Efficiency and Equivalency of Barrier-Systems

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Abstract

Liner systems built up from natural or synthetic materials are widely used in the environmental engineering both at waste disposal facilities, both during remedial activities.

The structure of bottom lining systems and landfill covers are controlled by acts, technical guidelines or standards. The regulations for compacted clay liners describe the required mineral compound, compaction, and hydraulic conductivity. Nowadays new lining materials are introduced (s.a. Geosynthetic clay liner, sand-bentonite mixtures, clayey polymers, sand and potassium silicate mixtures) because of their smaller thickness, more homogeneous quality, and due to that its relative cheapness in comparison to the traditional compacted clay liner systems.

The selection of the technically-economically best solution and the predestination of the applicability of competitive alternatives is considered using the term equivalency.

The paper presents the recently used lining systems in waste disposal, describes the Hungarian regulations on the mentioned field. It gives a detailed explanation of the theory of calculation of barrier equivalency and efficiency by analytical and numerical solutions of the transport equation. To demonstrate the possible fields of applications two studies are performed. The first study compares and evaluates the standard barrier-systems based on the regulations of selected European countries. The second study is the evaluation of the possible use of geosynthetic clay liners(GCL) to substitute the traditional compacted clay liners (CCL).

Introduction

Barriers built upon natural and synthetic materials have widely been used in environmental engineering since the isolation of different pollution sources is one of the most important issues to avoid extensive contamination in environment or to restrict the penetration of hazardous substances into the intact areas.

From regulatory and waste management aspects the easiest way to control the application is to define the standard barrier types to be used for different waste or contaminant species. The recommended standard barrier types, however, may not often be implemented in practice because of technical or financial reasons. In these cases only construction of such barriers is allowed which has the same or even higher efficiency in isolation than that of the prescribed ones. The approval of barrier replacement might be completed by means of contaminant transport equivalency calculations. The paper presented summarises the theoretical aspects of transport equivalency and the methods of calculations thereto.

The Hungarian Regulation of waste disposal

In Hungary, the governmental decree No. 102/1996. controls the problem of barriers for waste disposal. The principle of that regulation is that the wastes are divided into three main groups: municipal wastes, and first and second class hazardous wastes.

The required technical barrier depends on thickness and hydraulic conductivity of the subsoil and on the quality of the waste is to be deposited.

Requirements for the subsoil of the landfill

The subsoil of the landfill and its immediate environment play a major role in the site selection process. Requirements regarding the subsoil quality are ordained only by the hazardous waste decree:

- the suitability of the territory has to be proved by geological investigation
- the thickness of the high adsorbing capacity subsoil must be at least 3.0 meters. In case of the bedding subsoil the clay mineral content must be at least 10%.
- if there is no natural mineral subsoil barrier having the above-mentioned quality, then an equivalent, built layer from mineral material is suitable. The condition of equivalence is that the contaminant concentration of the leachate, seeping through the built lining layer must not be higher than in case of the necessary 3.0-meter thick natural lining layer for a 30 year period.
- the hydraulic conductivity for water of the natural or built lining layer must be determined by laboratory and field measurements, the required value of it for hazardous wastes is $k \leq 5 \cdot 10^{-8}$ m/s.

While, in case of municipal landfills there is no specified regulation of legal force regarding the quality of the subsoil, when the above mentioned tenders are judged, the setting up of the lining system is determined as the function of the hydraulic conductivity of the subsoil. Unfortunately, it does not correspond to the European practice. Unquestionably, the Environmental Impact Assessment, which is a mandatory element of the licensing process, can guarantee certain level of safety.

The drafting of subsoil requirements of hazardous waste landfill construction is a remarkable progress. In contradiction to the previous regulations the principle of liner equivalency has been composed which of course must be considered not just in case of subsoil substitution, but also when any mineral liner is substituted by other (e.g., GCL, layers improved by waterglass or bentonite, etc.) liners. According to the decree, the condition of equivalency is that the contaminant concentration of the leachate, seeping through the substituting liner must not be higher than that of the subsoil layer or natural lining layer with the ordained thickness in a 30 year period. This definition corresponds to the theoretical criteria of equivalency, namely that two lining layers are equivalent if their cumulative transport characteristics are the same in case of the same conditions of application [10].

The decree requires minimum 3.0 meters thick subsoil with high adsorption capacity. The high adsorption capacity can guarantee the high contaminant retention capacity. Its determination is the following:

- Quantitative and qualitative analysis of the clay mineral content. It is especially favorable when the subsoil contains TOTA$_i$C-type minerals (especially montmorillonite), which belong to the smectite group.

- Determination of Cation Exchange Capacity. According to international opinion [15], it is very favorable when the value of Cation Exchange Capacity exceeds 25meq/100g and favorable when its value is between 15-25meq/100g.

The regulation of the liner system structure

The structure of the liner system on an area which is qualified as capable for waste disposal must be determined by an integrated consideration of the natural capabilities of the subsoil and the hazard potential of the disposable waste. The site which is selected as a result of a site screening process must be categorized into subsoil categories based on their thickness and permeability (Table 1.)

Table 1.
Subsoil categories of landfill

Thickness of Subsoil	**Hydraulic conductivity of subsoil (m/s)**		
	$k > 10^{-6}$	**$10^{-6} > k > 5 \times 10^{-8}$**	**$k < 5 \times 10^{-8}$**
1,5-3,0	S1	S2	S3a
> 3,0	S1	S2	S3b

S1,S2, symbol of categories

The hazard potential of the disposable waste can be determined:

- without any previous examination based on the effective decree. The Hungarian decree of hazardous waste management assigns I-III. hazardous categories and gives the list of type of wastes belonging to each of these categories.
- according to a classification of wastes into eluate categories based on analytical and ecotoxical test of wastes or extracts (eluates).

The proposed decree distinguishes three eluate categories similarly to the Austrian regulations. The required level of protection – it means the minimal requirements for the structure of the lining system for each landfill construction categories – must be determined upon the category of subsoil and hazard degree of the waste, i.e. the eluate category. The selection of landfill construction categories is shown in Table 2. Regulation for the structure of the barrier system on the bottom and the sidewalls are shown in Figure 2. Construction category No. 1. cannot be seen in the figure because there are no rules for the lining system, as this category of "wastes" having practically potable water quality leachate.

Municipal wastes can be disposed in landfills with the lining system of construction category No. 4., it means a combined barrier system consisting of 3x20cm compacted soil layer (k<10-9m/s), a minimum 2 mm thick geomembrane and a leachate collection system.

The disposal of III. degree hazardous waste is allowed in the landfill with a protection of construction category No. 4. Disposal and operation must be separated from that of other municipal wastes. The method of separation is determined in each case by the environmental authorities.

Table 2.
Construction categories of landfill depending
on the subsoil categories and leachate and waste quality

Subsoil Categories	Construction category of landfill				
	C1	C2	C3	C4	C5
S1	E1	E2	E2	E3	E3
S2	E1	E2	E2	E3; M	E3
S3a	E1	E2	E3	E3; M	E4; M3
S3b	E1	E3	E3	E3; M; H3	E4; H3; H2; H1

E1-E4, eluate category; M, municipal waste; H1-H3, hazardous waste categories I-III. according to the Hungarian decree; S1-S2, subsoil categories in accordance with Table 1.

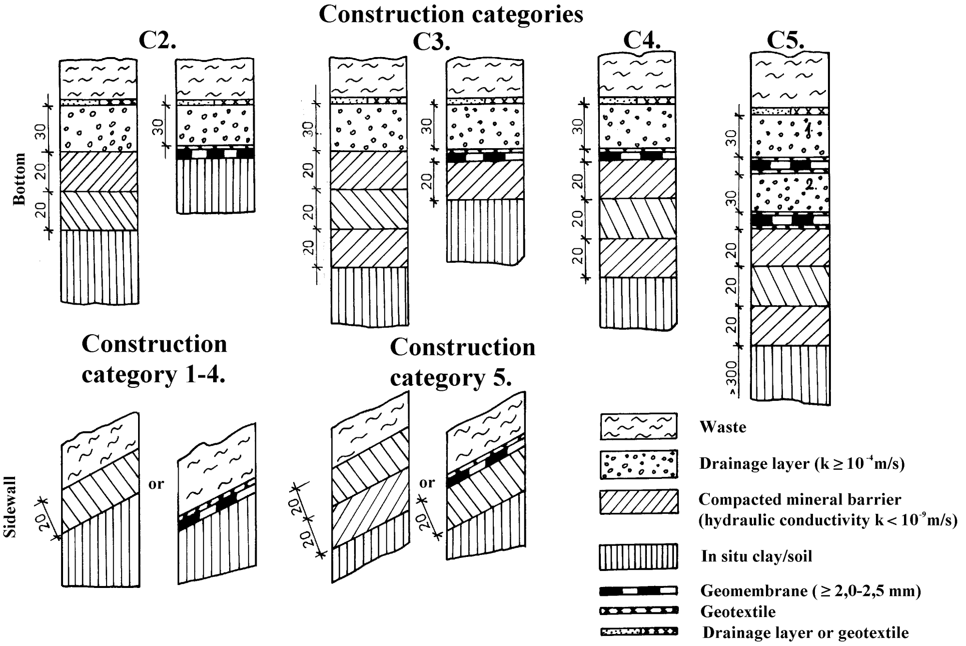


Fig. 1. The Hungarian regulation (C5.) and recommendations (C1.-C4.) for bottom lining systems of landfills

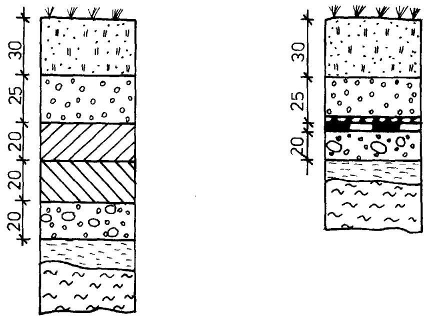
Regulations require the use of construction category No. 5. of Figure 1., when I. and II. degree hazardous wastes are disposed. The decree orders the use of double geomembrane with 3x20cm thick clay mineral liners. The drainage under the top geomembrane has a monitoring function as well.

The use of eluate categories is not widely used yet, thus the construction category is usually determined by the subsoil characteristics and the type of the disposable waste (municipal or hazardous).

Regulation of landfill capping

The regulation of final surface cover of both municipal and hazardous wastes is similar to that of the international standards. Its structure is demonstrated on Figure 2.

Construction category 1-4.



Construction category 5.

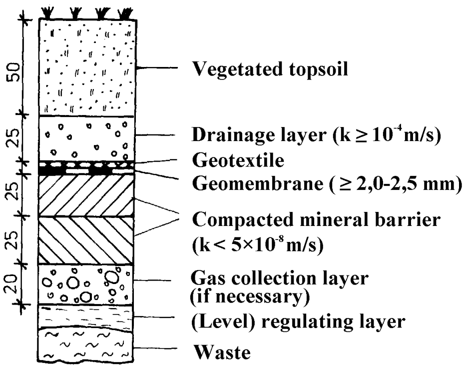


Fig. 2.The Hungarian regulation (C5.) and recommendation (C1.-C4.)
for cover systems of landfills

Theoretical Considerations (The migration of Contaminants in Porous Media)

The migration of contaminants consists of four different processes: advection (convection), dispersion, adsorption and degradation (Fig. 3). The advection is the transport process due to the seepage of the groundwater. The dispersion means the spreading of contaminants caused by local concentration inhomogenity or seepage velocity. On one hand, the diffusion (contaminant transport due to concentration gradient) results in a spreading. On the other hand, there are some hydrodynamic reasons of this phenomena as well. Both the variation of the pathlines of the transport, the changes of pore diameter and the difference of seepage velocities within the pore; and the large scale inhomogenity of rock bodies lead to the dispersion of contaminants. However, the three different processes (diffusion, hydrodynamic dispersion and macrodispersion) listed above result in similar effects and that is the reason why they constitute jointly the dispersive transport.

Since the linear adsorption and desorption of contaminant are mostly independent processes, the term of retardation containing both factors is taken into account during the calculations. However, the sorption process is usually non-linear, therefore the non-linear adsorption isotherms (Freundlich or Langmuir) have to be used to characterize the sorption side process.

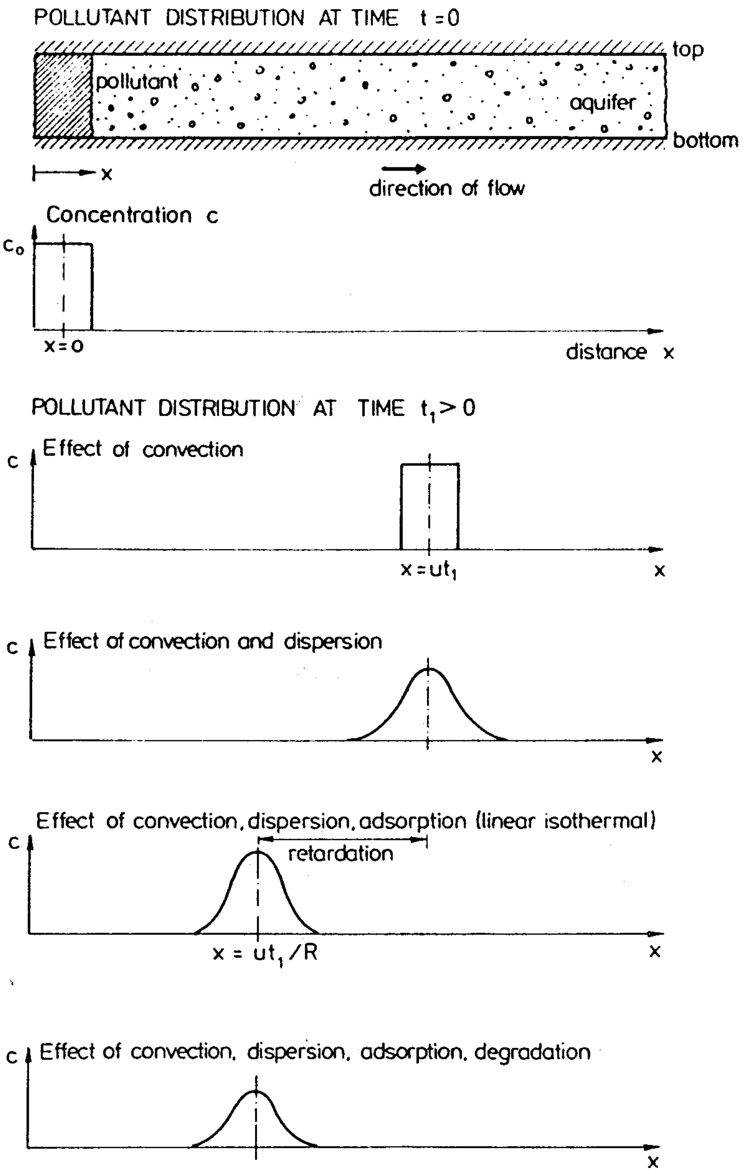


Fig. 3. Schematic of elements of contaminant transport in porous medium [8]

In case of special contaminants, the effect of radioactive decay or biodegradation might be significant [8]. Consequently, their flux has also significant impact on the net process and neglecting those simultaneous phenomena can deteriorate the reliability of the calculations.

The effects of all listed phenomena result in changes of contaminant concentration both in time and space, and it can be mathematically written in the following form, called general as a transport-equation:

$$
\begin{aligned}
&R\frac{\partial c}{\partial t}= \\
&= D_{xx}\frac{\partial^2 c}{\partial x^2}+D_{xy}\frac{\partial^2 c}{\partial x \partial y}+D_{xz}\frac{\partial^2 c}{\partial x \partial z}+D_{yx}\frac{\partial^2 c}{\partial y \partial x}+D_{yy}\frac{\partial^2 c}{\partial y^2}+D_{yz}\frac{\partial^2 c}{\partial y \partial z}+ \\
&+D_{zx}\frac{\partial^2 c}{\partial z \partial x}+D_{zy}\frac{\partial^2 c}{\partial z \partial y}+D_{zz}\frac{\partial^2 c}{\partial z^2}-\frac{\partial}{\partial x}\left(\frac{v_x c}{n}\right)-\frac{\partial}{\partial y}\left(\frac{v_y c}{n}\right)-\frac{\partial}{\partial z}\left(\frac{v_z c}{n}\right)-\lambda Rc
\end{aligned}
\tag{1}
$$

where c is the concentration, D_{ij} are the elements of the dispersion matrix, v is the pore velocity of seepage, n is the porosity, λ is the degradation coefficient, R is the rate of retardation, and x, y and z are the axes of the local (Descartes) coordinate system, respectively [1].

Since our task was to determine the possible concentrations on the safe side of the barrier, the main goal was to solve either analytically or numerically this transport equation. Taking the fact into account that the v seepage velocity is a parameter of the transport equation, first the determination of piezometric head distribution was needed to calculate the seepage velocity field using the Darcy-law.

Types of Barrier Equivalency

We call „A” and „B” barrier systems equivalent if the concentrations at the protected side in time are equal presuming that the hydraulic and the concentration gradients are the same. This means that the „B” being an alternative barrier-system might only be used if the calculated concentrations on the protected side are less than the appropriate values using the „A” standard (recommended) barrier-system [17].

Although this description is quite easy and clear, we may face a lot of practical and theoretical problems determining the equivalency. Understanding the problems it is expedient to discuss the types of equivalency.

The Advective Equivalency (Hydraulic Equivalency)

Two barriers are advectively equivalent if the concentrations on the protected side - due to equal hydraulic and concentration gradient - are equal taking only the advective transport process into consideration. Since the advective term of the transport equation is given as the seepage velocity multiplied by the concentration in the pore volume, the advective equivalency means the hydraulic equivalency as well.

Some calculations on hydraulic equivalency of different barriers are listed in Table 3. It was proved that about 1.5 cm thick GCL (geosynthetic clay liner) is advectively equivalent to 60 cm compacted clay liner, and 7.5 cm thick, multilayered GCL is needed to assure the same hydraulic equivalency with a geomembrane covered by 3x20 cm compacted clay liner. Practically, it might be said that an average GCL of about 1 cm thickness is advectively equivalent only to 2x20 cm compacted clay liner.

To calculate the hydraulic equivalency the following formula should be used:

$$
\frac{\sum_{i=1}^{n} M_i}{\sum_{i=1}^{n} \frac{M_i}{k_i}} = \frac{\sum_{j=1}^{m} M_j}{\sum_{j=1}^{m} \frac{M_j}{k_j}}
\tag{2}
$$

where n and m are the number of layers in the standard and the alternative barrier-system, M_i and M_j are the thicknesses of the layers and k_i and k_j are the hydraulic conductivity values, respectively.

The Diffusive Equivalency

Two barrier-systems are diffusively equivalent if the concentrations due to diffusion mass transport at identical concentration gradient are equal on the protected side of the barrier. To investigate the diffusive equivalency let us see the analytical solution of the Fick's first law. In a homogeneous medium the change of concentration in time and space is given by:

$$c_i(x,t) = c_{0i} \operatorname{erfc} \frac{x}{2\sqrt{D_i t}} \tag{3}$$

where c_{0i} is the constant concentration of the i contaminant at the polluted side of the barrier, D_i is the effective diffusion coefficient of the pollutant in the medium, and c_i is the concentration at x distance in time t.

Table 3.
The hydraulic equivalency of different barrier-forming materials

Barrier-material	**Average hydraulic conductivity [m/s]**	**Thick-ness [cm]**	**Case A [m]**	**Case B [m]**	**Case C [m]**
Compacted clay liner	1,00E-09	60	0,6	3,1	93
Mixture of sand and 3% bentonite*	5,00E-07	(60)	300	1550	46500
Mixture of sand and 5% bentonite*	1,00E-07	(60)	60	310	9300
Mixture of sand and 10% bentonite*	1,00E-09	(60)	0,6	3,1	93
Mixture of sand and 15% bentonite*	8,00E-11	(60)	0,048	0,248	7,44
Geomembrane	8,00E-13	0,2	0,00048	0,00248	0,0744
Geomembrane with 5 mm diameter hole**	4,70E-12	0,2	0,00282	0,01457	0,4371
Geomembrane with 1 cm diameter hole**	9,50E-12	0,2	0,0057	0,02945	0,8835
Geomembrane with 2 cm diameter hole**	1,90E-11	0,2	0,0114	0,0589	1,767
GCL (Geosynthetic clay liner)	2,50E-11	1	0,015	0,0775	2,325
Hydraulic asphalt liner	3,00E-11	5	0,018	0,093	2,79

Case A: Equivalent thickness [m] with 60 cm thick, $k=10^{-9}$ m/s compacted clay liner
Case B: Equivalent thickness [m] with 60 cm thick, $k=10^{-9}$ m/s compacted clay liner covered by 2 mm HDPE geomembrane
Case C: Equivalent thickness [m] with 60 cm thick, $k=10^{-9}$ m/s compacted clay liner covered by 2x2 mm HDPE geomembrane with drainage layer between
* Average hydraulic conductivity determined by using the experiments of Chapuis [2]
** Average hydraulic conductivity calculated by using spherical flow field [15]

If „A” and „B” barriers are diffusively equivalent, then the c_i concentrations due to equal c_{i0} concentrations at the same x distance in time t are equal to

$$\frac{x_A}{\sqrt{D_A}} = \frac{x_B}{\sqrt{D_B}} \tag{4}$$

It means that „B” liner is diffusively equivalent to the „A” barrier of x_A thickness if its thickness is

$$x_B \geq \frac{x_A \sqrt{D_B}}{\sqrt{D_A}} .[9] \tag{5}$$

In Table 4. the results of diffusive equivalency calculations based on data from the literature ([3],[15]) are summarized. Investigating the results of the calculations it seems to be obvious that the efficiency of the HDPE geomembrane and the GCL barriers against diffusive transport processes is much lower than that of the compacted clay liners. Depending on the product the HDPE geomembrane of 2 mm thickness or a GCL of 10 mm thickness is equivalent to 5-10 cm compacted clay liner regarding only the diffusive transport.

Table 4.
Diffusive equivalency of geomebrane and compacted clay liners

Pollutant	**Effective diffusion coefficient [x10^{-10} m^2/s]**	**Effective diffusion coefficient [x10^{-12} m^2/s]**	**Equivalent thickness of compacted clay with HDPE geomembrane of 2 mm thickness [cm]**	**Equivalent thickness of HDPE geomembrane with comp. clay liner of 60 cm thickness [mm]**
	Comp. clay liner	**Geo-membrane**		
Methanol	4.8	0.8	4.9	0.00167
Acetone	3.4	0.6	4.8	0.00187
Ethyl-methyl ketone	3	0.55	4.7	0.00202
Acetic acid-ethylester	2.8	0.15	8.6	0.00017
Formaldehyde-solution	5.9	0.8	5.4	0.00110
Chloroform	3.1	0.25	7.0	0.00039
Carbon tetrachloride	2.9	0.25	6.8	0.00045
Trichloro ethylene	2.9	0.25	6.8	0.00045
1,2-Dichloroethane	3	0.25	6.9	0.00042
Tetrachloro ethylene	2.5	0.25	6.3	0.00060
Chlorobenzene	2.7	0.25	6.6	0.00051
Benzene	3	0.2	7.7	0.00027
Ethylbenzene	2.3	0.2	6.8	0.00045
Xylene	2.4	0.2	6.9	0.00042
Toloene	2.7	0.2	7.3	0.00033
Pentane	2.7	0.2	7.3	0.00033
Hexane	2.4	0.2	6.9	0.00042
Heptane	2.2	0.2	6.6	0.00050

Advective-Dispersive Equivalency

The above mentioned calculations of equivalency took only one transport phenomenon into consideration, namely, the advection or the diffusion. For investigation of more complex transport procedure *Shackelford* [16] proposed a solution. Shackelford derived the 1D transport equation’s analytical solution [14] in the following form:

$$\frac{c}{c_0} = \frac{1}{2}\left[\operatorname{erfc}(z_1) + \exp(z_2)\cdot \operatorname{erfc}(z_3)\right] \tag{6}$$

where c is the concentration of the solution on the polluted side of the barrier, $\operatorname{erf}(z) = \frac{1}{\sqrt{\pi}}\int_0^z \exp(-\xi^2)d\xi$, $\operatorname{erfc}(z) = 1 - \operatorname{erf}(z)$ is the standard error function and its complementer function, $z_1 = \frac{x - v_s t}{2\sqrt{D^* \cdot t}}$, $z_2 = \frac{x \cdot v_s}{D^*}$ and $z_3 = \frac{x + v_s t}{2\sqrt{D^* \cdot t}}$, where x is the distance from the surface of the barrier.

Using this method the average transit time of a pollutant in a given barrier media was calculated considering a uniform flow field during a predefined pathline. (If a given concentration of the pollutant on the protected side of the barrier at a given time is allowed, we can calculate the average pathlength in the uniform flow field, which is equal to the required minimal L thickness of the barrier.). Introducing the dimensionless T_R and P_L parameters we may obtain:

$$T_R = \frac{v_s \cdot t}{R_d \cdot x} = \frac{v_R \cdot t}{x},\ P_L = \frac{v_s \cdot x}{D^*} = \frac{v_s \cdot L}{D^*} \quad , \tag{7}$$

then
$$z_1 = \frac{1 - T_R}{2\sqrt{T_R / P_L}},\ z_2 = \frac{1 + T_R}{2\sqrt{T_R / P_L}}\ z_2 = P_L, \tag{8}$$

Rewriting the analytical solution (Eq.6) using the dimensionless parameters (Eq. 7., Fig. 4.) the following expression is obtained:

$$\frac{c}{c_0} = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{1 - T_R}{2\sqrt{T_R / P_L}}\right) + \exp(P_L)\cdot \operatorname{erfc}\left(\frac{1 + T_R}{2\sqrt{T_R / P_L}}\right)\right]. \tag{9}$$

Thus, the calculation consists of the following steps:

- Determination of the constants of the calculation (I: hydraulic gradient, k: hydraulic conductivity, n: porosity, c: allowable concentration at the protected side of the barrier at time t, c_0: concentration at the polluted side of the barrier, D*: effective dispersion coefficient of the pollutant in the investigated barrier, R_d: retardation coefficient),
- Determination of the seepage velocity in the pore volume: $v_s = \frac{k \cdot I}{n}$,
- Estimation of an L (required barrier-thickness) which assures that the c concentration on the protected site is lower at time t then the recommended limiting value,

- Determination the $P_L = \frac{v_s \cdot L}{D^*}$ value,
- Determination of c/c_0 value and from Fig. 4. we determine the T_R value using the previously calculated c/c_0 and P_L values,
- The average transport time of the pollutant can be calculated using $t_1 = \frac{T_R \cdot R_d \cdot L}{v_s}$.
- If $t_1 > t$ then the barrier of L thickness is efficient, if not the calculation must be repeated using higher L value.

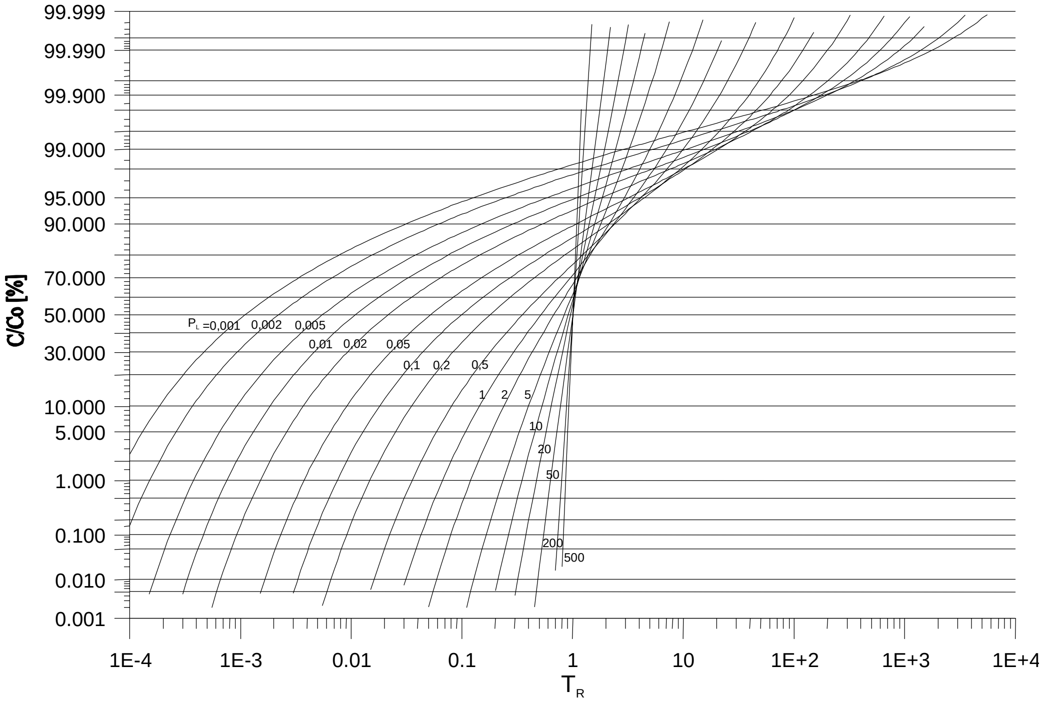


Fig. 4.: The relationship of dimensionless parameters and the relative concentration [16]

The Complex (Numerical) Equivalency

The presented equivalency calculations, however, have several limitations. The most crucial problems are as follows:

- Not all, but only some of the transport processes are considered;
- The barrier-forming material must be homogeneous (only one layer);
- Linear and monolayer adsorption is supposed (Henry-isotherm, Langmuir-isotherm) or no adsorption allowed at all;
- Constant concentration at the polluted side of the barrier required;
- Hydraulic gradient, hydraulic conductivity, porosity, effective diffusion or dispersion coefficient for the pollutant in the investigated barrier medium must be constant both in space and time.

For practical calculations these simplifications are too strict, so a new calculation method using the numerical solution of the transport-equation had to be introduced. Using the implicit finite difference method with the Peclet and Courant stability criteria all the above mentioned problems could be eliminated. The barrier is handled as a column of elements, where each element is characterized with its own thickness, hydraulic and transport properties. The mass equilibria of the pollutant due to any transport process is taken into consideration which is represented in the 1D transport-equation.

Using the FD method the effluent concentration vs. time function is calculated for any layer in the barrier-system irrespectively to the varying influent concentration. As a first step, the average seepage velocity in the barrier system is to be calculated. Then, the transport properties of the medium should be determined. As a precondition, the initial concentration distribution in the barrier system, as boundary condition the constant or varying concentration at the polluted side of the barrier is used. The calculation is performed layer by layer, starting with the top layer of the barrier. The concentration vs. time relationship at the bottom of the layer was calculated using the initial and boundary conditions. This concentration distribution in time is the input for the second layer, etc..

For the complete numerical calculation of the equivalency the mentioned procedure must be run two times. At the first time, the calculations should be run using the data of the standard barrier system, and the second time applying the investigated alternative barrier system. The equivalency is proven if the concentration at the protected side of the alternative barrier system is lower than in case of the standard barrier system at the same time interval.

Calculation Methodology of the Complex Equivalency

Since incompatibility problems may arise between different leachates and barrier-forming media (particularly in case of compacted clays, GCL, geomembranes, geotextiles, etc.) it is highly recommended to perform the numerical equivalency calculations simultaneously for different contaminants. There are six groups of contaminants with rather different behaviour for the different barrier elements, which are the following:

- Cations of alkali metals and alkali-earth metals (Na, K, Mg, Ca)
- Anions of halogenides (Cl, Br, I)
- Toxic metals and heavy metals (Sr, Cd, Cu, Ni, Zn, Pb, Fe)
- Chlorinated hydrocarbons (mono and dichloro benzene, carbon tetrachloride, etc.)
- Alcohols and their derivatives (alocohols, aldehydes, ketones)
- Aromatic organic compounds (benzene, xylene, toluene, etc.)

For each group it is recommended to make the calculation using the data of the most hazardous component. The environmental hazard might be estimated using the c/c_0 value (allowed concentration at the protected side/maximal concentration on the polluted side).

The equivalency calculation of any contaminant groups can be omitted if the occurrence of that leachate components is irrelevant. If the leachate composition in the planning phase is not known, a chemical analysis of leachates at similar pollution sources is advised. The general (representative) transport properties of the different contaminant groups for some barrier elements are listed in Table 5.

Using the numerical calculations, the equivalency of standard and alternative barrier systems or their elements can be determined at much higher safety level, because the prescription made only by the hydraulic equivalency does not assures the equivalency if other transport processes are also taking place.

Table 5.
Representative hydraulic and transport-parameters
for calculations of the numerical equivalency

Property	Representative value			
	HDPE geo-membrane	Compacted clay liner	Substratum[1]	Drainage layer[2]
hydraulic conductivity [m/s]	10^{-13}	10^{-9}	10^{-8}	10^{-4}
Effective diffusion coefficient [m^2/s]				in saturated conditions
1.group	$2\cdot10^{-16}$	10^{-10}	10^{-10}	$5\cdot10^{-9}$
2.group	$3\cdot10^{-16}$	$5\cdot10^{-10}$	$5\cdot10^{-10}$	$7\cdot10^{-9}$
3.group	10^{-16}	$3\cdot10^{-11}$	$3\cdot10^{-11}$	$5\cdot10^{-10}$
4.group	$2\cdot10^{-13}$	$3\cdot10^{-10}$	$3\cdot10^{-10}$	$6\cdot10^{-10}$
5.group	$6\cdot10^{-13}$	$2\cdot10^{-10}$	$2\cdot10^{-10}$	10^{-9}
6.group	$2\cdot10^{-13}$	$3\cdot10^{-10}$	$3\cdot10^{-10}$	$6\cdot10^{-10}$
Dispersivity [m] (layer thickness[m])	0,0001 (0,002)	0,01(0,2) 0,025(0,6)	0,08 (3)	thickness dependent[3]
„A” parameter of the Langmuir isotherm [mg/kg]	T=0,001 meq/100g[4]	T=10 meq/100g[4]	T=5 meq/100g[4]	T=2 meq/100g[4]
„K” parameter of the Langmuir isotherm [m^3/g]	0,1	0,03	0,1	0,01
λ decay factor [1/s]	0	0	0	0
n porosity [-]	0.000001	.5	0.45	0.33
n_0 eff. porosity [-]	0.000001	0.02	0.04	0.33

[1] only at barriers for hazardous waste deposits

[2] only at drainage layers between isolation layers

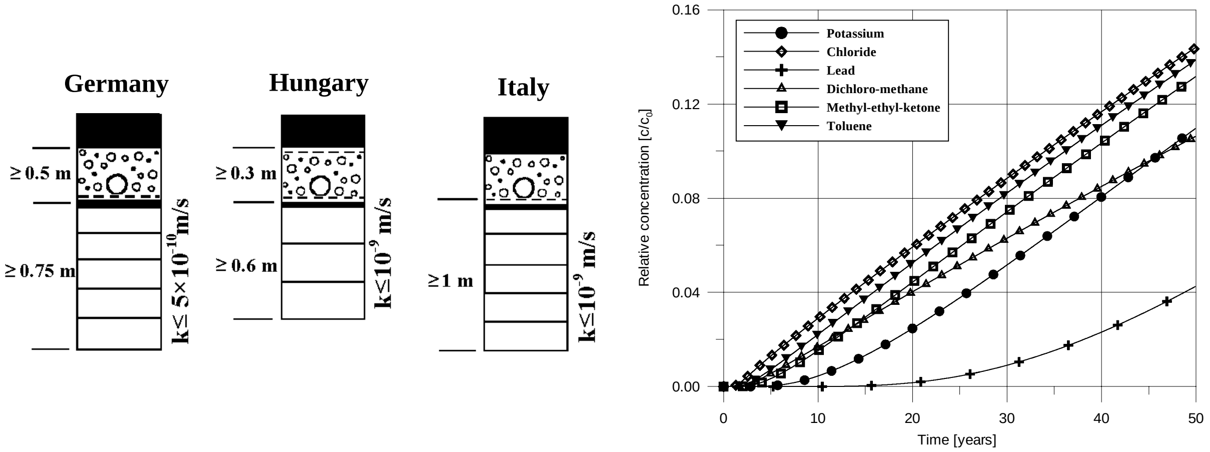
[3] dispersivity might be determined depending on layer thickness using data from the literature

[4] The parameter in case of contaminant groups 1.-2.-3. might be calculated from CEC (T[meq/100g]) values. A[mg/kg]=M*10*T[meq/100 g], where A is the parameter of the Langmuir isotherm, M is the relative atomic weight. In case of group 4., 5. and 6. the values are to be determined during laboratory measurements

Application of general equivalency calculations

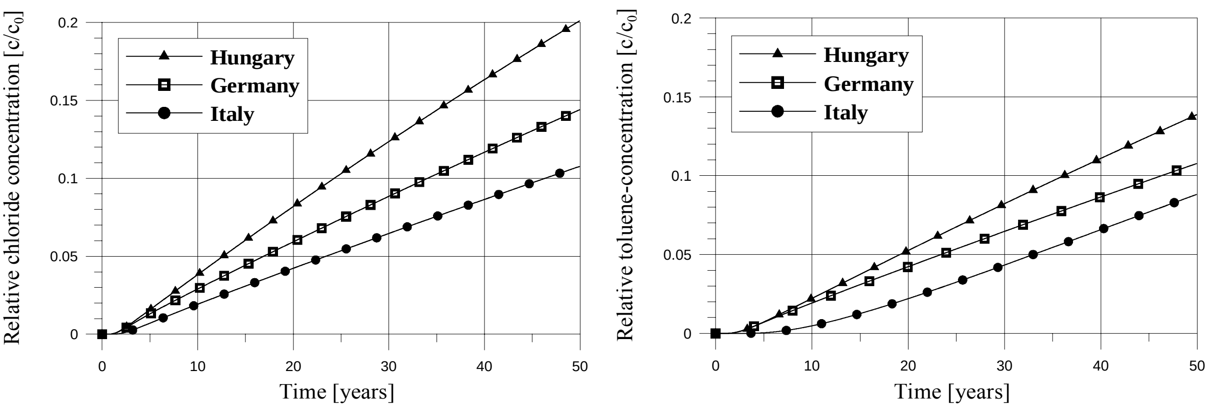
Comparison of bottom liner system standards

To demonstrate the complex equivalency calculations let us investigate and compare the standard bottom lining systems for municipal wastes of some European countries (Fig.5a). The standard lining system is described in the relevant literature [17]. Considering six different types of pollutant rather big difference in break-through curves may occur (Fig. 5b.). Calculating the concentrations on the protected side of the barrier for two different kinds of pollutant (toluene, chloride) using the same material properties for geomembrane, drainage and clayey layers a small difference seems to occur (Fig. 5c and d). It might be concluded that the three standards are nearly equivalent, the Hungarian one is slightly less effective. It must be declared that equivalency or barrier efficiency is always pollutant/leachate and lining material specific, that is why the equivalency in general case is indefinable.



a, The considered standard bottom lining system in different countries of municipal waste deposits

b, Breakthrough curves of pollutants considering the Hungarian standards



c, Efficiency of the barriers against chloride

d, Efficiency of the barriers against toluene

Fig. 5. Comparison of efficiency of standard barrier-systems

Evaluation of the GCL vs. CCL barrier-efficiency using equivalency calculations

Geosynthetic Clay Liners (GCL) appeared at the end of the 80's and since then they have increased the role among mineral liner systems. The related commerce in North America has multiplied itself more than 10 times in the last ten years [11]. Several of their beneficial characteristics result in a wide scale of applicability in road-, and railway construction, hydraulic engineering, and in the field of environmental protection.

Their application in landfill lining systems as substitute of the multiple layered clay lining is usually not adhered by the Hungarian regulative bodies. In case of one landfill (Tatabánya) it was used though, but only as the mineral liners of the landfill sidewalls. The experimental results of geosynthetic clay liners are usually very favorable. ([4], [5], [14]), however, when using as landfill base liners we must be careful, because:

- the conditions of laboratory measurements are different from the real on site conditions

- its thickness is significantly smaller than that of the compacted clay liners' (60-150cm or 5-10mm) which can cause a remarkable different in the liners contaminant retention capacity.

The following shows an example of the above mentioned concerns.

The hydraulic conductivity of GCL-s is usually measured in triaxial cells [5], but the use of other instruments, such as compression permeability device or oedometer [6] is also known, one of the latter one is the Rowe's oedometer. The hydraulic conductivity of GCL-s is largely influenced by the hydration of its bentonite content.

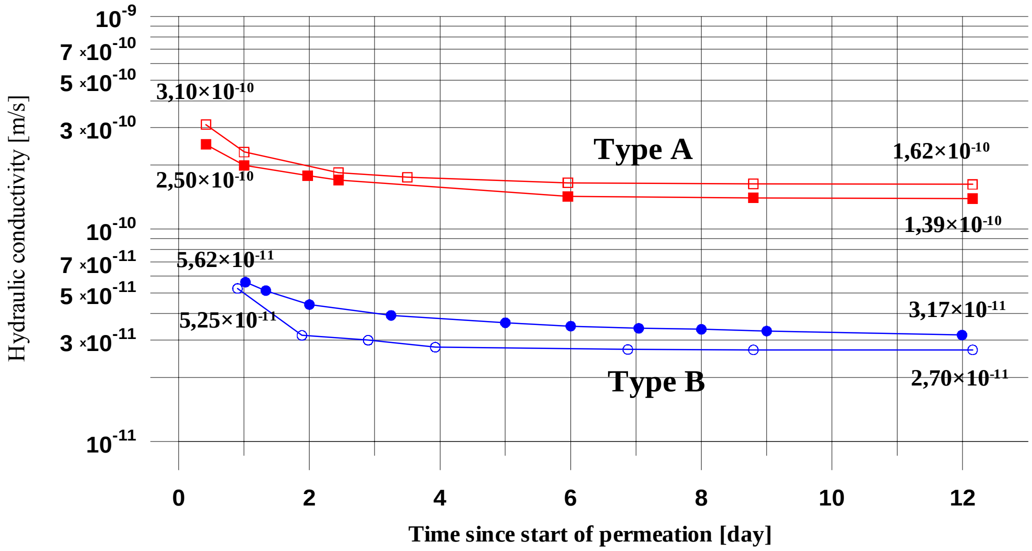


Fig. 6.: Hydraulic conductivity vs. time for two different types of GCL

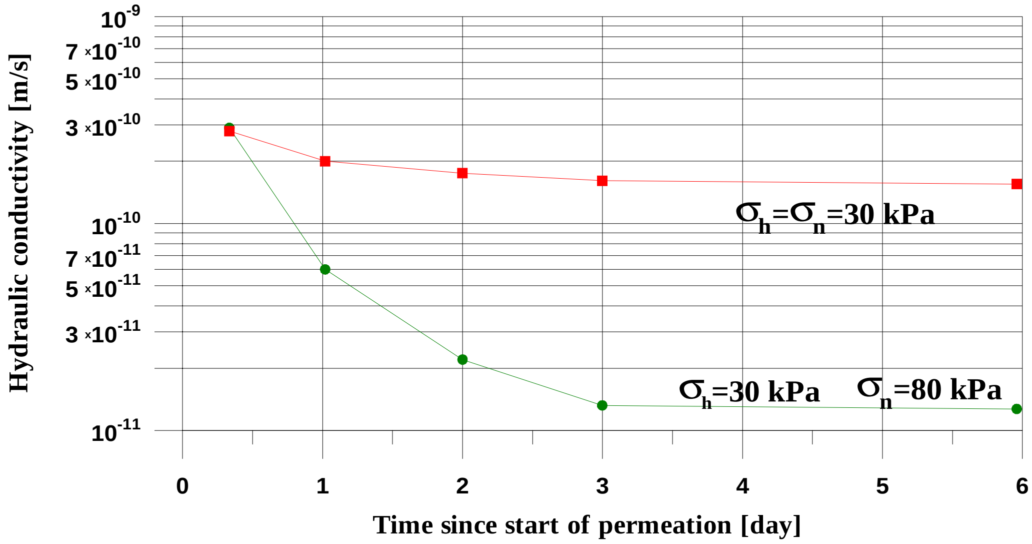


Fig.7.: Effect of normal load on the hydraulic conductivity of GCL type A

In real conditions it common that the GCL is exposed to rainfall or its hydration occurs before the waste load would be placed above it. Figure 6 shows the different behavior of two saturated GCL-s (A and B) in a triaxial cell with 30kPa cell pressure. (Type A and B are both European commercial GCL-s available in Hungary, so their brand name is intentionally not mentioned.) The hydraulic conductivity of the two bentonite GCL-s measured under same conditions after their saturation, resulted one order of magnitude difference. However, if the saturation of type B in the triaxial cell was conducted at σ_h=30kPa cell pressure and

σ_n=80kPa normal pressure, the measured value of hydraulic conductivity was much favorable, and was smaller with approximately one order of magnitude (Figure 7).

Figure 8 shows the mineralogical content and the water intake (by Enslin) of the materials of the two liners. It is apparent, that the mineral composition of type A is more favorable, with its higher ability to expand, and even in the lack of normal stress the desired density and impermeable structure is achievable. On the contrary, in case of type B the desired impermeability was achieved only, when the expansion was hindered or obstructed while saturation occurred. The different behavior of the two GCL is also obvious on Figure 9. The wetting/drying and freeze/thaw cycle tests of type B also resulted in less favorable data, when the expansion of the sample was not hindered, which is the most likely on site scenario.

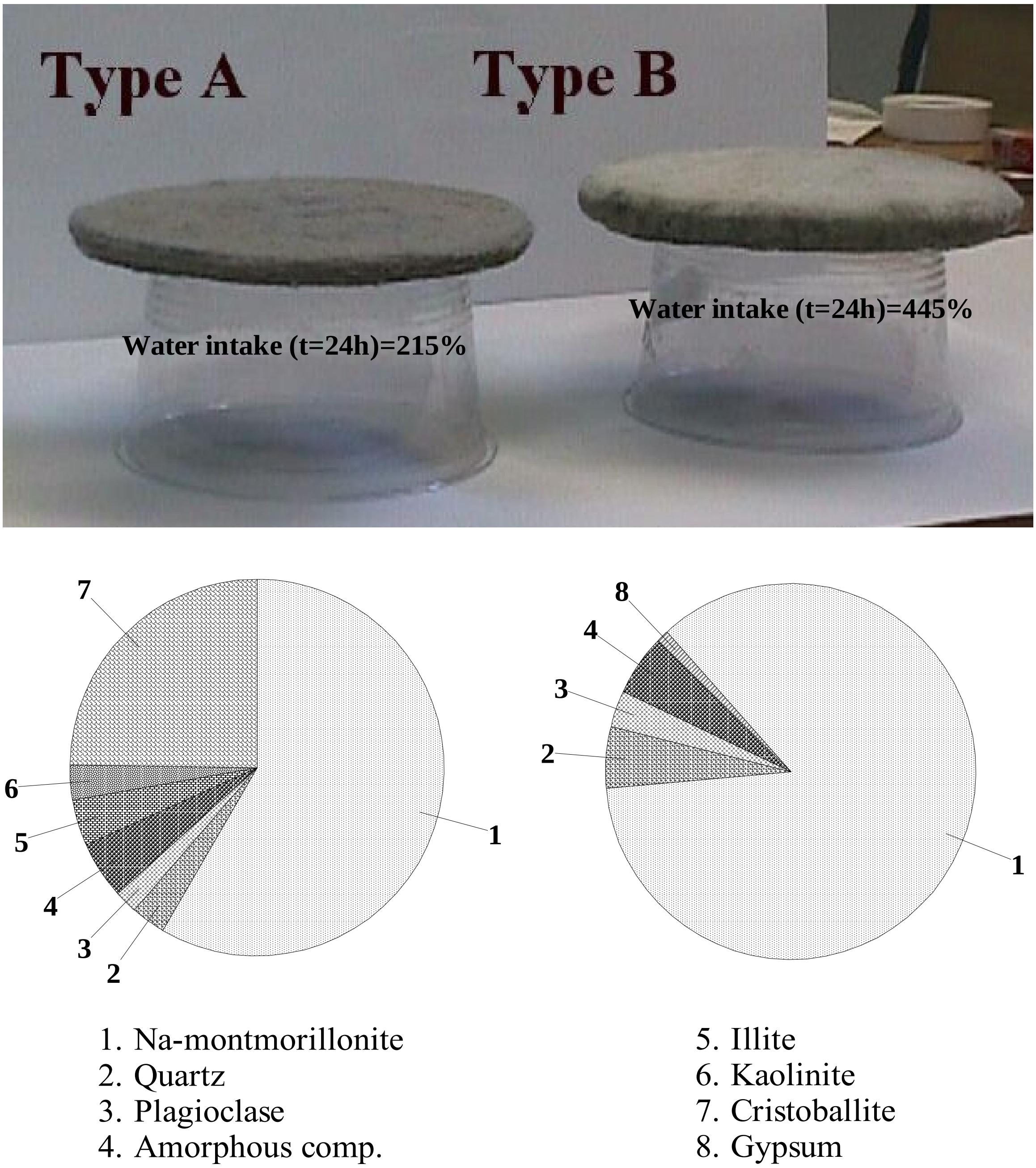


Fig 8.: The different swelling and mineralogical content of the GCL-s

The behavior of the GCL-s and clay liners are strongly different during the transport processes. Concerning the contaminant retention capacity of GCLs' it was proved, that

- the GCL layer is generally equivalent to a compacted clay liner (CCL) of 20 cm thickness in terms of advective transport fluxes. The condition of equivalency is the high smectite (montmorillonite) content, which causes a big swelling capacity and a hydraulic conductivity less than or equal to $5\text{-}8 \cdot 10^{-11}$ m/s.
- the GCL is generally not equivalent to the CCL concerning the diffusive contaminant transport. To fulfill the equivalency, the ratio of effective diffusion coefficient of the GCL should be 400 times less then that property of the clay liner, taking respectively 1 cm versus 20 cm thickness into consideration.
- since the seepage velocity is low through the barrier, the diffusion is dominant over the advection, so the complex equivalency of GCL to CCL is not reached.
- the higher adsorption capacity of GCL is generally not enough to compensate the lack of diffusive equivalency.
- since the transport process is solute specific, the efficiency of the GCL barrier is pollutant dependent.

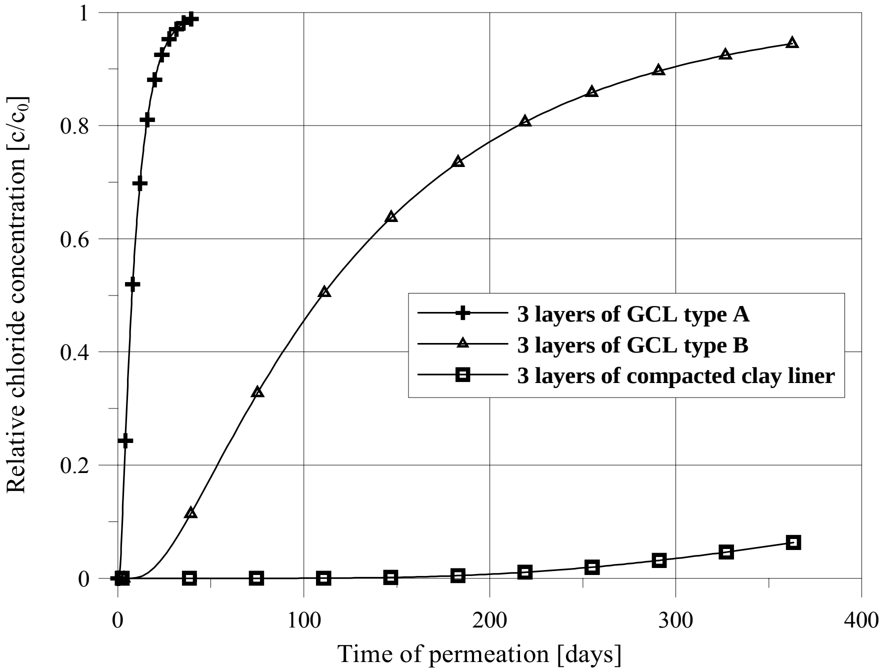


Fig.9. The calculated break-through curves (GCL, CCL)

To demonstrate the above statements, calculations were completed concerning chloride transport through the investigated two GCL-s and a compacted clay liner. The calculations were completed with the code developed for complex equivalency calculations [3]. The material and transport properties and the hydraulic conditions are listed in Table 6. The results are presented on Figure 9. The completion of the break-through took 41 days in case of the less effective GCL (type A), and 14 months even for the good quality GCL (type B), taking

0,3m hydraulic head of the leachate into consideration in both cases. In comparison with the compacted clay the relative concentration for the fast migrating chloride was about 6 %.

The statements above must draw our attention to an internationally accepted standardization of suitability testing, which must target the most accurate modeling of the in situ conditions.

Table 6.
The input data of chloride-transport calculations

Parameter	GCL type A	GCL type B	CCL
Hydraulic head of the leachate [m]	0.3	0.3	0.3
Thickness of barrier [m]	0.024	0.042	0.6
Hydraulic gradient [-]	12.5	7.1	0.5
Hydraulic conductivity [m/s]	1.7E-10	3.7E-11	1.0E-09
Seepage velocity [m/s]	2.1E-09	2.6E-10	5.0E-10
Seepage velocity [m/day]	1.8E-04	2.3E-05	4.3E-05
Effective porosity [-]	0.08	0.08	0.10
Density [kg/m^3]	1950	1950	1950
Montmorillonite content [%]	59	81	n.m.
Water intake (Enslin-test) [%]	215	445	n.m.
Effective diffusion coefficient [m^2/s]	1.0E-12	1.0E-12	3.0E-10
Estimated longitudinal dispersivity [m]	0.014	0.023	0.196
"A" 1st parameter of Langmuir isotherm [mg/kg]	2550	3500	700
"K" 2nd parameter of Langmuir isotherm [m^3/kg]	0.03	0.03	0.03
Decay constant [1/s]	0	0	0

Conclusion

1) There is no commonly used system of equivalence criteria for the barrier systems and this fact obstructs the selection of the most - technically and economically - advantageous solution.
2) For determining the equivalency of different barrier systems all the elements of the transport process (the hydrodynamic, the diffusive and the reactive-adsorptive processes) are to be included.There is no general equivalency criteria for two barrier systems. The equivalency is boundary condition specific, time interval specific and contaminant specific.
3) The investigated German, Italian and Hungarian standard barrier sytems are nearly equivalent, the Hungarian one is slightly less effective. The Hungarian regulation is unique since alternative barrier structures are allowed in case of its proven equivalency with the standard barrier.
4) The alternatively used GCL-s mineralogical compound, hydraulic and soil mechanical behaviour is varying in a wide range. The transport calculations based on flexible wall permeability tests proved that the barrier efficiency of a GCL is highly dependent from the QCL quality. In general cases, a high quality GCL is equivalent to 20 cm thick CCL

regarding the advective transport processes, but it is not equivalent against the diffusive transport.

References

[1] BEAR – VERRUIJT (1987): „Modeling Groundwater Flow and Pollution", D. Reidel Publ. Co., pp. 225

[2] CHAPUIS, R. P. (1990): „Sand - Bentonite Liners: Predicting Permeability from Laboratory Tests", Can. Geotech. J. 27:47

[3] CZINKOTA, I., KOVÁCS, B., LAKATOS, I., SZABÓ, I. (1998): Practical application of contaminant transport modeling - The equivalency of barrier systems, In: K. Czurda and I. Szabó (Editors), Abfallentsorgung und Altlastensanierung, AGK Schriftenreihe 54, pp.141-162.

[4] DANIEL, D. E. (1997): Critical issues for waste containment in landfills and contaminated sites. In: Proc. 14th Int. Conf. on Soil Mechanics and Foundation Engineering, Hamburg, Vol. 4. pp. 2503-2516.

[5] ESTORNELL, P. M. AND DANIEL, D. E. (1992): Hydraulic conductivity of three geosynthetic clay liners. Journal of Geotechnical Engineering, ASCE, 118(10): 1592–1606.

[6] HEYER, D. (1995): Basic examination on the efficiency of GCLs. Geosynthetic Clay Liners. Proc. of an Int. Symp. Nünberg/Germany, 14-15. April 1994: pp. 101-111.

[7] ISSMFE TC 5 (Ed. Manassero, M.) (1997): „Environmental Geotechnics" (Report of the Technical Committee TC5 on Environmental Geotechnics), Ruhr-Universität, Bochum

[8] KINZELBACH, W.: (1986): „Groundwater Modelling (An Introduction with Sample Programs in BASIC)", Elsevier, pp. 212

[9] KOHLER, E.E. - HEIMERL, H. (1995): „Untersuchungen zur Bewertung der Gleichwertigkeit von Deponieabdichtungsmaterialien, Sanierung von Altlasten (Hrsg. Jessberger)", pp. 127

[10] LAKATOS, I. – SZABÓ, I. (1997): „A környezetvédelemben alkalmazható vertikális és horizontális szigetelőgátak egyenértékűségének feltételei", Közl. és Mélyépítéstudományi Szemle, XLVII., 11:423

[11] VON MAUBEGE, K. - DÜRBAUM, A. (1996): „Alternative Dichtungssysteme mit geosynthetischen Tondichtungsbahnen", MBS Seminar, AGK Schriftungreiche 44

[12] MAZZIERI, F. AND PASQUALINI, E., (1997). Experimental results on hydraulic bebaviour of a GCL. In: Proc. 14th Int. Conf. on Soil Mechanics, and Foundation Engineering, Hamburg, Vol. 3. pp. 1919-1922.

[13] MÜLLER-KIRCHENBAUER, H. - ROGNER, J. - FRIEDRICH, W.: (1991) „Einfluß der Versuchsrandbedingungen auf die Ergebnisse von Dichtmassenuntersuchungen", Bautechnik, 68:421

[14] OGATA: (1960) „Theory of Dispersion in Granular Medium", US Geological Survey Professional Paper, 411-I., US. Government Printing Office, Washington

[15] OWEIS – KHERA: (1990) „Geotechnology of Waste Management", Butterworth, pp. 273

[16] SHACKELFORD, CH. D.: (1990) „Transit Time Design of Earthen Barriers”, Engineering Geology, 29:79

[17] SZABÓ I.: (1995) „Hulladékelhelyezés”, Ipar a Környezetért Alapítvány, Budapest