LABORATORY TESTING OF GCL UNDER CHANGING HUMIDITY

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SUMMARY: The use of GCL in cover lining systems demands reliable forecasts about the long-term function under various conditions. The proper operation of such geocomposite liners depends on several parameters, such as the mechanical and mineralogical characteristics of the GCL as well as the chemical, biological and hydraulic conditions within the lining system. Furthermore, the permeability is influenced by the history of changes of the bentonite’s water content. The paper deals with a laboratory testing method which determines the permeability of a GCL under changing conditions of humidity. A special testing equipment will be described which facilitates the simulation of relevant conditions of a GCL in cover lining systems. These test conditions are changes of climatic and mechanic impacts. The investigations focus on the behaviour of GCL’s during and after several periods of drying and rewetting.

1. INTRODUCTION

All over the world Geocomposite Clay Liners (GCL) are used as a single barrier or as a part of a compounded hybrid capping. The main advantages of GCL in a cover lining are a low rate of infiltration, a high capability of assimilating deformations, and a simple and quick construction in addition to relatively low costs. In order to design an appropriate landfill cover lining, various impacts on the composite have to be taken into account. The cover lining should ensure a low permeability, and therefore a low rate of annual infiltration into the landfill over a period from 50 to 100 years. Since a GCL ought to function as a barrier, following qualities are important: (1) mass and characteristics of the bentonite, (2) mechanical resistance of the GCL under field conditions, and (3) climatic impact in the course of use.

Mass and quality of the bentonite can be selected according to the resources available. Currently, we use GCL filled with either sodium or calcium bentonite, and mass loads of about 4 up to 10 kg/m² (in dependence on the choice of resource). Sodium bentonite is used more frequently because of its superior swelling capacity and lower initial permeability. Calcium bentonite has a smaller swelling capacity and a somewhat higher initial hydraulic conductivity. However, it is more likely to resist an exchange between external cations, which results in a more constant behaviour as shown in Alexiew (2000). A further advantage, represented in Gleason et al. (1997), is the shear strength of calcium bentonite being approximately twice as high as that of sodium bentonite under realistic normal stresses. Nevertheless, the internal shear strength of a GCL will be influenced by the kind of bonding the geotextiles. The influence by the ion exchange is explained in detail by James et al. (1997) and by Egloffstein (2000), whereas Shackelford et al. (2000) describes chemical effects of exchange.

The mechanical resistance of a GCL also depends on the process of manufacturing. Here we distinguish needle-punched products of less thickness, adhesive-bonded GCL as well as stich-bonded geotextiles to wrap bentonite into a higher mass load (Koerner, 1997). Each of those products has its special qualities regarding internal friction, reinforcement effects, and the placement of the bentonite. The skin of the geosynthetics can be covered by sand or gravel to increase the angle of friction. Another crucial mechanical parameter is the grain size of the adjacent soils as well as the confining load due to the overlaying soils, as examined by Fox et al. (2000). All these parameters can be influenced by the specification of the GCL, and by the design of a compound lining system.

Nevertheless, one of the main impacts concerning the long-term sealing effect is the climatic condition of the location, and thus the balance of water within the global compound of a landfill capping. In contrast to a standard laboratory test, we normally do not have permanently saturated field conditions. The short-term permeability of an unsaturated GCL is influenced by the degree of saturation, by the effective stress, by the air pressure, and eventually by the mineralogical or chemical conditions. Therefore, there must be a significant temporal variation of the permeability under real field conditions.

The decrease in humidity influenced by climatic impacts or by bioturbation will at first cause a considerable decrease in the unsaturated permeability of the GCL. But due to desiccation cracks may result, leading to an increase of hydraulic conductivity in the order of magnitudes. Such phenomena are described by Heerten et al. (1997), Markwardt (2000), Melchior (1999) and by Petrov et al. (1997). The process has not to be reversible in case of rewetting. This effect of self-healing depends on several boundary conditions, especially on mineralogy, on the level of confining stress, and on the sequence of hydration. Further details about these effects can be found in Lin et al. (2000), and in Cazaux (1999). Considering that the percolation and infiltration of water through a powerful capping layer will happen only sporadic and in short–time, the effect of infiltration through a cracked GCL as a barrier is immense. The reason for this is that the initial hydraulic conductivity after drying can be much higher than the laboratory's test results under saturated conditions. This refers to the need for approximately reproducible laboratory tests as concerns the hydraulic conductivity of GCL. In the following, experimental options will be introduced, which facilitates the simulation of field-representative conditions by changing the confining stress and the humidity during the percolation process.

2. TEST EQUIPMENT

For determining the hydraulic conductivity of confined GCL during several cycles of drying and rewetting, a modified permeameter has been designed and produced at the MFPA Weimar. With the help of the equipment, one is enabled to evaluate the hydraulic conductivity under a varying confining stress, and the conditions of humidity often found in landfill cover lining systems. Figure 1 shows a schematic cross section of the test device.

The main element is a rigid-wall permeameter consisting of an acrylic tube with a diameter of 190 mm, and acrylic end plates. The GCL specimen is fixed to a double-ring, to prevent boundary-effects, such as sidewall leakage. Attaching the GCL to the flange also ensures that the GCL rather cracks than volumetrically shrinks during desiccation. The test equipment corresponds to the set-up for the determination of the geosynthetics' permeability as described in E DIN 60500-4 (1997-02). The static load of up to $\sigma = 35$ kPa is transferred through the head plate by a pneumatic pressure stamp. Perforated acrylic plates cover and support the GCL specimen to cause both, a constant distribution of the confining stress as well as a uniform

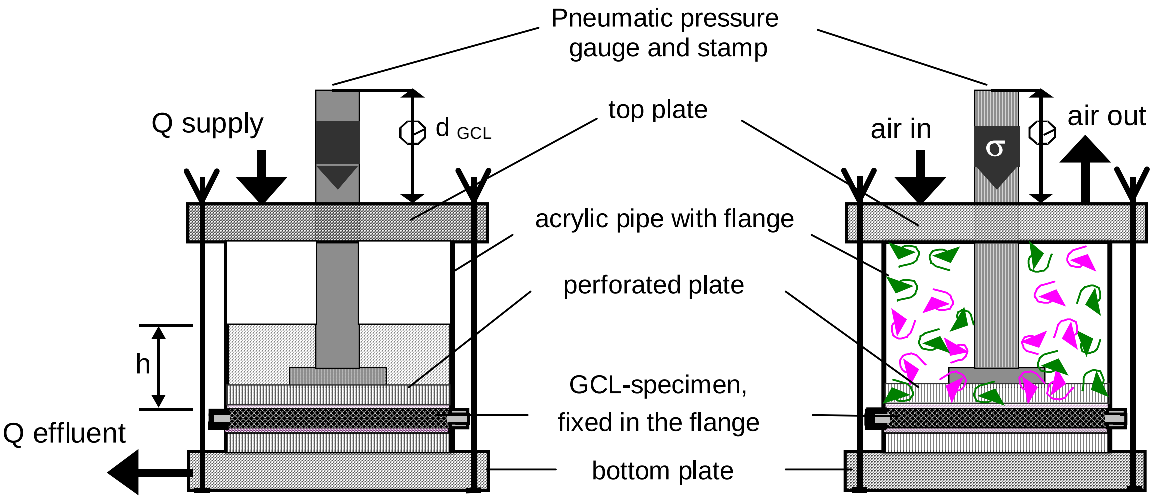

Figure 1: Schematic cross section of the device

circulation of the air throughout the drying period. The average thickness of the GCL may be measured during all sequences of testing: the initial hydrating stage, the hydraulic conductivity test, and the drying period. The effluent is collected in glass bottles by means of an equipment for preventing evaporation losses during the test. After dewatering the cell, the drying of the specimen can be carried out by blowing atmospheric air - either from the head or from the bottom - into the apparatus in a continuous stream ranged from 1.5 to 4.8 m^3/h. A diffusor guarantees a homogeneous contact of the inflowing air with the specimen. The temperature and the humidity of the air can be measured in the discharge.

After the initial hydration and after each drying period, the hydraulic conductivity can be determined by carrying out standard permeability tests with the same configuration of the apparatus. The specimen can be discharged in an upward or downward direction. To saturate the specimen the equipment makes also a backpressure possible, before it is discharged with a low gradient. However, the backpressure technique wasn't used in the tests reported in this paper.

Under field conditions, there will be only little accumulation of infiltrated water at the top of the GCL. This can be simulated in the process of rewetting when the permeability test is started after drying. The procedure begins with an initial rehydration of the specimen by a hydraulic head of about $h < 5$ cm. When the seepage through a cracked GCL has stopped due to rehydration, the water head is raised in increments over several days. Finally, the head remained constant according to the standard determination of the hydraulic conductivity.

Thus, the test equipment makes it possible to simulate various impacts typical of a landfill cover lining system. This happens without removing or disturbing the GCL specimen: (1) Field conditions of bedding by using the original adjacent soils as a support or a cover during the test; (2) Determination of the permittivity under confining stress and realistic rates of seeping with various permeant liquids (e.g. defined ionized or deionized water), and (3) Control of the climatic impact by a defined drying and rewetting procedure. Water content, unit weight, void ratio and bulk water of the GCL during the sequences of the test can be determined without removing the specimen.

3. TEST RESULTS

Several series of tests were performed at the MFPA Weimar using the set-up described above. Most of them were carried out as a part of comprehensive tests to investigate their suitability for use according to German set of rules. This research concerns special products, but all the investigations are not to be discussed in this paper. For this reason, only general results and phenomena shall be introduced and discussed below. All tests were based on the following boundary conditions: (a) the GCL were covered with a geocomposite drain (geospacer), (b) the confining stress was kept on a constant level of σ = 15 kPa during the test, (c) after rewetting the hydraulic conductivity was determined with deionisized water in a downward direction at a pressure drop of Δh = 30 cm.

After the hydration of the specimen under the fixed confining stress over several days, the test was continued by determining the initial hydraulic conductivity by an upward flow at a constant head. The results are represented in terms of permeability k and permittivity Ψ as defined by Darcy’s law.

$$\Psi = \frac{k}{d} = \frac{v}{i \cdot d} = \frac{v}{\Delta h} \qquad (1)$$

where v is the discharge velocity, Δh the difference in total head, d the thickness, and i the hydraulic gradient across the specimen. The use of the permittivity - instead of the permeability common in soil mechanics - is advantageous for thin compressible geosynthetics such as GCL, because the variation of the thickness does not need to be estimated. The initial conductivity test lasted about four weeks. During this time, one could observe further effects of hydration and saturation.

During all stages of conductivity test one could observe a significant correlation between the permittivity and the atmospheric pressure caused, for instance, by an incomplete saturation.

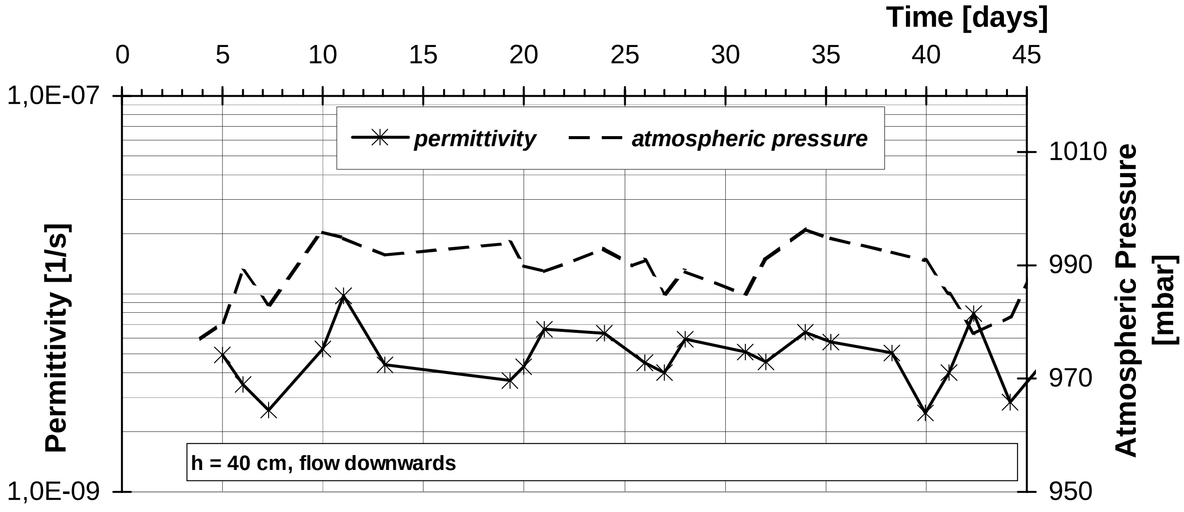

Figure 2: Typical course of changes of atmospheric pressure and permittivity

Figure 2 shows such a typical course of a test after rewetting a calcium GCL. While the air pressure changes within 20 mbars, the permittivity shows a variation factor of 4. This phenomena can be explained by two effects. On one hand, increasing atmospheric pressure leads to a compression of the remaining pore air, and thus to an increase in useable pore space. On the other hand, especially fast changes of atmospheric pressure may influence the effective stress within the GCL.

After dewatering, the specimen was dried by circulating air. The decrease in the GCL's water content could be determined by continuously pondering the complete cell. Another criterion is the matric potential ψ_{air} above the GCL, which can be approximated in dependence on its relative humidity using an empirical relationship for calculating the evaporation in soil physics:

$$\Psi air = 6{,}502 + \log(2 - \log H) \qquad (2)$$

where ψ_{air} = is the matric potential of the air in terms of pF-value (logarithm of the tension in hPa) and H is the relative humidity in %. This dependence is shown in Figure 3 as a result of many drying tests with different bentonites, and also different densities. The matric potential is given as a logarithm of the tension in hPa versus the volumetric water content of the bentonite within the GCL. The diagram shows that there is no significant difference in the behaviour of several types of bentonite.

The tests began with nearly saturated specimen with a gravimetric water contend of about $w = 175\%$ (sodium bentonite), and $w = 105$ % (calcium bentonite) respectively (Figure 6). The beginning of micro-cracking could be examined by x-raying the total specimen. Due to an over-burden pressure of $\sigma = 15$ kPa, first cracks could be observed at a water content of about $w = 100$ % (sodium), and $w = 80$ % (calcium and exchanged sodium) corresponding to a suction of $pF = 6.0$ until 6.2 at the interface to the drying air. In the bentonite, the suction must be much smaller at the beginning of the cracking under these conditions of over-burden stress. According to theoretical considerations of Morris et al. (1992) and Holzlöhner (1992), cracks will arise if the suction in the bentonite is higher than the effective (horizontal) stress. This leads to a critical suction of $pF = 1.875$ corresponding to a coefficient of static earth pressure $K_o = 0.5$.

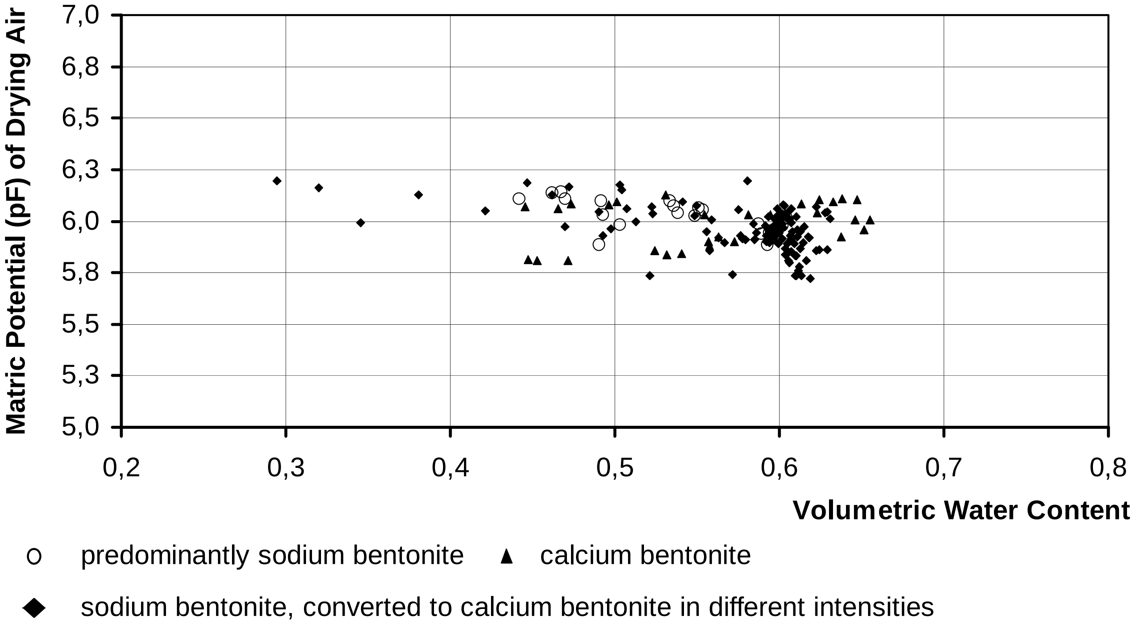

Figure 3: Matric potential of the drying air versus volumetric water content of the bentonite

Figure 4 shows a dehydration diagram of a common calcium GCL as reported in Mühfriedel (2001). All values of volumetric water content are related to the initial wet volume of the GCL. Thus, effects of compression and shrinking are neglected. The graph can be converted into the gravimetric water content by using the equation (3), knowing the void ratio and the dry density of the bentonite respectively. The values of the GCL tested are given in the small table of the diagram.

$$w_{mass} = w_{vol} \cdot \frac{\rho_{water}}{\rho_d} \qquad (3)$$

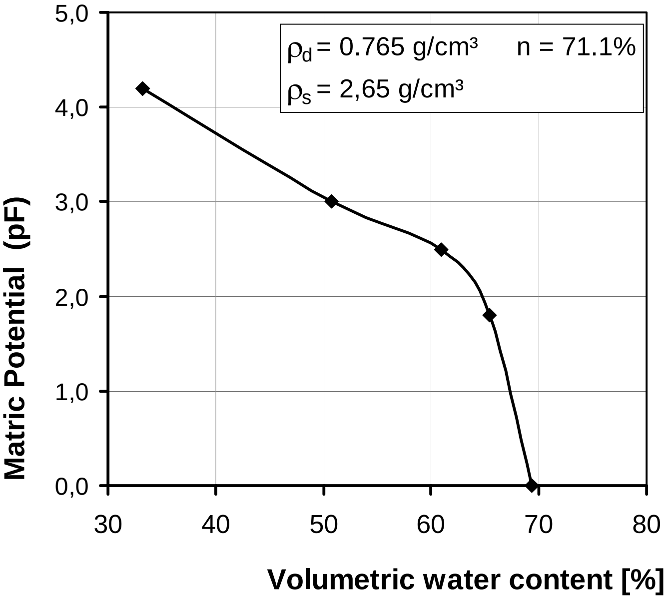

Figure 4: Typical dehydration diagram of a calcium GCL

In consideration of shrinking effects the critical matric potential mentioned above leads to a gravimetric water content of $w \approx 85$ %. A further drying, i.e. a smaller water content, would produce cracks in this GCL. But a higher confining stress would also allow a higher limit of water tension, and thus a stronger drying. So, these theoretical considerations are in accordance with the limits established during the tests.

One of the tests' aims was the investigation of the capability of self-healing after an extremely long period of drying. Therefore, the tests were carried out up to the desiccation of the specimen, which can be noticed by a net of open cracks. Figure 5 shows characteristic results of a test with a calcium GCL and deionized water as permeant. The development of the relative permittivity is

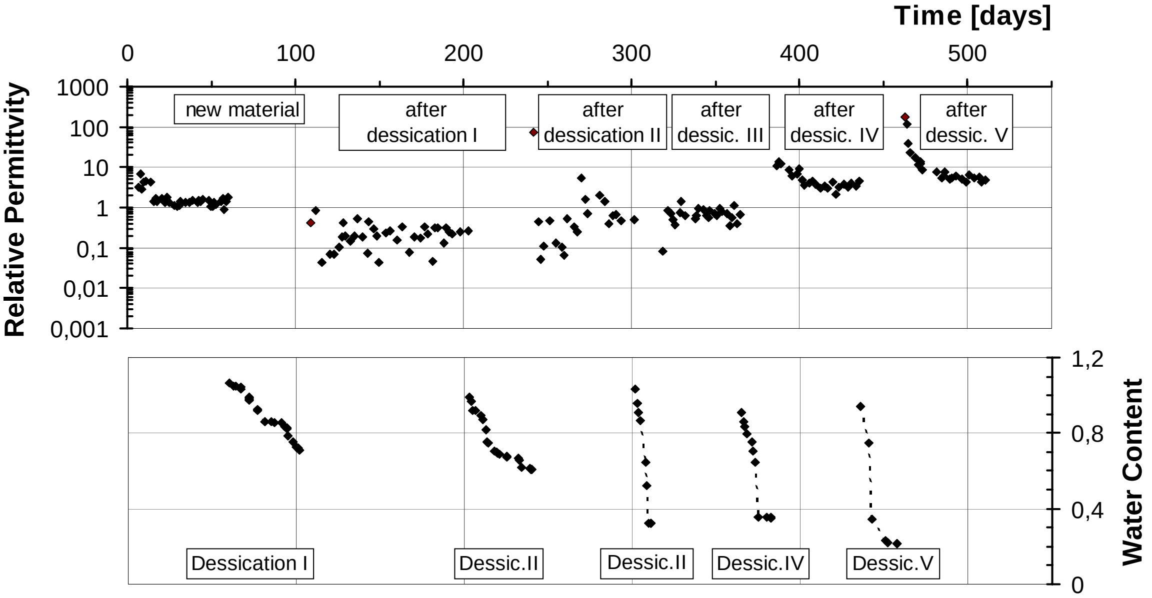

Figure 5:Typical course of a drying-rewetting test. Relative permittivity (upper graphs) and gravimetricwater content (lower graphs) versus time

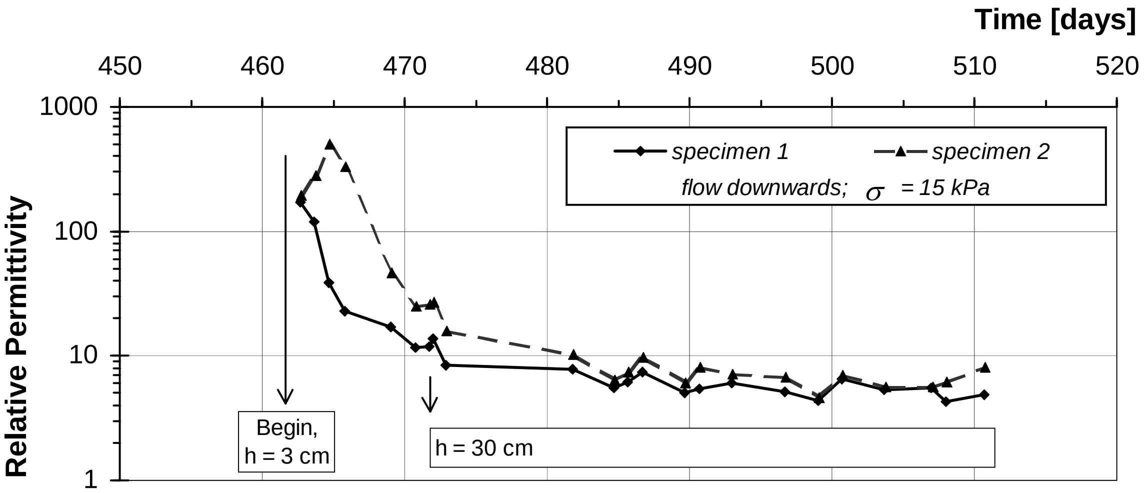

Figure 6: Development of the relative permittivity after a 5th cycle of drying

shown in the upper curves. Reference permittivity is the manufacturer's specification. The decrease in the water content of the bentonite during five drying cycles is represented in the lower graphs. When the desiccated GCL were rehydrated, water initially seeped rapidly through the open cracks. Thus, we have preferred flow conditions at the beginning far beyond the laws of Darcy or van Genuchten. But at all specimen tested, the bentonite swelled and expanded such that the hydraulic conductivity decreased as soon as the bentonite began to adsorb water. The long-term residual permittivity after drying was almost the same as before the desiccation. Only a slight tendency towards an increase in permittivity could be observed at the tests with calcium bentonite. This might have been caused by a decreasing ability of self-healing due to washing out bentonite at the beginning of seeping through the open cracks. At tests with sodium bentonite, the tendency towards an increase in permittivity was the same, but it is superimposed by effects of the ion exchange, especially if using solutions of calcium chloride as permeant.

Figure 6 shows a detail of the development of permittivity after the 5th circle of drying. As the most important result, it has to be referred to the fact, that the restoration of the initial sealing capacity takes a period of about 10 to 15 days. This effect of self-healing was established both, with sodium and at calcium GCL.

4. CONCLUSIONS

Depending on the composition of the capping, there is the danger that a mineral sealing, especially a GCL, dries out until damage. Unsaturated conditions will reduce the hydraulic conductivity according to the law of van Genuchten (1980). But if micro-cracking occurs in the GCL, a very strong increase of permeability will happen suddenly due to preferential flow through the cracks. Such an effect of desiccation can arise by an insufficient thickness of the cover in relation to the climatic impacts or due to bioturbation (roots). The limit state conditions can be calculated by using the common rules of soil physics, such as dehydration diagrams, and considerations concerning the tensile stress. The seasonal change of humidity can also be calculated by using complex programmes for simulating the balance of water as shown in Zeh and Witt (2001). However, we need a characteristic limit of usability for the GCL that is to be determined by experimental investigations.

The laboratory tests described above make it possible to illustrate the change of the GCL's hydraulic conductivity under various static and climatic impacts, and to investigate the self-healing capacity of such liners depending on the confining stress. In addition, effects due to unsaturated conditions can be investigated with various liquids. The results exemplarily represented here, show that even after an extreme desiccation - leading to a considerable increase in permeability - a self-healing takes place in case of rewetting. However, this restoration takes some time as shown in the experiments. Since seepage through the covering soils arises only sporadicly, there will occur a preferential flow through the cracks rather than through the matrix of the GCL during the regenerating period. The amount of water retained by the GCL will be very low in comparison to the sealing effect, which one might expect from saturated laboratory tests.

Thus, the limit state conditions of a GCL within a cover lining system should be examined with the tests described above. For GCL used currently, the limit water content was determined as approximately $w \approx 80\%$ (calcium bentonite) and $w \approx 100\%$ (unchanged sodium bentonite) concerning overlying soils with a thickness of at least 1 m. This limit of water content corresponds to a suction of $pF \le 1.825$ in the GCL (corresponding to a matric potential of 75 hPa). The climatic conditions of the location as well as the storage capacity of the overlying soils will influence the annual change of the balance of water within the sealing, and thus its reliability in the course of use. The thicker the overlying soil, the smaller is the probability, that cracks will arise within the GCL. For landfills of a relatively uniform annual percipitation and a heavy superposition (> 2 m) of the barrier, as demanded for example in the standards of Denmark or Austria, there is no danger of desiccation at all, while dry locations with a thin cover in addition (< 1,5 m) should be paid a greater attention. For such cover lining systems we need an examination of the long-term balance of water as well as a design of the soils, used in the superposition in particular. Siegmund et al. (2000) established a case study using laboratory investigations as well as detailed field measurements to evaluate the reliability of a cover lining system. The barrier of that capping is a calcium GCL protected by a thin silty layer to guarantee steady conditions of humidity during the seasonal changes of climatic impacts.

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