SOIL & GROUNDWATER PROTECTION BY THE MINERAL BARRIER TRISOPLAST (APPLICATIONS AND NEW DEVELOPMENTS)

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SUMMARY: Trisoplast is a patented innovative mineral barrier developed and first introduced in the Netherlands in the early 90's. It consists of a mixture of granular filler (normally sand), bentonite and a special polymer. The result is a durable, flexible and effective seal. Intensive and ongoing research has been carried out on Trisoplast in order to evaluate its performance under various conditions and environments including comparative testing with other mineral liners. A summary of the main relevant material properties and latest research on Trisoplast for landfill and other applications is given. Test results from excavations and sampling in the field on existing 'older' Trisoplast sites are reported. The importance of the functional lifetime of a lining system in respect of aftercare measures is discussed.

1. INTRODUCTION

Mineral barriers are extensively used in various applications to protect the environment from hazardous substances in the form of liquids (leachate) and/or gas. Mineral barriers can be used either independently or in combination with other sealing components. Traditional thick mineral barriers are often the preferred option due to their robustness and their high, natural durability. The EU council directive prescribes that protection of soil, groundwater and surface water is to be achieved by a mineral layer at the base and sides of the landfill which meets specified requirements for the protection of soil groundwater and surface water in combination with a top liner during the passive/post closure phase. In addition a leachate collection and sealing system must be added during the operational/active phase consisting of an artificial sealing layer and a drainage layer. The most commonly used mineral barriers are Compacted Clay Liners (CCL) and Bentonite Enriched Soils (BES). Geosynthetic Clay Liners (GCL) are mainly used as a top liner.

When used under the right circumstances all sealing systems can achieve good results, however all liners, mineral barriers as well as geomembranes, have certain limitations. It is necessary to understand these limitations in order to avoid any unpleasant surprise occurring during their entire functional working life. This article focuses on mineral liners and thus the pros and cons of geomembrane are not discussed at the same time. Three aspects that might adversely affect the functionality of such mineral liners are (1) strain arising from differential settlement of the underground, e.g. the waste body and (2) crack formation due to desiccation and shrinkage and (3) reduction of swelling capacity caused by changes of the initially sodium rich cation composition of the clay complex.

New concepts have been developed to improve the properties of the mineral barrier in order to cope with such detrimental effects. On Trisoplast, as one of these modified mineral barriers, intensive independent testing has proven that the performance of the mineral material can be significantly improved in several aspects by making use of this special bentonite-polymer technique. Trisoplast offers a prolonged functional lifetime, which is particularly relevant for landfill and contaminated land applications where the lining system is exposed to severe conditions such as chemical attack and mechanical stresses. The Trisoplast mixture is installed as a robust layer of generally between 6 and 9 cm and should be covered shortly after by a layer which provides the necessary confining pressure. After finishing the construction the Trisoplast layer absorbs the first water from the environment that reaches the layer. This causes the bentonite clay to swell and form a network of chemical bonds with the dissolved polymer to create a strong, dense hydro gel structure. Whereas Trisoplast predominantly gets its mechanical strength from the sand, the bentonite-polymer gel provides the necessary flexibility and hydraulic performance which is about 100 to 1000 times better than with traditional mineral barriers.

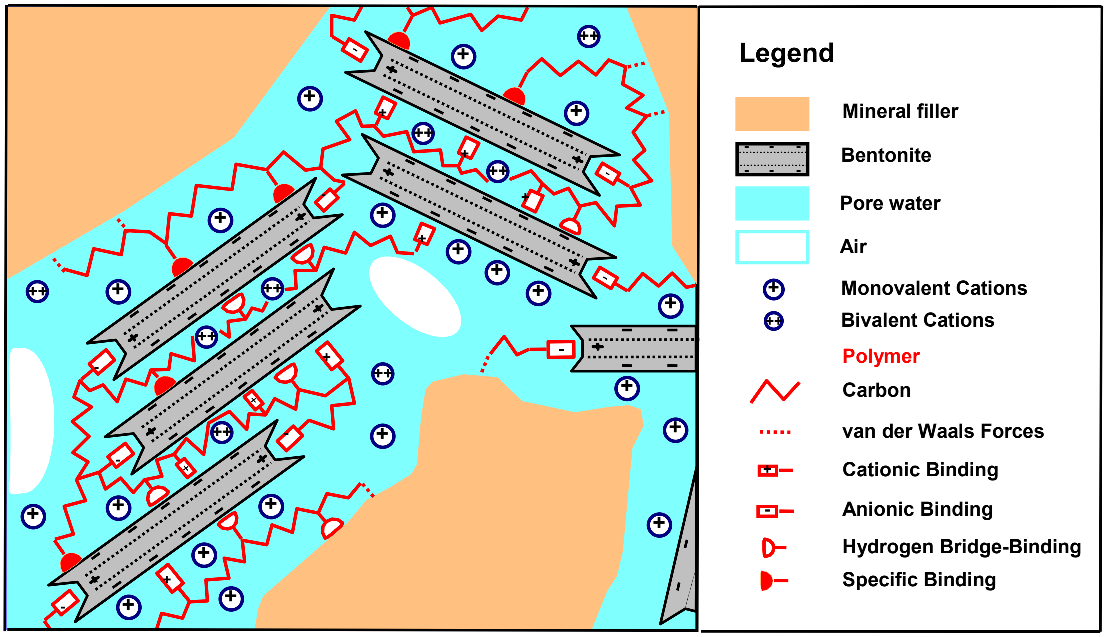

Figure 1 - Schematic presentation of the Trisoplast principle

Based on its performance in the last ten years after intensive independent, partly government sponsored research and testing Trisoplast has become the preferred mineral barrier for landfill applications in the Netherlands. As a result of its performance combined with further intensive and ongoing testing the use of Trisoplast has also rapidly spread throughout Europe and other continents. Figure 2 shows the countries where Trisoplast has been applied or application is planned. The main reason for this widespread application is that Trisoplast raises the level of soil and groundwater protection significantly higher than the level required for landfills by the legislations. Another important aspect in the successful introduction of Trisoplast is the continuing effort in further developing the material. Ongoing investigations prove that the clay gel has much better properties than the traditionally used mineral barriers.

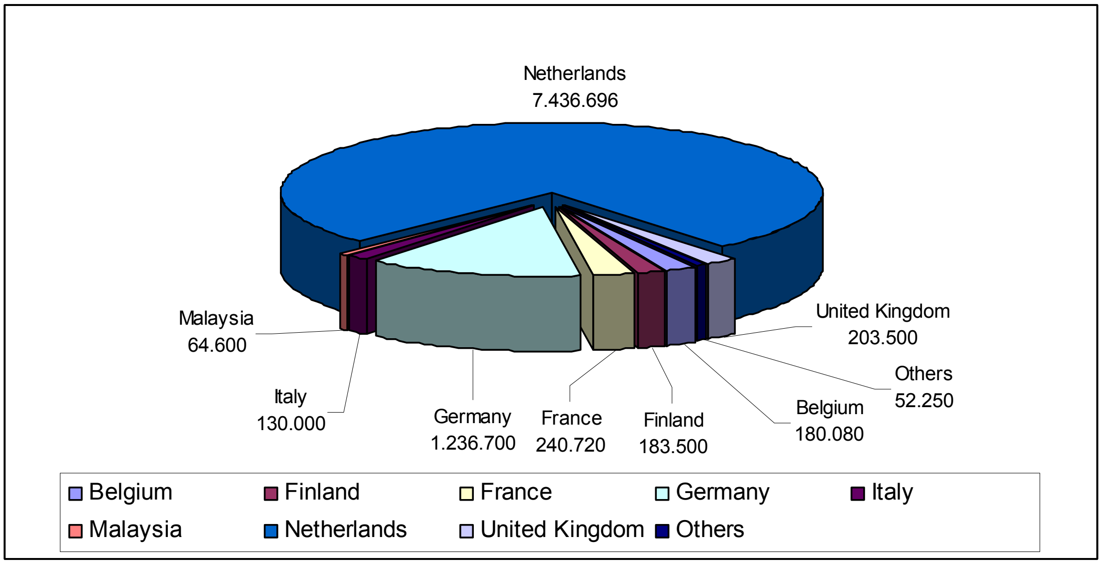

Figure 2 - Trisoplast applications (in m²) shown by countries

2. CATION EXCHANGE, DESICCATION AND PLANT ROOT PENETRATION

Since intensive field and lysimeter investigations especially in the 90ies were performed it is commonly known that CCLs may fail within several years even under rather humid climatic conditions due to desiccation (upwardly directed liquid and vaporous water transport in dry topsoil), penetration and water uptake by plant roots, and shrinkage, if they are not protected by a thick layer of topsoil with high storage capacities for plant-available water or by other protective measures, e.g. geomembranes (Melchior, 2001). Additionally the low tensile strength of thick clays and BES can lead to crack formation due to stresses resulting from differential settlements.

Desiccation of mineral liners underneath landfills resulting from moisture movement under the influence of temperature gradients have also been modelled (Döll, P., 1996) and reported (Philip et al., 2002).

GCL, too, are sensitive to desiccation, plant root penetration, and shrinkage. Furthermore cation exchange leads to a rapid decrease of the swelling capacity of sodium bentonites. Field data on the performance of GCL are given in Melchior, 2002.

Comparisons of exhumed samples of GCLs from four landfill covers with other data from the United States and Europe indicate that exchange of Na by Ca and/or Mg is likely to occur in the field unless the overlying cover soil is exceptionally sodic (sodium rich). The comparison also shows that hydraulic conductivities in the order of 10^{-6} to 10^{-4} cm/s should be expected if exchange occurs coincidently with dehydration, and the effects of dehydration are permanent once the water content of the GCL drops below approximately 100%. Evaluation of field data shows that covering a GCL with a soil layer of 750-1,000 mm thickness or with a geomembrane overlain by soil does not ensure protection against ion exchange or large increases in hydraulic conductivity (Meer, S. and Benson, C., 2007).

Cation exchange is a process by which the high swelling sodium bentonite is gradually changed into calcium bentonite. The replacement of the monovalent sodium ion Na^+ by the bivalent calcium ion Ca^{2+} leads to a significant decrease of the swelling capability (from 25 to 30 ml/2g for sodium bentonite to 8 to 15 ml/2g in calcium bentonite, when tested according to ASTM D5890, Melchior, 2002). This not only leads to a general increase in permeability (by a factor of approximately 10) but can, in combination with desiccation and cracking, be the cause of a dramatic loss of the sealing function of the mineral seal as the remaining swelling capacity of the bentonite is not sufficient to re-seal the gaps and cracks that were initially caused.

The polymer in Trisoplast interacts with the bentonite and sand forming a spider-web like gel structure. As a result of these bonds the total cation exchange capacity (CEC) of the clay gel in Trisoplast is reduced (Hoeks et al., 1991). Therefore less cations can be exchanged in Trisoplast. Investigations show that cation exchange in Trisoplast is significantly lower when compared to BES and GCLs, making it more stable and more analogous to the relatively stable clay mineral Illite (Boels 2001, Guyonnet 2008). Field investigations described in paragraph 6 confirm these results.

Permeability tests with a wide range of salt solutions are currently under investigation to determine the performance of Trisoplast under extreme conditions. The tests indicate that if high salt concentrations which are strongly Ca^2 dominated are present in the filler material (e.g. sand) of Trisoplast a negative influence on the performance of Trisoplast can also be expected. The initial gel formation thus is negatively influenced by the reduced swelling capacity of the clay. Therefore it is advised to limit the electric conductivity value of the sand to 500 µS/cm, whenever the Ca^{2+} to Na^+ ratio is uncertain or strongly dominated by Ca^{2+}.

Desiccation is a result of water evaporating from within the soil and depends on several factors (heat conductivity, soil temperature, air convection etc.). Ductile behaving soils reduce their volume in relation to the moisture escaping and the shrinkage of the material itself. The shrinkage is caused by the loss of moisture content due to drying. The process continues until the shrinkage limit, as defined in soil mechanics, is reached. The occurring shrinkage is almost directly proportional to the moisture content until this point is reached. Further reduction in volume leads to characteristic shrinkage cracks caused by tensile stresses as a result of the menisci bending into the void spaces, which pull the soil particles together. The volume reduction leads to tensile forces between these relatively dry-resistant areas. If the tensile strength of the soil is exceeded cracks start forming.

The tensile strength of different soil types varies significantly. The tensile strength σ_z is related by Coulomb's break conditions to the shear angle φ and the cohesion c respectively ($\sigma_z = 2c * \tan (45 - \varphi/2)$).

Behrens & Egloffstein, 2002 showed that the tensile strength at break (slow loading) of Trisoplast and clays according to Coulomb can be determined related to the moisture content. Figure 2 shows the results for both Trisoplast and average clay values.

Trisoplast shows significant advantages compared to conventional clay based mineral barriers when assuming that the prevention of crack formation as a result of drying out can be related to the tensile strength of the material (Behrens et al., 2002).

This remarkable behaviour is confirmed by laboratory experiments in a purpose built apparatus to simulate field conditions. Trisoplast and a natural clay barrier were subjected to drying and wetting cycles with calcium rich water and their behaviour was compared. Whilst the clay sample showed desiccation cracks and quick responses to changing conditions after the first drying cycle, the Trisoplast sample remained homogeneous and undisturbed even after a second desiccation period with soil water tensions of well above 1,000 hPa (Melchior et al., 2001).

Further laboratory tests showed a similar behaviour of the mineral materials when subjected to plant root penetration in combination with desiccation. Whereas the clay barrier had dried out with open gaps all Trisoplast samples maintained their integrity and the permeability remained unaffected (Melchior et al., 2001).

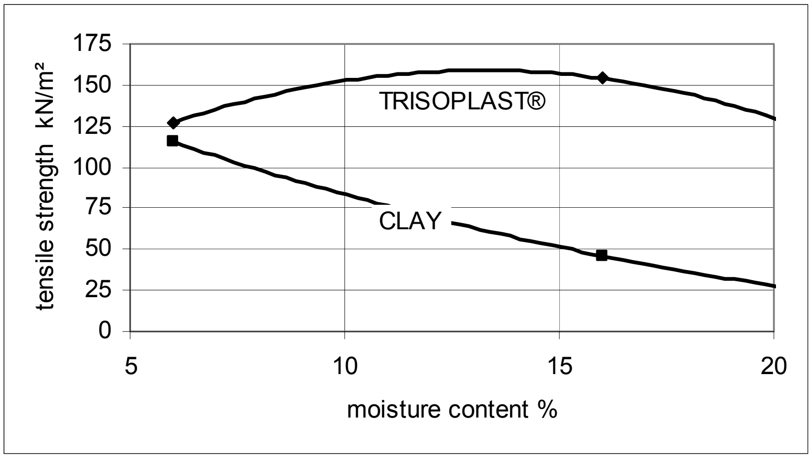

Figure 3 -Tensile strength of Trisoplast and clay (Behrens et al., 2002)

3. SLOPE STABILITY

Long term slope stability can be a problem when designing with clay based mineral barriers. The problem occurs due to the clay's generally very low friction angle. This can be a particular problem with the very low shear strength of a pure bentonite layer. The problem is addressed within GCL by mobilising the tensile strength of fibres or threads in needle punched or stitch-bonded GCL respectively. Their durability under the aggressive environmental conditions of a landfill is critically important for long term slope stability. A subject of present discussion and research work is the selection of the correct design value as GCL show a significant difference between the peak and the residual shear strength.

Trisoplast makes use of the advantages of both non-cohesive and cohesive behaviour because its sandy structure gives high shear angles, with numerous contacts of the coarse grained particles, combined with high cohesion values resulting from the clay fraction. This means that significantly steeper slopes can be designed, without the need for further reinforcement.

The German AK Trisoplast, 2002 recommends using the shear characteristics shown in Table 1 as typical values for the construction phase (moisture content on the dry side of the proctor curve) and the long term evaluation (wet side of the proctor curve up to full saturation). These values include a safety margin and offer a guideline for preliminary design planning with Trisoplast. Behrens & Neumann, 2002 report significantly higher cohesion values gained from laboratory measurements.

Table 1 - Shear characteristics of Trisoplast (recommended for slope stability calculations for preliminary design planning for landfill covers according to AK Trisoplast, 2002

Construction phase		Long term shear parameters	
State of failure	State of sliding	State of failure	State of sliding
φ' = 35°	φ'r = 30°	φ' = 30°	φ'r = 30°
c' = 20 kN/m^2	c' = 10 kN/m^2	c' = 10 kN/m^2	c' = 10 kN/m^2

4. DIFFERENTIAL SETTLEMENT

The heterogeneity of the waste body leads to differential settlement that causes extra stresses and deformation within a landfill cap. Due to the low tensile strength of clays and BES this can easily lead to the formation of cracks resulting in an increase in permeability. Whereas GCL can potentially cope with significant stretching depending on the chosen geotextiles and the bonding technique it might become critical after cation exchange or desiccation has taken place.

In order to demonstrate the deformation capability of Trisoplast a special testing device was developed by Boels which allows the measurement of the permeability after subsequent deformation steps. Tests were performed on a 2.5 cm thick layer of saturated as well as unsaturated Trisoplast. It is remarkable that even at 10% biaxial deformation, which locally reached even higher values, the permeability was not significantly affected (Boels et al., 1999).

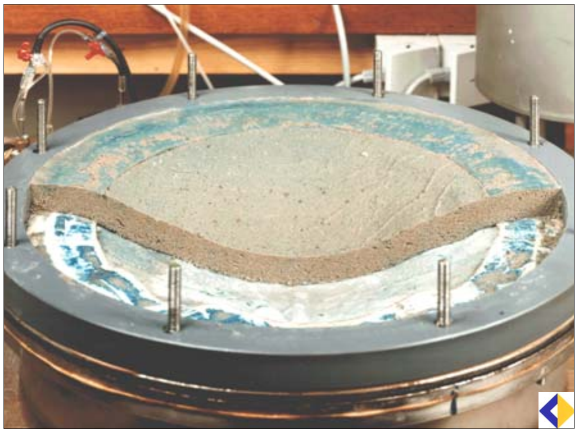

Figure 4 - Trisoplast layer after deformation in opened strain testing equipment

TD Umwelttechnik (Trisoplast Germany) determined the stretching limits for Trisoplast by direct tensile tests. Neglecting the general stretching (normally less than 0.01 % and insignificant when comparing it to the stretching of about 1% to 3% at the outer surface) the acceptable radius (R) as shown in Figure 5 can be determined in accordance with the deformation requirements of the Deutsche Gesellschaft für Geotechnik e.V. (DGGT), 1997:

$R = \frac{2 * d}{3 * \varepsilon_{rF}}$, (d = barrier thickness, ε_{rF} = stretching at surface incl. a safety factor of 2 at break)

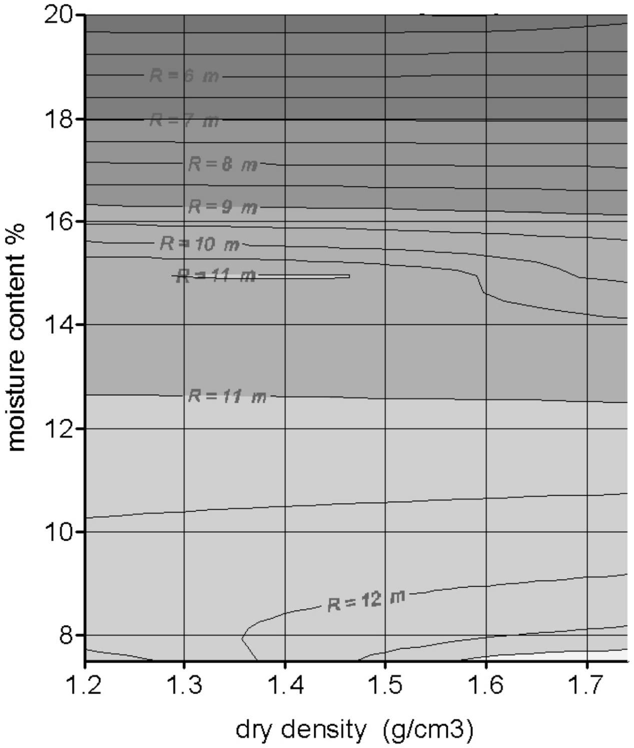

Figure 5 -Acceptable minimum bending radius R in m for a 0.1 m thick layer of Trisoplast

The above mentioned permeability results by Boels et al., 1999 show that in practice even smaller radii (< 1 m) are possible. The reasons for this derive from the positive effects caused by the high swelling and healing ability of the bentonite-polymer component in combination with the loads applied by the covering materials.

5. DURABILITY OF THE POLYMER

Before its market introduction in the Netherlands the chemical and physical durability of Trisoplast was examined intensively. Various tests showed that Trisoplast was not or only negligibly affected by any of the tested conditions. Based on the investigation results it was concluded that the polymer in the clay-polymer gel will not be attacked or degraded to a measurable level. The clay-polymer gel was evaluated as a resistant system for basal lining and capping of landfills.

Additional intensive experiments were carried out by Dr. Reinhard Wienberg – Umwelttechnisches Labor in Hamburg, Germany . Wienberg labelled the functional pendant groups of the polymer using radioactive isotopes (^{14}C isotopes) and subjected the samples to a variety of microbiologically and chemically active environments in closed reactors and studied the degradation. Over two years of quantifying testing on ^{14}C-labelled polymers showed that the actual polymer is marginally or totally non-degradable even under extreme microbiological conditions. It can be concluded that the microbiological degradation of the polymer offers no risk for the application of Trisoplast as sealing material (Wienberg, 2003).

6. FIELD INVESTIGATION & TESTING ON EXCAVATED TRISOPLAST SAMPLES

Excavations of Trisoplast samples two to almost ten years after their installation were carried out in order to gain field data regarding the performance of the mineral barrier under different conditions. The permeability values measured at the samples of the excavated locations in the Netherlands are listed in Table 2. At two locations a combined barrier system with an HDPE membrane had been constructed. The other locations were selected especially where single barriers had been applied, because any potential aging effects are more likely to occur on these. In order to examine the durability of the layers, the moisture content and permeability of each layer was determined after a visual inspection. In addition, electron microscope photographs were taken in order to be able to determine the quality at a microscopic level.

Table 2 - Permeability values of excavated Trisoplast samples

Project	*Covering layers*	*Age in years*	*K-value in m/s*
Landfill VBM, Rotterdam	*With geomembrane and 0.6 m covering soil* *Without geomembrane and 0.6 m covering soil*	*6*	*$2,6 * 10^{-11}$* *$1,3 * 10^{-11}$*
Tank park VOPAK, Rotterdam	*Geotextile and 0.6 m covering sand/gravel*	5	*$1,6 * 10^{-11}$*
Landfill Braambergen, Almere	*Geotextile, 0.2 m drainage sand and 0.8 m covering soil*	5	*$1,5$ to $4,3 * 10^{-11}$*
Landfill Tammer, Soesterberg	*With geomembrane, drainage mat and 1.0 m covering soil*	5	*$2,1 * 10^{-11}$*
Highway T106 Badhoevedorp	*Road construction and 1.3 m covering soil*	9	*$1,4 * 10^{-11}$*
Landfill, Mook	*Drainage mat and 0.8 m covering soil*	4	*$9,6 * 10^{-12}$*
Tank Park Pulles, ‘s-Hertogenbosch	*Geotextile and 0.4 m sand/gravel covering layer*	6	*$2,0$ to $3,0 * 10^{-11}$*

The excavated sites showed no signs of desiccation, cracks or other structural changes within the Trisoplast barrier. The samples were still moist and plastic (see Figure 6, photograph 1). Electron microscopy demonstrated that at the microscopic level, too, the composition of the layer was homogeneous (see Figure 6, photo No. 4). In this photograph it can clearly be seen how the polymer forms a gel with the bentonite which binds into the pores of the individual sand grains, and forms an almost impenetrable, elastic layer. The findings confirm the results regarding desiccation and root penetration behaviour gained from the laboratory tests as mentioned in paragraph 2. The remarkable behaviour is due to the special composition of sand and bentonite reinforced by the behaviour of the polymer.

Figure 6 – Pictures of Trisoplast taken during and after excavation

7. FUNCTIONAL LIFETIME & AFTERCARE

As ‘eternal’ aftercare of closed landfill sites plays an increasingly important role, the expected functional lifetime of a sealing system has to be considered when determining the funds that have to be reserved for overhaul and/or repair. The functional lifetime of a mineral barrier is defined as the elapsed time until the performance of the material drops below the required minimum performance. There are a number of factors as described in the former paragraphs that lead to negative changes within the mineral barrier’s performance. A method for determining the functional lifetime as a function of the surrounding environment controlled by the chemical composition of the soil layers adjacent to the liner and the liquid passing through is described in Boels et al. 2003.

In the past ten years approximately 80% of the landfill basal liners and cappings in the Netherlands were constructed using Trisoplast. Trisoplast was chosen even if the initial investments (installation costs) were higher compared to other barrier constructions. Nevertheless it was financially more attractive because of its longer functional lifetime resulting in lower funds required for aftercare of closed landfills. Unlike the Netherlands the majority of countries do not have similar regulations for fund reservations ensuring sufficient aftercare costs to be taken into consideration. Unfortunately this often results in short term solutions purely based on the lowest installation costs resulting in significantly higher costs in the long run.

8. COMPLIANCE WITH EUROPEAN DIRECTIVE

It has been proven in a number of European Countries that a 7 cm to 9 cm thick layer of Trisoplast meets the criteria to fully replace the reference clay barrier of 0.5 m to 1 m thickness. Table 4 shows a comparison of the percolation through the individual mineral barriers based on Darcy's law. It clearly shows that Trisoplast is equivalent or more effective in this respect and the difference is likely to increase with time when considering the superior durability of Trisoplast. Permeability is not the only property that has to be considered when looking at equivalency.

Table 3 - Percolation rates of landfill barriers (calculation using Darcy´s equation and the following assumptions regarding the hydraulic gradient i: hydraulic head on top of barrier (h1): +0.3 m, hydraulic potential at the upper boundary of the barrier (H1): h1 + thickness of barrier d, hydraulic potential at the bottom of the barrier (H2) equals the hydraulic potential of the subgrade underneath the barrier: -0.63 m (field capacity); hydraulic gradient (i = (H1 – H2) / d)

	Trisoplast		GCL	BES	Geological Barrier / CCL		
Barrier thickness d [m]	0.07	0.09	0.01	0.25	1.00	1.00	5.00
Hydraulic conductivity k [m/s]	3×10^{-11}	3×10^{-11}	3×10^{-11}	1×10^{-10}	1×10^{-7}	1×10^{-9}	1×10^{-9}
Hydraulic gradient i [-]	14.3	11.3	94.0	4.7	1.9	1.9	1.2
Percolation rate q [mm/a]	14	11	89	15	6086	61	37

Mechanical properties such as crack-free deformability or resistance to desiccation or cation exchange play a significant role when evaluating the performance of barriers. In this respect Trisoplast is clearly superior to traditional clay barriers. The mechanical stability of the sand structure in Trisoplast offers strong resistance to puncturing or other forms of damage, leads to high friction angles for Trisoplast and in combination with its high cohesion values to a good resistance to shrinking cracks.

While the permeability for water and landfill gas may be the key factors for the design and the performance of landfill covers, diffusive fluxes and adsorption of contaminants also have to be taken into account when considering landfill basal liners or other environmental applications. The retardation of contaminants is not only dependent on the permeability of the barrier against landfill leachate but also a function of the barrier thickness and its adsorption potential. 'Ranking the performances of different liners in a construction after the EC-guidelines on the basis of the emission attenuation, the following sequence was found: Trisoplast > clay (clay fraction 40%) > sand-bentonite > clay (clay fraction 10%) > GCL' (Boels et al. 2003).

According to the EU Directive a natural geological barrier is required. If such is missing the situation has to be improved by an artificial barrier giving a level of protection equal to the clearly defined geological barrier. A 50 cm thick artificially improved barrier is allowed to fully replace the natural barrier as long as the level of protection is at least the same. A 9 cm thick Trisoplast layer in combination with a prepared subgrade offers an even better environmental protection than the specified mineral barrier. As a result of the high performance offered by Trisoplast the subgrade only has to serve as an extra barrier for the diffusive contaminant transport and the mechanical support for the Trisoplast layer.

Elaborate modelling research after measuring diffusion and adsorption properties with radioactive labelling showed that, with regard to its pollutant retention capacity, the Trisoplast layer (0.09 m) – particularly in combination with a naturally existing mineral layer (0.41 m) – is equivalent to the natural reference impermeable mineral layer) as specified in the EU Landfill Directive (Wienberg, R, 2005).

9. CONCLUSIONS

The environments in which barriers of all kinds are used can have a negative effect on their performance and as a result on their functional lifetime. Mineral barriers are being widely used for various sealing applications, either on their own or in combination with other materials. New concepts have been developed to improve the properties of the mineral barrier in order to cope with such detrimental effects. On Trisoplast, as one of these modified mineral barriers, intensive independent testing has proven that the performance of the mineral material can be significantly improved in several aspects by making use of this special bentonite-polymer technique. Trisoplast offers a prolonged functional lifetime, which is particularly relevant for landfill and contaminated land applications where the lining system is exposed to severe conditions such as chemical attack and mechanical stresses.

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