The evaluation of geotechnical barriers using equivalency calculations

L'évaluation des isolants geotechnique avec l'utilisation des calculations d'égalité

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ABSTRACT: The authors presents the methodology of equivalency calculations of geotechnical barriers and focus on the different behaviour of several GCL brandings and soil-bentionite mixtures during the contaminant transport processes.

RÉSUMÉ: Les auteurs present la théorie de la méthode des calculations d'égalité pour les isolants geotechnique avec la prise en consideration de la difference de la caractère des materiux geosynthetique et des sol-bentonite mixtures avant le transport des pollutants.

1 INTRODUCTION

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 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.

The structure and composition of bottom lining systems, landfill covers and other technical barriers 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 (GCL), sand-bentonite mixtures, clayey polymers, sand and potassium silicate mixtures, etc.) because of their smaller thickness, more homogeneous quality, and due to that its relative cheapness in comparison to the traditional compacted clay liner (CCL) systems.

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

From regulatory and waste management aspects the easiest way to control the isolation 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 presents the recently used lining systems in waste disposal, shortly 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 problems of equivalency some studies based on laboratory measurements are presented.

2 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 t0he subsoil and on the quality of the waste is to be deposited. All the professional regulatory aspects are discussed in the relevant literature (Szabó & Kovács, in press), that is why here only a short summary is given.

2.1 *Requirements for the subsoil of the landfill*

For the subsoil the European Council Directive 1999/31/EC is taken into consideration, which requires at least 5 m thick subsoil with the hydraulic conductivity less then 10^{-9} m/s for hazardous wastes and 1 m thick subsoil with the same permeability as above for non-hazardous wastes. If there is no natural mineral subsoil barrier having the mentioned quality, then an equivalent, built layer from mineral material is suitable. Depending on the thickness of suitable subsoil and its permeability determined using laboratory and field tests subsoil categories are established.

2.2 *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 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.

Regulation for the structure of the barrier system on the bottom and the sidewalls are shown in Figure 1. 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

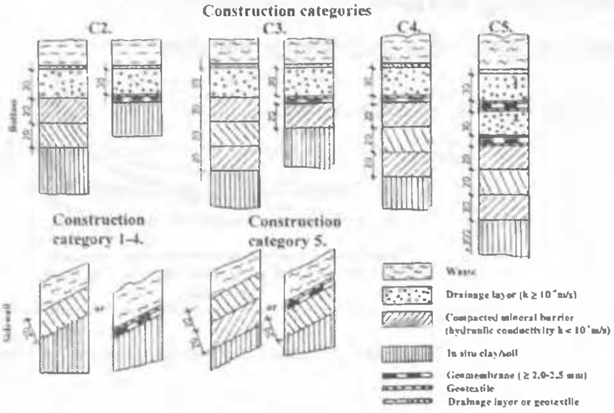


Fig. 1. The Hungarian regulation (C5.) and recommendations (C1.-C4.) for bottom lining systems of landfills

be disposed in landfills with the lining system of construction category No. 4., it means a combined barrier system consisting of 3 x 20 cm compacted soil layer ($k < 10^{-9}$ m/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. 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 3 x 20 cm thick clay mineral liners. The drainage under the top geomembrane has a monitoring function as well.

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 (Lakatos & Szabó (1997)).

3 BARRIER EQUIVALENCY - THEORETICAL CONSIDERATIONS

3.1 *The migration of Contaminants in Porous Media*

The migration of contaminants consists of four different processes: advection (convection), dispersion, adsorption and degradation. 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.

In case of special contaminants, the effect of radioactive decay or biodegradation might be significant. 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:

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

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 coordinate system, respectively (Bear & Verruijt, 1987).

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 is required to calculate the seepage velocity field using the Darcy-law.

3.2 *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.

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.

3.2.1 *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.

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.

Some calculations on hydraulic equivalency of different barriers are listed in Table 1. It was proved that about 1.5 cm thick GCL is advectively equivalent to 60 cm CCL, and 7.5 cm thick, multilayered GCL is needed to assure the same hydraulic equivalency with a geomembrane covered by 3 × 20 cm CCL. Practically, it might be said that an average GCL of about 1 cm thickness is advectively equivalent only to 2 × 20 cm CCL.

Table 1. 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 (CCL)	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
Geosynthetic clay liner (GCL)	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 a drainage layer between

* Hydraulic conductivity measured by Chapuis (1990)

** Average hydraulic conductivity calculated using spherical flow field (Oweis & Khera, 1990)

3.2.2 *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:

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

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.

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, and therefore „B" liner is diffusively equivalent to the „A" barrier of x_A thickness if its thickness is

$$x_B \ge \frac{x_A\sqrt{D_B}}{\sqrt{D_A}} \quad \text{(Kohler \& Heimerl, 1995)} \tag{4}$$

In Table 2. the results of diffusive equivalency calculations based on data from the literature (Czinkota et. al, 1998; Oweis & Khera (1990)) 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 CCLs. Depending on the product the HDPE geomembrane of 2 mm thickness or a GCL of 10 mm thickness is equivalent to 5-10 cm CCL regarding only the diffusive transport.

Table 2. Diffusive equivalency of geomebrane and compacted clay liners

Pollutant	Effective diffusion coefficient [$\times 10^{-10}$ m^2/s] CCL	Effective diffusion coefficient [$\times 10^{-12}$ m^2/s] Geo-membrane	Equivalent thickness of CCL with HDPE geomembrane of 2 mm thickness [cm]	Equivalent thickness of HDPE geomembrane with CCL of 60 cm thickness [mm]
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

3.2.3 *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 (1990) proposed a solution.

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. Introducing the dimensionless T_R Courant number and P_L Peclet number for the barrier and using the solution of Ogata (1960) of the 1D transport equation we may obtain:

$$\frac{c}{c_0} = \frac{1}{2}\left[\mathrm{erfc}\left(\frac{1-T_R}{2\sqrt{T_R/P_L}}\right) + \exp(P_L)\cdot\mathrm{erfc}\left(\frac{1+T_R}{2\sqrt{T_R/P_L}}\right)\right] \tag{5}$$

For a barrier with thickness L in a uniphorm flow field with constant seepage velocity v using the effective diffusion coefficient D for the contaminant the P_L Peclet number is to be calculated. From equation (5) performing an inverse calculation the Courant Number T_R is to be determined for the given P_L and the considered c/c_0 value using a nomogram. The transit time of the pollutant through the barrier is determined using T_R, L, v and the R retardation coefficient.

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.

3.2.4 *The complex equivalency*

Using the implicit finite difference method all the previously 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.

4 BEHAVIOUR OF ALTERNATIVE BARRIER MATERIALS DURING CONTAMINANT TRANSPORT PROCESSES

Our investigations focused on the hydraulic characteristics and pollutant retention capacity of two groups of alternative barrier material: the geosynthetic clay liners and soil-bentonite mixtures

4.1 *Geosynthetic clay liners (GCLs)*

GCLs appeared at the end of the 80's and since then they have increased the role among mineral liner systems. 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, although the experimental results of GCLs are usually very favorable. (Daniel (1997), Mazzieri & Pasqualini (1997)), 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 CCLs' (60 – 150 cm or 5 – 10 mm) which can cause a remarkable different in the liners contaminant retention capacity.

Since there is a big interest for using GCLs, five different branding were investigated in the laboratory. As reference material Bentofix NSP 4900-1 (Type E) and NSP 4900-3 (Type D) and Bentomax (Type B) were used and another two products of another manufacturer was also investigated we call them as Type A (older product) and Type C (newer product). All the investigated products are commercially available in Hungary.

All the five products were tested on several specimens for hydraulic conductivity in triaxial cell, for water intake by Enslin and for mineralogical compound by X-ray diffraction method (Table 3).

Table 3. Representative properties of tested GCLs

Parameter	Type A	Type B	Type C	Type D	Type E
Water intake (Enslin)	215 %	445 %	370 %	415 %	420 %
Na –Montmorillonite	59 %	81 %	70 %	72 %	68 %
Kaolinite	3 %	n.d.	n.d.	n.d.	n.d.
Illite	4 %	n.d.	n.d.	n.d.	n.d.
Cristoballite	25 %	n.d.	6%	13 %	15 %
Quartz	3 %	5 %	1 %	6 %	4 %
Plagioclase	2 %	3 %	5%	3%	n.d.
Alkali-feldspars	n.d.	n.d.	n.d.	n.d.	3 %
Gypsum	n.d.	1 %	n.d.	n.d.	n.d.
Dolomite	n.d.	n.d.	3 %	n.d.	n.d.
Calcite	n.d.	n.d.	9 %	1 %	5 %
Pirite	n.d.	n.d.	1 %	n.d.	n.d.
Amorphous	5 %	5 %	5%	5 %	5 %

Type A: Old branding, Type B: Bentomax, Type C: New branding, Type D: Bentofix NSP 4900-1, Type E: Bentofix NSP 4900-3

There were rather big differences detected between the different GCL brandings. In real conditions it common that the GCL is exposed to rainfall and its hydration occurs before the waste load would be placed above it. Figure 2 shows the different behavior of five GCLs saturated in a triaxial cell at 30 kPa hydrostatic cell pressure. The hydraulic conductivity of the GCLs measured under same conditions after their saturation,

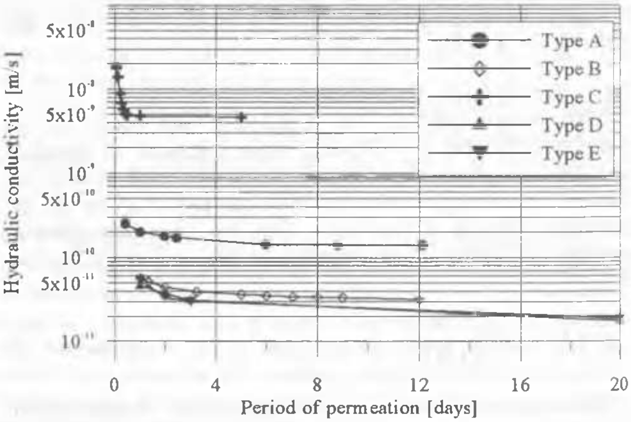


Figure 2. Hydraulic conductivity vs. time for the investigated GCLs

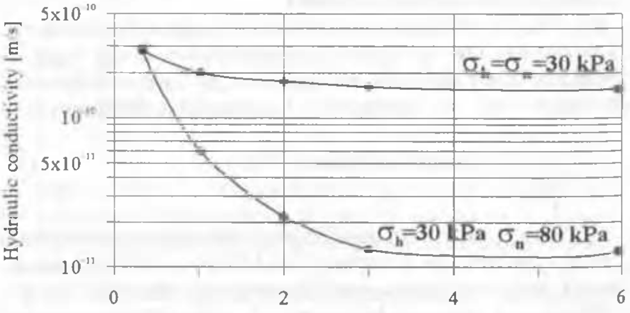


Figure 3. Effect of normal load on the hydraulic conductivity of GCL type A

resulted more than two order of magnitude difference. However, if the saturation of GCL type A in the triaxial cell was conducted at $\sigma_h = 30$ kPa cell pressure and $\sigma_n = 80$ kPa normal pressure, the measured value of hydraulic conductivity was much favorable, and was smaller with approximately one order of magnitude (Fig. 3).

Taking into consideration the mineralogical content and the water intake (by Enslin) of the materials of the liners (Table 3) it is apparent, that the mineral composition of type B, D and E 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 A the desired impermeability was achieved only, when the expansion was hindered or obstructed while saturation occurred. The wetting/drying and freeze/thaw cycle tests of type A also resulted in less favorable data, when the expansion of the sample was not hindered (Fig. 4), which is the most likely on site scenario (Kovács & Szabó, 2000). In case of GCL Type C we get high permeability although the fill-material's good mineralogical compound. This product had only few contact between the two geotextile layers and that it might be the reason of the achieved high conductivity during the laboratory tests.

Just upon this few experiments it is to be concluded that this alteration on permeability causes different behavior during contaminant transport and different isolation efficiency.

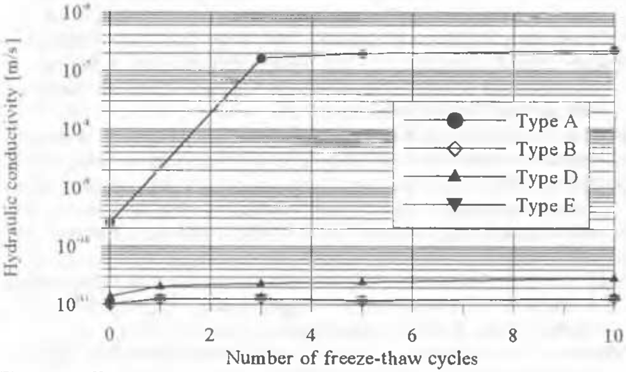


Figure 4. Effect of freeze-thaw cycles on the permeability of GCLs

4.2 *Soil-bentonite mixtures*

As alternative barrier materials it might be also advantageous to use soil bentonite mixtures replacing CCLs. In Hungary we have various natural bentonite occurrences with both Ca-montmorillonitic and both Na-montmorillonitic character (Table 4). For triaxial laboratory permeability testing samples were prepared with the same method and on similar water content. The soil used for mixture was an infusion loess with a grain size distribution - from soil mechanical point of view – as a sandy silt. This soil in its natural form has a hydraulic conductivity 4 – 5 × 10^{-8} m/s.

Table 4. Representative properties of tested natural bentonites

Parameter	Szék-völgy	Isten-mezeje	Mád	Sóskút	Egyházas-kesző
Water intake (Enslin)	280 %	380 %	290 %	180 %	350 %
Na -montmorillonite	40 %	n.d.	37 %	n.d	n.d
Ca-montmorillonite	n.d.	64%	n.d.	36 %	76 %
Kaolinite	n.d.	n.d.	15 %	6%	3%
Illite	5 %	1 %	n.d.	n.d.	n.d.
Muskovite	n.d.	n.d.	n.d.	4 %	n.d.
Cristoballite	24 %	14 %	n.d.	n.d.	n.d.
Quartz	2 %	6 %	33 %	33 %	9 %
Plagioclase	17 %	1 %	n.d.	3 %.	2 %
Alkali-feldspar	n.d.	n.d.	5 %	2 %	n.d.
Calcite	3 %	5 %.	6 %	10 %	trace
Dolomite	n.d.	n.d.	n.d.	trace	n.d.
Hematite	1 %	n.d.	n.d.	3 %	n.d.
Klinoptilolite (zeolite)	1 %	1%	n.d.	n.d.	n.d.
Amorphous	7 %	5 %	4%	3 %	10 %

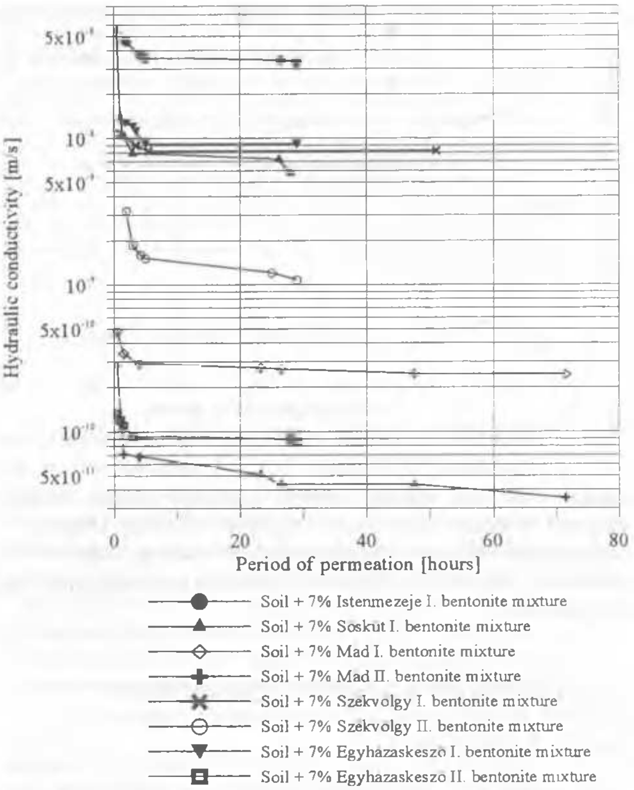


Figure 5. Isolation efficiency of different bentonite-soil mixtures

On Figure 5 the hydraulic conductivities of the mixtures during the tests are presented. It is clear that the worst results were achieved with the bentonites with Ca-montmorillonite content (Egyházaskesző, Istenmezeje, Sóskút). Even a much lower, but Na-monmorillonitic bentonite content (Mád) results much lower permeability and higher isolation efficiency.

However, it is possible the exchange the calcium-ions to sodium ones using sodium-sulphate as bentonite activator. The bentonites numbered I. are the natural ones, the samples numbered II. were activated. This activation reduces the permeability of soil-bentonite mixtures about one order of magnitude but at Egyházaskesző bentonite this reduction was more than two orders in magnitude. This can be explained by the high (76%) Ca-montmorillonite content of the bentonite, which after activation resulted a very good mixture component after activation.

On Figure 6 it is to be seen that even Na-montmorillonitic bentonites (Mád) can be activated, and that results about one order reduction of hydraulic conductivity at 5 – 7 % bentonite content of the mixture.

Using the mentioned types of bentonite and soil 7 – 10 % of

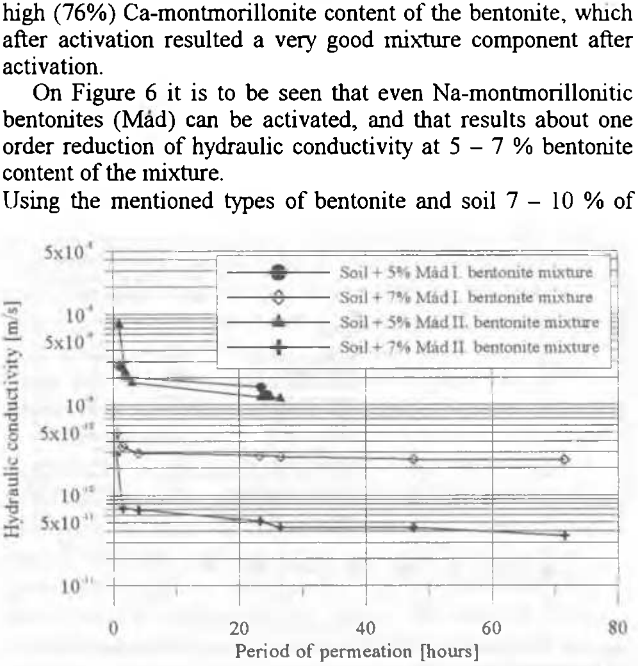


Figure 6. Effect of bentonite activation on the permeability of mixtures

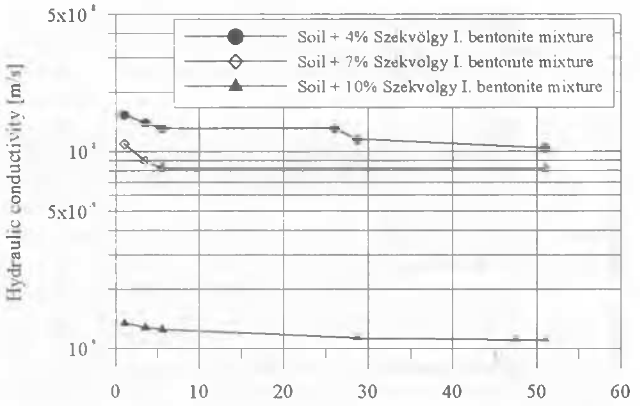


Figure 7. Effect of bentonite content on the permeability of mixtures

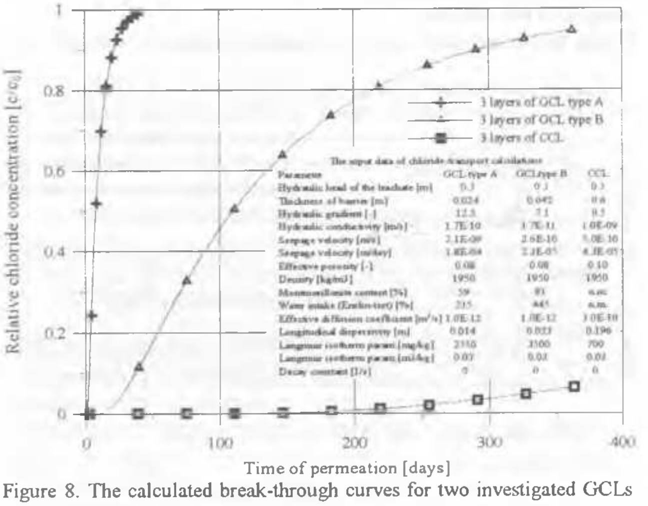
natural bentonite should be mixed into the barrier forming material to reach the required isolation efficiency (Figure 7.) Considering the less accuracy of field mixing compared to laboratory test the 10 % bentonite content is adviced in field test experiments.

5 APPLICATION OF GENERAL EQUIVALENCY CALCULATIONS FOR THE DETERMINATION OF BARRIER EFFICIENCY

This short presentation shows that not only GCLs but the soil bentonite mixtures have very different hydraulic and transport properties. Concerning the alternative barrier materials it was proved, that

- a GCL layer is generally equivalent to a compacted clay liner (CCL) of 20 cm thickness in terms of advective transport fluxes if it has high 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 since the ratio 1 to 20 in thickness requires the ratio 1 to 400 in effective diffusion coefficient. At low seepage velocity the diffusion is dominant over advection, so the complex equivalency of GCL to CCL during the transport process is not reached. The higher adsorption capacity of GCL is generally not enough to compensate the lack of diffusive equivalency.
- the soil-bentonite mixtures hydraulic equivalency to CCLs depends on the bentonite content of the mixture, the monmorillonite type of the bentonite and on some other factors. It is easier to fulfil the diffusive equivalency for this mixtures than to reach the hydraulic equivalency. That is why not only laboratory but field tests, and continuous control during the construction should be performed, if used.

Since the transport process is solute specific, the efficiency of the GCL barrier is pollutant dependent. To demonstrate the above statements, calculations were completed concerning chloride transport through two of the investigated GCLs and a CCL using the code developed for equivalency calculations (Czinkota et.al., 1998). The material and transport-properties, the hydraulic conditions and the results are presented on Figure 8. 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 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	2.2E-05	4.3E-05
Effective porosity [-]	0.08	0.08	0.10
Density [kg/m3]	1950	1950	1950
Montmorillonite content [%]	59	93	n.m.
Water intake (Enslin-test) [%]	215	445	n.m.
Effective diffusion coefficient [m²/s]	1.0E-12	1.0E-12	3.0E-10
Longitudinal dispersivity [m]	0.014	0.023	0.196
Langmuir isotherm param [mg/kg]	2350	3500	700
Langmuir isotherm param [ml/kg]	0.03	0.03	0.03
Decay constant [1/s]	0	0	0

Figure 8. The calculated break-through curves for two investigated GCLs and a compacted clay liner

REFERENCES

Bear, J. & Verruijt, A. 1987. Modeling Groundwater Flow and Pollution, D. Reidel Publ. Co.

Chapuis, R. P. 1990. Sand - Bentonite Liners: Predicting Permeability from Laboratory Tests, Can. Geotech. J. 27: 47

Czinkota, I., Kovács, B., Lakatos, I. & Szabó, I. 1998. Practical application of contaminant transport modeling - The equivalency of barrier systems, In K. Czurda & I. Szabó (Eds), Abfallentsorgung und Altlastensanierung, AGK Schriftenreihe 54, pp.141-162.

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. Balkema

Kohler, E.E. & Heimerl, H. 1995. Untersuchungen zur Bewertung der Gleichwertigkeit von Deponieabdichtungsmaterialien, In Sanierung von Altlasten Jessberger (Ed.), pp. 127

Kovács B. & Szabó I. 2000. The Problems of Equivalency of Alternative Barrier Systems Used as Waste Deposit Liners, in D. Hengerer, M. Hofer, K-E. Lorber, A. Ragossnig & M. Nelles (eds), Abfallvermeidung und –verwertung, Deponietechnik und Altlastensanierung, Proc. of DEPOTECH 2000 Int. Conf., pp. 201-206. Balkema

Lakatos, I. & Szabó, I. 1997. A környezetvédelemben alkalmazható vertikális és horizontális szigetelőgátak egyenértéküségének feltételei, Közl. és Mélyépítéstudományi Szemle, XLVII., 11:423

Mazzieri, F. & 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. Balkema

Ogata, A. 1960. Theory of Dispersion in Granular Medium, US Geological Survey Prof. Paper, 411-I., US GPO, Washington

Oweis, I. S. & Khera, R. P. 1990. Geotechnology of Waste Management, Butterworth, pp. 273

Shackelford, CH. D. 1990. Transit Time Design of Earthen Barriers, Engineering Geology, 29:79

Szabó, I. & Kovács B. Hungarian Standards for Waste Encapsulation Systems, Clay Sciences, Elsevier, in press

Szabó, I., Kovács B., Lakatos I. & Horváth I. 2000. Efficiency and Equivalency of Barrier Systems, in Lakatos I. (ed), Novelties in Enhanced Oil and Gas Recovery, Akadémiai Kiadó, Budapest