual precipitation the same system would not be able to prevent desiccation of an unprotected mineral liner. For such conditions we need a much thicker earth cover as a storage.

Depending on the site conditions the stratification of the system can be designed precisely enough with help of regional experience and with an numerical analysis of the water balance, using the available programmes (ZEH & WITT, 2002A.). If there is any doubt in long term reliability the system can be strengthened enormously by wrapping the upper side of the mineral liner with a so called capillary protection layer CPL. A 15 cm layer out of a silty sand is able to decouple the seasonal peaks of suction in the earth cover and will tune down the amplitudes of impact to the mineral liner extremely. Very good results and long term experience with this simple measure are reported by SIEGMUND ET AL., 2001, and WITT ET AL., 2004.

Conclusion

Following the strategy to compare the imposed actual and the specific ultimate suction within the mineral liner, the risk of desiccation for covers with exclusive mineral liners out of compacted clay or geosynthetic clay liners can be analysed and assessed by designing the stratification and thickness of the different soil layers. Improvement of knowledge and therefore research is needed to understand the physical aspects of crack initiation in detail and to describe the limit state equation in terms of total stresses and deformations considering common soil physical and soil mechanical parameters. Nevertheless, for the central Europe humid areas, standard solutions work reliable over a long life cycle if we use suitable soils and adequate dimensions. However, under very dry or semiarid conditions we need very thick earth covers to prevent desiccation. Therefore exclusively mineral cover systems grow uneconomically in comparison to composite liners using geomembrans against desiccation and root penetration.

References

August, H.; Holzlöhner, U.; Meggyes, T. (Eds)(1998): Optimierung von Oberflächenabdichtungssystemen, BAM, Springer-Verlag, Berlin

BayForrest (2002): Statusbericht, Berichtsheft 13, Berichte des Bayrischen Forschungsverbands für Abfallforschung und Reststoffverwertung

Deponieverordnung DepV (2002): Verordnung über Deponien und Langzeitlager und zur Änderung der Abfallablagervverordnung, BUM Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Bundesgesetzblatt Jahrgang 2002 Teil 1 Nr. 52, 29. 07. 2002

EU landfill directive (1999): Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste Official Journal L 182 , 16/07/1999 P. 0001 - 0019

Heibrock, G., Zeh, R. M., Witt, K. J. (2003): Tensile strength of compacted clays. in SCHANZ (ed) 2004. Unsaturated Soils: Experimental Studies. Proceedings of the International Conference 'From Experimental Evidence towards Numerical Modelling of Unsaturated Soils', Weimar, Germany, September 18 – 19, 2003, Volume I, *Springer Proceedings in Physics* 93, Springer, Berlin, pp. 395 – 412

Köditz, J., Witt, K. J. u. v. Maubeuge, K. P. (2004): Laboratory tests on the effect of static load to the desiccation of GBR-C. Proc. 3rd Europ. Geosynthetics Conf., Munich 2004

Ranke, H.-G., Gartung, E., Heibrock, G., Lükewille, W., Melchior, S., Vielhaber, B., Bohne, K., Maier-Harth, U., Witt, K. J., Hrsg. (2002): Tagungsband - Austrocknungsverhalten mineralischer Abdichtungsschichten in Deponie-Oberflächenabdichtungssystemen, Status-Workshop, Höxteraner Berichte zu angewandten Umweltwissenschaften, Heft 03

Roesler, A. C., Benson, C. H. (2002): Field Hydrology and Model Predictions for Final Covers in the Alternative Assessment Program - 2002, Geo Engineering Report No.02-08, Geo Engineering Program, University of Wisconsin-Madison, <http://www.acap.dri.edu/>

Schanz, T., Agus, S. S., Tscheschlok, G. (2004): Hydraulisch-mechanische Eigenschaften einer polymerverbesserten Sand-Bentonit-Mischung beim Einsatz im Deponiebau. Geotechnik, Heft 4/2004S. 344-355

Siegmund, M., Witt, K. J. u., Alexiew, N. (2001): Calcium-Bentonitmatten unter Feuchtigkeitsänderungen, 7. Informations- und Vortragsveranstaltung über , Kunststoffe in der Geotechnik', März 2001 München, DGGT

Thomas, H. R. and Sansom, M. R. (1995): Fully coupled analysis of heat, moisture and air transfer in unsaturated soils. J. Eng. Mech. 121(3), pp 392-405

Witt, K. J., Zeh, R. M. (2004): Maßnahmen gegen Trockenrisse in mineralischen Abdichtungen. KRANERT (Hrsg.): *Stuttgarter Berichte zur Abfallwirtschaft*, Band 81, März 2004, S. 83 – 98

Witt, K. J., Zeh, R. u. Fabian, F. (2004): Kapillarschutzschichten für mineralische Dichtungskomponenten in Oberflächenabdichtungen. Müll und Abfall, 11/2004, S. 540-546

Zeh, R. M., Witt, K. J. (2002a): Water balance models and programmes - Comparisons and calculation results. DE MELLO & ALMEIDA (eds): *Environmental Geotechnics*. Proc. 4th. Intern. Congr. Environmental Geotechnics, Rio de Janeiro, 2002, A.A. Balkema Publishers, Vol. 1, pp. 113 – 118

Zeh, R. M., Witt, K. J. (2002b): Untersuchungen zum Langzeitverhalten von Oberflächenabdichtungen von Hausmülldeponien. Endbericht - Ergebnisse und Empfehlungen. Bauhaus-Universität Weimar 2002, www.uni-weimar.de/geotechnik (→Mitarbeiter)

Zeh, R. M., Witt, K. J. (2005): Tensile Strength of Compacted Clays as a Criterion of Crack Initiation in Clay Liners of Landfills. Int. Conf. on Problematic Soils, Famagusta, Cyprus, May 2005

Zhou, Y. and Rowe, R. K. (2005): Modeling of clay liner desiccation. Int. J. of Geomech. ASCE 3/2005