Are TRISOPLAST barriers sustainable?

Trisoplast Mineral Liners, Kerkdriel, The Netherlands

Are TRISOPLAST barriers sustainable?

An evaluation of old barriers in landfill caps

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ABSTRACT

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Trisoplast is a mineral barrier material composed of sand, bentonite (>10.7%) and a non biodegradable polymer. Its permeability is less than 3 x 10 $^{-11}$ m.s^{-1} , which in general is not seriously affected by external physical-chemical influences. Trisoplast barriers, installed in 1995 / 1996 were excavated to check the occurrence and potential effects of ageing phenomena in situ. Incidentally root penetration in Trisoplast was observed, which obviously had not caused visible disiccation and crack formation. The actual permeability had not significantly changed since the installation. The safety factor of the barriers according to the regulations in The Netherlands actual varies from 2.1 – 10.2 and it is expected that due to possible future worst case conditions the variation can drop to 2.2 – 6.4. As this is still above the required value of 1, Trisoplast is sustainable at these sites. The average infiltration rate derived from water and salt-balances of the barriers without a geomembrane, ranges from 1 till 2 mm annually and only amounts to 5 – 10% of the permitted maximum rate of 20 mm annually.

Keywords: Ageing, root penetration, desiccation, crack formation, permeability, safety factor, infiltration rate

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Contents

Preface

After officially being approved in 1995, Trisoplast has been used in The Netherlands at a large scale for all kinds of environmental applications. Recent theoretical, laboratory and field investigations regarding ageing phenomena in bentonite containing barriers urged the developer of Trisoplast to check the presence and effects of these ageing processes in installed Trisoplast barriers. On behalf of Trisoplast Mineral Liners, Kerkdriel, The Netherlands, the oldest available barriers were excavated and evaluated jointly by Alterra, Wageningen, The Netherlands and melchior + wittpohl Ingenieurgesellschaft, Karolinenstrasse 6, 20357 Hamburg, Germany. The authors would like to thank the site owners for their co-operation.

Summary

Trisoplast is a mixture of sand, bentonite and a non-biodegradable polymer, which constitutes a spherical structure with a high plasticity and a low permeability as well as a mechanical stability on slopes comparable to compacted sand. Trisoplast is mixed in plant on site and installed at a moisture content less than the Proctor optimum. Investigations prior to the market introduction of Trisoplast in 1994, have shown no serious adverse effects from liquids of different kinds like leachate, crude oil, phenols or water with an extremely high salinity (seawater), pH as low as 1.5 or as high as pH 11. Bi-axial strain (tested to a maximum of 10%), cyclic in vitro drying and rewetting did not affect its functionality.

Recent laboratory research and (numerical) model calculations, however, unveiled that when the calcium concentration in the pore water strongly dominates and occurs at high concentrations, the permeability of Trisoplast may adversely be affected. From these findings an empirical function was derived to predict potential future change of the permeability. This research, however, gave no evidence whether this phenomenon in reality occurs and if it occurs to what extend adverse effects might be expected. Further research in Germany indicated that mineral barriers with clays and geosynthetic clay barriers might fail due to desiccation and plant root penetration. While Trisoplast performed much better in laboratory experiments than traditional mineral barriers with respect to crack formation, these laboratory results also needed additional validation from field data. To check the occurrence of ageing phenomena in practise, Trisoplast barriers installed in the years 1995 and 1996 were excavated and sampled in fall 2001.

All inspected barriers were homogeneous in colour, water content, density, thickness, plasticity and structure. No indications for desiccation, crack formation or ageing processes were found by visual and microscopic inspection.

At the sites without a geomembrane, incidentally root penetration was observed, however, without causing visible drying or forming cracks. The dry bulk density at all locations, except the one with a 0.3 m gravel cover, varied from 1490 till 1660 $kg.m^{-3}$, which was in the recommended range and equals more ore less the density directly after installation (1544 – 1571 $kg.m^{-3}$). The moisture content has increased by about 3% in Trisoplast barriers with a geomembrane and almost reached saturated in barriers without a geomembrane.

The chemical composition of pore water in the barriers with a geomembrane had obviously not significantly changed since the installation, while a certain change could be observed in the other ones.

An estimate of the average infiltration rate during the period since the barrier installation was derived from the water balance and likely changes of the chemical pore water composition. At sites without a geomembrane these rates range from1 to

2 mm annually, which is only 5 – 10% of the maximum allowed rate for standard conditions.

The permeability of the barrier varied from 1.3 – 4.3 x 10^{-11} $m.s^{-1}$, that is more or less complying with the range which was observed during the installation: 2.0 – 3.3 x 10^{-11} $m.s^{-1}$. The performance of the barrier is expressed as a safety factor and defined as the ratio of the maximum allowed infiltration rate over the actual infiltration rate of the Trisoplast barrier under standard conditions taking the observed thickness and permeability into consideration. The actual safety factor ranges from 2.1 – 10.2, which is much more than the required minimum value of 1. The potential future change of this factor is derived for a worst case situation assuming that the pore water composition of the barrier becomes the same as in the adjacent soil layer (drainage layer in situations without a geomembrane and subgrade in situations with a geomembrane). The future safety factor will range from 2.2 – 6.4, which implies a decrease as well as an increase of the future permeability. The performance of Trisoplast, however, will most likely not deteriorate beyond the required level. So Trisoplast is sustainable in the investigated sites.

1 Introduction

TRISOPLAST is a mineral barrier for landfills, storage facilities of hazardous wastes, industrial areas, tank parks etc. to prevent pollution of soil and ground water. It is composed of a mixture of sand or sand like material, bentonite and amended with a non-biodegradable polymer. Production occurs by mixing in plant and on site at a moisture content slightly less than the optimum proctor value. The permeability of Trisoplast is in general less than $3*10^{-11}$ $m.s^{-1}$. Applied at a thickness of 7 – 8 cm, Trisoplast performs better than the European and even Dutch legislation prescribes. The stricter Dutch legislation defines a minimum capacity of mineral barriers to retain leachate, expressed as a maximum leakage rate of 0.0001 m per day for barriers in landfill covers and 0.000055 m/d for bottom barriers, determined under standard boundary conditions. These conditions are a 1.0 or 0.8 m standing water table on top of barrier and free outflow at the bottom side for respectively cap and bottom barriers. Given a certain permeability of a barrier material, the (minimum) thickness of the barrier has to be chosen in order to meet the minimum requirements. Moreover legislation stipulates that effects from chemicals, irregular settlements and macro- and microbial activity should remain limited or at least should not violate the minimum containment capacity of the barrier. Legislation concerning the “eternal” after-closure care of landfills prescribes renewal of the barrier when its performance drops below the requirements as have been defined in the landfill permittance. Under the Dutch legislation any mineral barrier may be applied as far as one can prove that it performs comparable to or better than the reference sand-bentonite barrier.

After extensive testing according to the Dutch legislation of 1993, TRISOPLAST was the first alternative barrier, which was approved for application such as landill caps and basal lining. It was shown that the permeability of TRISOPLAST is hardly affected by changines of the dry bulk density, not affected by a prolonged elevated temperature (up to 40 ^{0}C), leachate, seawater (pre-saturated with tap water), low and high acidity, e.g. pH 1.5 – 10.5, crude oil, saturated phenol. Bi-axial strain up to 10% has only a slight adverse effect on the permeability of both saturated and unsaturated samples. The polymer is non-biodegradable (Weitz and Boels, 1993; Weitz et al., 1994 and 1997; Boels and Veerman, 1996; Boels and Schreiber, 1999; Boels and Beuving, 2000).

In Germany several studies focussed on the risk of crack formation in Trisoplast due to desiccation and plant root penetration (Melchior et al. 2001), the swelling and long term deformation behaviour of Trisoplast, and the durability of the polymer against microbiological and chemical impacts (tested in sequential batch reactor experiments with radioactively labelled polymer). Furthermore a benchmark test was performed in different laboratories on the water permeability of Trisoplast and a quality management programme has been developed to control the selection of components, the mixing process and the placement of Trisoplast barriers according to German standards.

In 2002 an independent committee (AK Trisoplast) with representatives of the federal and state agencies for environmental protection and non-governmental experts evaluated Trisoplast and came to the conclusion that Trisoplast successfully passed all tests required to be approved as alternative mineral landfill barrier according to the regulations of the German authorities (see www.nloe.de).

Recent research has shown that the initial equilibrium composition of the pore water in all barrier material can change due to migration of dissolved substances (cations and anions) to or from adjacent soil layers. Consequently the composition of the clay complex changes too, causing under certain conditions a decrease of the maximum swelling capacity and an increase of the barrier's permeability (Boels and van der Wal, 1999; Boels, 2001; Boels and Breen, 2001; Boels et al. 2002). This process has been identified as on of the most prominent reason for ageing of bentonite containing barriers.

Another process involved in ageing of barriers and potentially causing adverse effects is the cyclic drying and rewetting of clay barriers. Drying causes shrinkage of clay, generally followed by crack formation. Melchior et al., 2001, conclude from excavations of landfill covers that clay barriers compacted wet of optimum, may fail within several years even under rather humid climate conditions due to desiccation and plant root penetrating. This most likely will occur when the covers are relatively thin and while the water retention capacity is limited. The same applies to geosynthetic clay liners (Melchior, 2002).

The surface of the cracks acts as an evaporation surface where the water content decreases and the salt content increases. This causes exchange of adsorbed sodium and dissolved calcium and magnesium and migration of dissolved salts towards the centre of the clay aggregates. By these processes a thin layer could be formed at the crack surface, which has a lesser swelling capacity than the material inside the aggregates. After rewetting these surface may constitute zones with an elevated permeability. When this phenomenon occurs, its impact is likely larger for clay barriers showing visible crack formation than for barriers of sand and bentonite, which do not show visible cracks during drying.

Melchior et al. 2001 compared the behaviour of a mineral barrier of glacial marl with Trisoplast in a laboratory root penetration test and in long term laboratory experiments with various wet-dry cycles under load and in presence of a calcium rich percolate during the wet phases of the experiments. While the glacial marle barrier failed due to desiccation and crack formation after reaching a soil water tension of 600 hPa, Trisoplast remained moist, plastic and low permeable even after several cycles with much higher soil water tensions.

However, the conclusions of the referenced research on cation exchange and desiccation behaviour were mostly drawn from laboratory research and (theoretical/numerical) model calculations. The excavation of Trisoplast barriers, five to six years after their placement, gave the opportunity to re-investigate the properties of the barriers in order to evaluate whether or not ageing phenomena adversely affect the performance of the barriers in practise.

2 Materials and methods

2.1 Site selection

Four sites were selected where Trisoplast barriers had been installed during the period of 1995-1996. These sites are located near Rotterdam (Europoort Rotterdam/ VBM Maasvlakte and VOPAK-Rotterdam), Almere and Soesterberg. At two sites the cap construction includes a combination of mineral barrier and a geomembrane. In these cases ageing of Trisoplast, caused by migration (diffusion) of dissolved salt from the subgrade into the mineral barrier can potentially occur. At the other transport of dissolved salt from the layers above the barrier with the infiltration flux and diffusion is also possible. Without a geomembrane on top of the mineral barrier, roots from vegetation possibly penetrate into the barrier and could locally cause crack formation and thus lead to an increase of the permeability. Upward moisture flow from the barrier into the rootzone during dry summer periods could have a similar effect. Table 1 gives details of the sites.

Table 1 Description of the locations

Code location ➔	**Europoort Rotterdam/ VBM Maasvlakte**		**VOPAK-Rotterdam**	**Almere**		**Soesterberg**
Profile ➔	**1**	**2**	**3**	**4**	**5**	**6**
Type	Industrial waste		Oil/petrol storage	Municipal waste		Demolition material
Year of installation	1995	1995	1996	1996	1996	1996
Vegetation	Grass		Gravel	Grass, shrubs		Grass, shrubs, trees
Orientation	North		-	South South West		North
Surface angle	Sloping		Even	Sloping		Slightly sloping
HDPE geomembrane	Y	N	N	N	N	Y
Thickness top cover (m)	0,55	0,60	0,30	1,40	1,20	1,25

2.2 Measurement programme

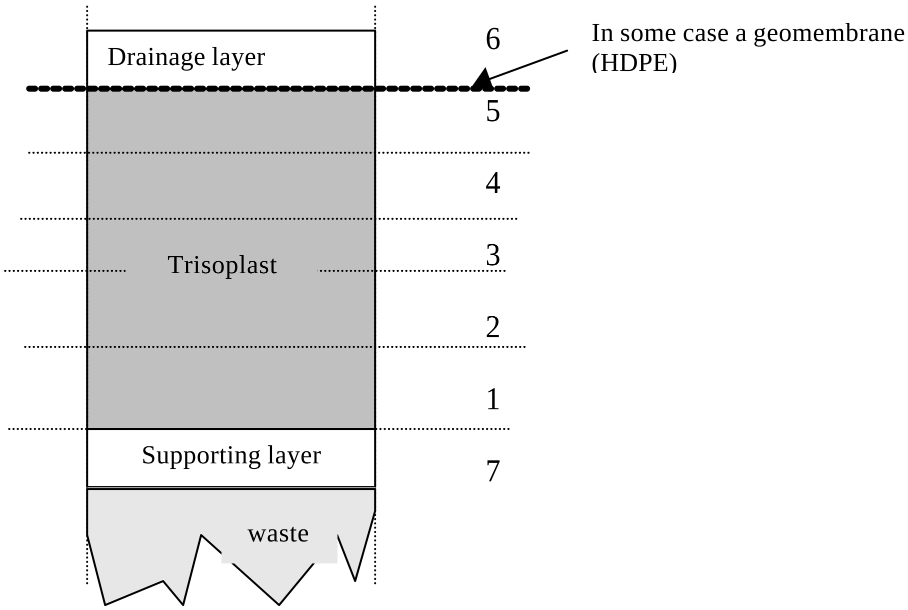
The profile of the cap construction includes a vegetative topsoil (“rootzone”), geotextile (optional), drainage layer (sand or artificial), geotextile (optional), geomembrane (HDPE 2mm, optional), Trisoplast, geotextile (optional) and a subgrade, separating Trisoplast from waste or subsoil.

Samples were taken from the topsoil, drainage layer, Trisoplast and the mineral layer below Trisoplast. The location and objectives of sampling are summarised in table 2.

Tabel 2 Sampling programme

Objective		Type	Size (diam.)	Layer	Sub layer
Moisture content	By weight	disturbed	-	Topsoil	-
				Drainage layer	-
				Trisoplast	1 – 2 cm
				Subgrade	Top layer
	By volume	undisturbed	0,05 m	Topsoil	
				Drainage layer	
				Trisoplast	
				Subgrade	
Dry bulk density		undisturbed	-	Topsoil	
				Drainage layer	
				Trisoplast	Top, middle, base
				Subgrade	
Chemical composition		disturbed	-	Topsoil	
				Drainage layer	
				Trisoplast	2 x 2cm top 1 x 2 cm middle 2 x 2 cm base
				Supporting layer	
Permeability		undisturbed	0.32 m	Trisoplast	
Particle size distribution		disturbed	-	Trisoplast	
Thin sections		undisturbed		drainage layer Trisoplast	
Scanning electron microscope		undisturbed		Trisoplast	
Soil water retention curve		undisturbed	100 cm^3	Topsoil Drainage layer Trisoplast Subgrade	

In the analysis the sampled layer number corresponds with a certain depth or layer type (see figure 1).



Figuur 1 Layer coding for sampling

For chemical analysis the minimum sample mass amounts 0.500 kg. The sampling technique for permeability measurements is described in Annex 1.

The measurements include:
1 Grain size distribution by sieving and sedimentation method;
2 Dry bulk density;
3 Moisture content in the distinguished (sub)layers;
4 Soil water retention;
5 Permeability of undisturbed large samples (diameter ~0,35 m);
6 Chemical analysis of topsoil and drainage layer with respect to clogging phenomena;
7 Chemical composition pore water in the barrier, and layers adjacent to Trisoplast;
8 Swelling capacity;
9 Microscopic analysis.

2.3 Methods

2.3.1 Profile preparation and description

The six profiles at the four sites were opened by help of a small backhoe. The drainage layers have been removed manually and the surfaces of the barriers have been very carefully prepared to allow a proper inspection of root growth, soil structure and other soil properties.

The soil profiles of the excavated landfill covers were described according to the German guidelines for soil surveys (AG Boden 1994; see appendix 1). For documentation, pictures were taken (appendix 2).

2.3.2 Grainsize distribution

A sample of about 50 grams is dryed during 24 hours at a temperature of 105 ^{0}C and ground (< 2 mm) to assure that no aggregates exist. The sample is weighted and mechanically sieved during 15 minutes. The content of the different sieves is weighted. The smallest mesh width is 63 micrometers.

The fraction < 45 micrometer is determined by a sedimentation method (Locher and Bakker, 1987).

2.3.3 Dry bulk density

The samples (diameter 5 cm, height 5 cm, content Vs = 98.18 cm^3) of which the weight of the sample ring is known (Wr, gr) are weighted (Ww, gr) and dried in a stove during 24 hours at a temperature of 105 ^{0}C. After drying the weight is again determined (Wd, gr). The volumetric moisture content is calculated from:

$$MCV(cm^3.cm^{-3}) = \{Ww – Wd\} / Vs$$

And the dry bulk denisty:

$$DBD (kg.m^{-3}) = \{Wd – Wr) / Vs \times 1000$$

2.3.4 Moisture content

Moisture content is determined of disturbed samples according to NEN 5747. The field samples are stored in glass pots at 4 ^{0}C. These samples are manually homogenised and a sample of about 15 gram is taken. This sample is put in an aluminium container (of known weight, Wc, gr) and cover with a lid (of known weight, Wl gr.). The gross weight (Ww, gr) is determined. The lid is removed and the sample is kept in a stove during 24 hours at a temperature of 105 ^{0}C. Before the sample is removed from the stove, the lid is put in place. The weight of sample plus container (Wd, gr) is determined.

The moisture content is expressed as a percentage of dry weight:

$$MC(\%) = \{Ww – Wd\} / \{Wd – Wc – Wl\} \times 100\%$$

2.3.5 Soil water retention

The soil water retention curve is determined with five parallel undisturbed samples in a pressure cell apparatus according Klute (1986). The wetting and dewatering procedure is described in appendix 5.

2.3.6 Permeability

The permeability is measured of undisturbed large samples with the falling head method (Hoeks et al. 1990). Sampling and the laboratory set up are described in Annex 1.

2.3.7 Soil chemical analysis

Soil pH as well as total content and sequential extraction of Fe, Al and Mn are determined for several samples of topsoil and drainage layer where clogging of metal oxides and hydroxides had been observed in the field (appendix 7).

2.3.8 Chemical composition of pore water

Determination of the chemical pore water composition includes:

1 a sample of about 500 gr;
2 moisture content determined of a sub sample (about 20 gr.) according to NEN 5747
3 adding destilled water to obtain a moisture content of 25%
4 incubation of wet sample to obtain chemical equilibrium in an ambient temperature of 20 centi-degree during 48 hour. Preventing evaporation;
5 extracting pore water by centrifuging, according Alterra standard working prescription E0002;
6 determination of EC according to NEN 5749 or NEN 7888;
7 determination of concentration of macro parameters (Al, Ca, Fe, Mg, Mn, Na, K, S) with ICP-AES, according to NEN 6426
8 determination of chloride content according to NEN 6651

All data are expressed in meq/l. It is assumed that the S-content represents more or less the SO4-content of the solution.

Checks are carried out:

1 comparison of the sum of all cation and anions (meq/l);
2 compare the sum of anion+cation concentration (meq/l) with EC-measurement. The relationship should be almost linear.

2.3.9 Water adsorption capacity

The potential water adsorption capacity is determined with the Enslin apparatus according to the procedure described in “CUR-Aanbeveling 33”.

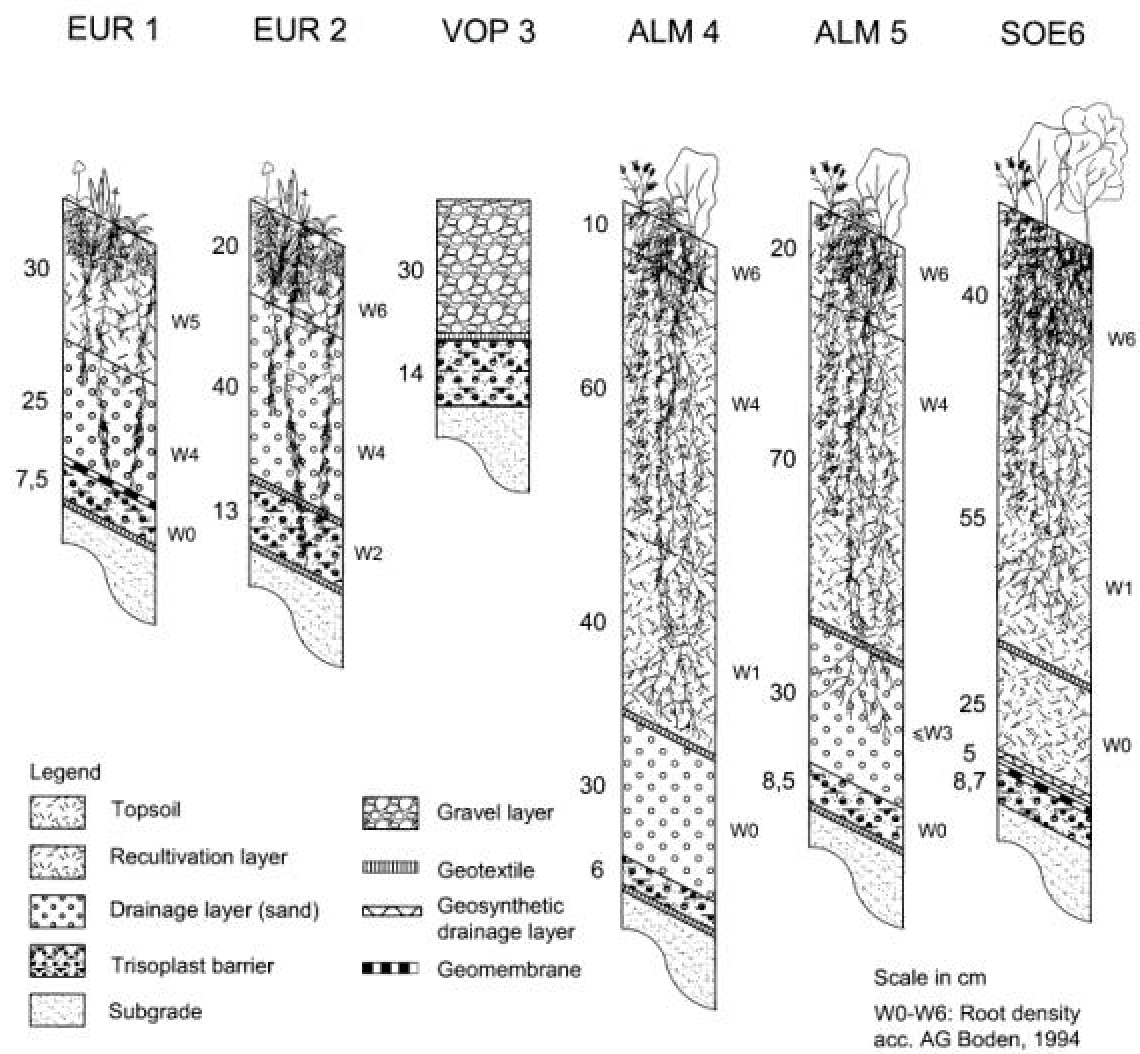
2.3.10 Microscopic analysis

Undisturbed samples of Trisoplast barriers were prepared for micromorphological investigations with the help of thin sections and scanning electron microscopy (for methods see appendix 3 and appendix 4).

3 Results

3.1 Profile description

Figure 2 shows the type of vegetation and the soil profiles of the inspected covers (further details in appendices 1 and 2).



Figuur 2 Profiles of caps on the four sites

Europoort Rotterdam / VBM Maasvlakte (profiles Eur 1 and Eur 2)
Both profiles show a relatively thin sandy loam topsoil with a moderate organic matter content and a significant carbonate content (photo 17 in appendix 2). The drainage layer consists of medium sand with very low organic matter. In both layers the density of roots is high. The vegetation is grass and different deep rooting herbs, typically for landfill covers (thistle, docks, see photos 13-15 in appendix 2).

Close to profile VBM2 rabbits had dug a warren till about midway of the drainage layer.

At profile Eur2 roots reach till the geomembrane (> 50 roots per dm², photo 18 in appendix 2). At profile EUR 2, without a geomembrane, 21 – 50 roots per dm² reached the surface of the barrier. Only 3 – 5 thin roots per dm², however, penetrated the barrier (photos 28 to 38).

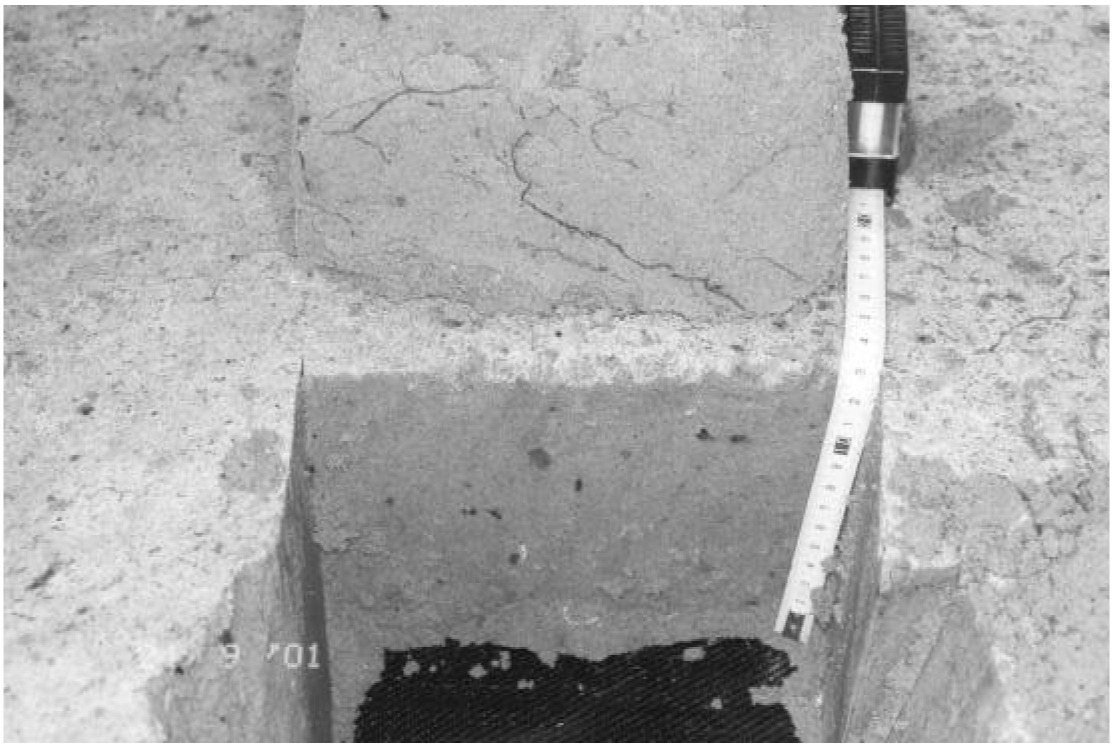
Figuur 3 Vegetation and rabbit warren close to profile Eur 2

At profile EUR1 very small fissures were observed in the surface of the Trisoplast barrier underneath the geomembrane (photos 19 – 24 in appendix 2). These fissures only reached 2 to 3 mm deep into the barrier and were probably formed during construction (wetting and drying of the surface before the placement of the geomembrane).

The moisture content and the plasticity of Trisoplast around these roots were not different from the barrier material in profile Eur1 and material obviously outside the influence zone of the roots at profile Eur 2. No visible differences could be observed and no clues were obtained for crack formation.

VOPAK Rotterdam (profile VOP3)

At this site Trisoplast is applied underneath a petroleum storage tank (photo 39 in appendix 2). The barrier is covered with a gravel layer and no vegetation is present (photo 40). The elevation of the drainage outlet at the sides are above the Trisoplast layer and leads to a permanent standing water layer on top of the bowl shape designed barrier. The moisture content of Trisoplast was high (~saturated).



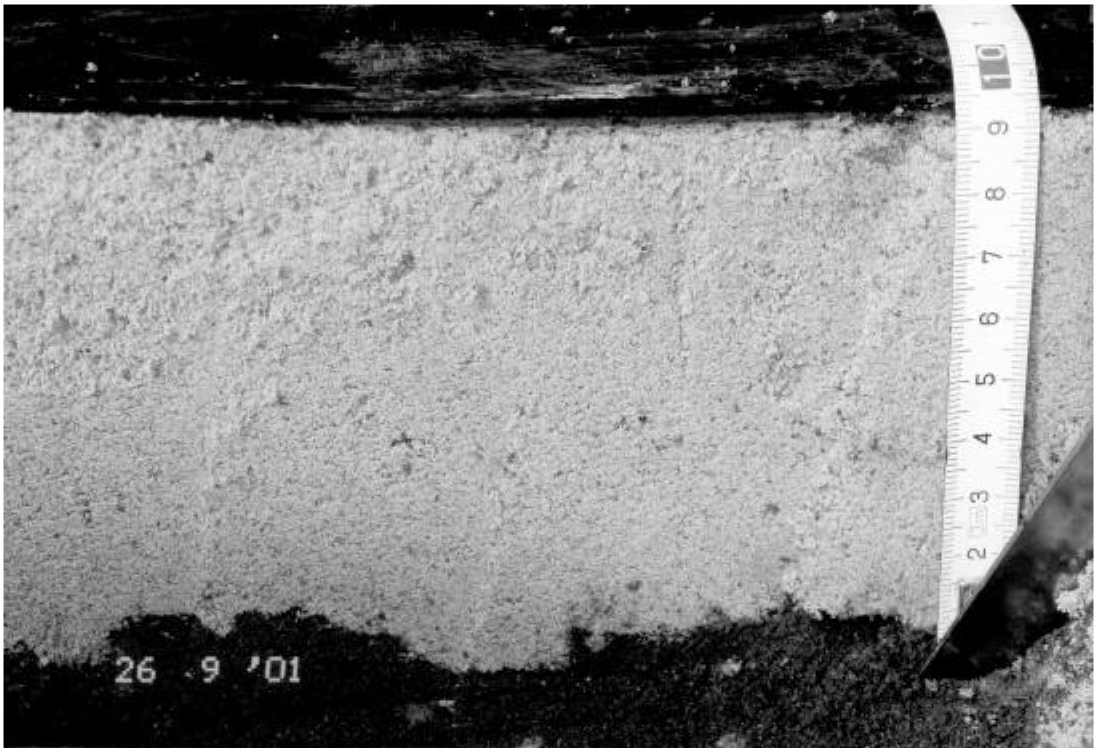
Figuur 4 Cross section of Trisoplast in the Eur 2 profile. The upper part of the picture shows Trisoplast cutted from the barrier showing plant roots at its base

Braambergen-Almere profiles (ALM 1 and ALM 2)

The topsoil and recultivation layers include different layers of sandy loam (photots 41, 42 and 49(. The organic matter content is high till very high and the carbonate content is significant. The roots of the grass and herbs vegetation penetrate down to 1.1 m and reach the upper part of the drainage layer to a depth of 0.1 m(photos 50 and 51). The root density is high in the upper layers and decreases gradually with depth. In the upper part of the drainage layer reddish spots as a result of the precipitation of iron oxides were observed (photots 43 and 44). The impression of the Trisoplast layer was a moderate wet, plastic and homogeneous layer without iron coatings (photo 46, 47 and 54).

Soesterberg profile (SOE6)

On this site a grass, herbs and shrubs vegetation with trees of 1 – 4 m height was found (photos 55-57). The multi-layer topsoil was heterogeneous: sandy loam and loamy sand with a moderate organic matter content and a significant carbonate content (photo 58). An artificial drainage layer was installed instead of a sandy drainage layer. This layer was compressed by the 1.2 m topsoil till about 50% of its original thickness (photos 59 and 64). The roots penetrate down to a depth of about 1 m (photos 57, 73-77). No visible changes had taken place in the Trisoplast barrier below the geomembrane (photos 66 – 72).



Figuur 5 Crossection of Trisoplast barrier below a geomembrane at the Soesterberg site (SOE6)

3.2 Grain size distribution and swelling capacity

The distribution of the grain size of Trisoplast and other layers is given in table 4.

Table 3 Grain size distribution of Trisoplast and other layers

Location / layer	Grainsize distribution (% dry weight)				
	< 2000 mu	< 63 mu	< 45 mu	< 16 mu	< 2 mu
VMB-Maasvlakte 0-20	87.3	39.5	31.7	19.6	9.5
VMB-Maasvlakte 20-60	90.3	4.3	2.5	0.7	<1.0
VMB-Maasvlakte Trisoplast	92.9	11.2	10.2	9.3	7.6
Vopak Trisoplast	92.7	13.6	11.8	11	9.1
Almere cover	79.8	39.3	32.8	23	11.3
Almere drainage layer	97.1	3.2	1.1	0.3	<1.0
Almere Trisoplast	95	10.7	8.9	7	5.7
Soesterberg Trisoplast	95.4	9.7	9	7.6	6.9

The expected content of particles less than 2 micrometer of Trisoplast is > 10%. Table 3 shows that this value is not reached, although the content at the VOAPK location is near to this recommended value. Because the sedimentation method is applied, it cannot be excluded that the polymer structure has only partly been destroyed during the sample preparation. This could imply that particles were still bound by the polymer, causing a higher sedimentation rate than is to be expected for individual clay platelets. The fraction less than 2 micrometer is most probably under estimated.

The water adsorption capacity of Trisoplast from different sites has been measured of samples taken from the barrier. The obtained water uptake is reduced by the quantity of water, which the sand skeleton would adsorb without bentonite. The observed quantity in excess of this quantity is adsorbed by bentonite. The quantity of bentonite is calculated from the bentonite percentage, obtained from the sedimentation test. Table 5 shows the results.

Table 4 Swelling capacity of the bentonite in barriers of different sites

Site	location	% < 2 mu	gram water / gram bentonite
Europoort Rotterdam / VBM Maasvlakte	1 (EUR1)	7.6	11.3
	2 (EUR2)	7.6	12.0
Vopak Rotterdam	1 (VOP3)	9.1	10.1
Braambergen Almere	1 (ALM4)	5.7	7.9
	2 (ALM5)	5.7	6.9
Tammer Soesterberg	1 (SOE6)	6.9	12.7

Table 4 demonstrates that the potential swelling capacity of the bentonite-polymer complex is high compared to the values reported by Weitz et al, 1994 (5 – 10 grams water per gram bentonite-polymer). A water adsorption capacity between 8 and 9 grams is quite normal for Trisoplast. So this capacity at location Almere ALM5 is low, although not extremely.

The clay fraction, determined by the sedimentation method, is possibly disputable. When a swelling capacity between 8 and 9 grams of water per gram bentonite-polymer is assumed, the clay fractions should have been between 10 and 11%, which complies with the standard bentonite content of Trisoplast.

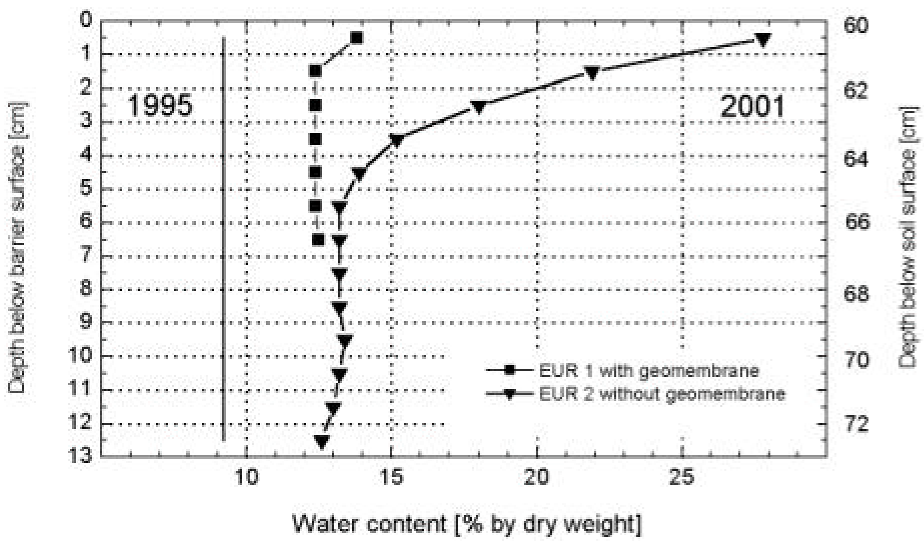
3.3 Dry bulk density and moisture content

The Trisoplast barrier was installed with a moisture content of 6.9; 8.0 and 9.2% at the Soesterberg, Almere and VBM sites respectively. The realised dry bulk densities directly after installation were 1571, 1544 and unknown respectively.

At Europoort Rotterdam / VBM-Maasvlakte location 1, a geomembrane was used and the moisture distribution indicates no ingress of water. The average moisture content of Trisoplast was 12.6% (by weight) and does not show any significant gradient. This moisture content is about 3% higher than during installation and probably caused by a very slow water uptake from the subgrade, maybe enhanced by thermally induced water transport. At Europoort Rotterdam / VBM-Maasvlakte location 2, no geomembrane was present. The moisture content in the top layers was significantly higher than in the lower layers, demonstrating clearly the ingress of water. Assuming an initial water content of 9.2 %, the total ingress of water at VBM-Maasvlakte location 2 into the Trisoplast layer amounts 12.5 mm during its life time until September 2001. It is likely that an upward capillary flow has increased the moisture content by 3%, so the average annual infiltration rate from above amounts about 1 mm. Ignoring the upward flow, yields an annual infiltration rate of 2 mm.

The dry bulk density at VBM 1 is 1560 kg.m^{-3} and at VBM 2 it varies from 1490 – 1560 kg.m^{-3}. Because the highest density is found in the top of the layer and the lowest in the base, the variation is likely attributed to the compaction method.

The observed thickness of the barrier at VBM 1 is 8 cm and 13 cm at VBM 2, and exceeds the recommended 7-cm for barriers in landfill covers.



Figuur 6 Water content distribution within the Trisoplast barriers of profiles EUR1 and EUR2

At the VOPAK-Rotterdam location no geomembrane was present. The moisture content of Trisoplast, was high: 35% (by weight) and is practically saturated (only 3% of the pores filled with air). This is attributed to the bowl shape barrier combined with an elevated drainage outlet, which was designed to create a standing water table, which keeps the barrier saturated and gives an extra protection to the barrier in case of significant leakage of the petroleum tank. The dry bulk density, 1360 kg.m^{-3}, is rather low. Possibly the overburden weight is low and allows significant swelling of Trisoplast. The observed barrier thickness at the excavated location amounts 14 cm, which is more than designed.

At the Braambergen-Almere location, a uniform moisture distribution is found (average 22%), which is significantly above the usual moisture content during installation. Because no geomembrane is present, most probably ingress of water from above explains the increase of the moisture content. Because no moisture gradient is found, no calculation of annual infiltration can be made. Assuming an initial moisture content of 0.13 $m^3.m^{-3}$ (8 % by weight), the infiltration rate is more than 1.9 mm per year. The Trisoplast layer is practically saturated (3 – 4% air). The observed dry bulk densities, 1640 and 1580 $kg.m^{-3}$, are higher than observed during the installation. The observed barrier thickness at Almere ALM4 amounts about 6 cm and the thickness at Almere ALM5 varies from 6 to 11 cm, so the uniformity at the inspected location was limited. The observed thickness, however, complies with the designed average of 7 cm and a maximum negative spread of 2 cm for individual measurements.

At the Tammer-Soesterberg location a geomembrane is found. The moisture content (average 10,4%) does not show any significant gradient and is about 3% higher than the moisture content during installation. The air content of the Trisoplast layer at this location amounts 25% (by volume). The dry bulk density of 1570 $kg.m^{-3}$ is similar to the one during installation. The observed 9 cm barrier thickness is about 2 cm more than designed.

Table 5 Description of the profile, moisture content and dry bulk density at different locations

Europoort Rotterdam / VBM Maasvlakte

Location 1 (EUR1)

Thickness (cm)	Layer	Sub-layer (cm - cm)	Sample code	Moisture content (%, by weight)	MC (m^3/m^3)		Dry Bulk Density (kg/l)
30	Topsoil						
25	Drainage layer						
0.2	Geomembrane						
8	Trisoplast	0-1	1/9	13.8	rep. 1	0.205	1.577
		1-2	1/10	12.4	rep. 2	0.198	1.563
		2-3	1/11	12.4	rep. 3	0.213	1.562
		3-4	1/12	12.4	rep. 4	0.216	1.570
		4-5	1/13	12.4	rep. 5	0.204	1.570
		5-6	1/14	12.4	rep. 6	0.205	1.541
		6-7	1/15	12.5	Average	0.207	1.564
-	Geotextile						
>	Subgrade						

Europoort Rotterdam / VBM Maasvlakte
Location 2 (EUR2)

Thickness (cm)	Layer	Sub-layer (cm - cm)	Sample code	Moisture content (%, by weight)		MC (m^3/m^3)	Dry Bulk Density (kg/l)
20	Topsoil				rep. 1	0.377	1.332
					rep. 2	0.332	1.343
					Average	0.355	1.337
40	Drainage layer				rep. 1	0.131	1.540
					rep. 2	0.197	1.506
					Average	0.164	1.523
-	Geotextile						
13	Trisoplast	0-1	2-1	27.8	^		
		1-2	2-2	21.9	|		
		2-3	2-3	18.0	|	0.261	1.563
		3-4	2-4	15.2	|		
		4-5	2-5	13.9	V		
		5-6	2-6	13.2	^		
		6-7	2-7	13.2	|		
		7-8	2-8	13.2	|	0.241	1.499
		8-9	2-9	13.2	| ^		
		9-10	2-10	13.4	V |		
		10-11	2-11	13.2	|	0.204	1.486
		11-12	2-12	13.0	|		
		12-13	2-13	12.6	V		
-	Geotextile						
>	Subgrade						

Vopak Rotterdam (VOP3)

Thickness (cm)	Layer	Sub-layer (cm - cm)	Sample code	Moisture content (%, by weight)		MC (m^3/m^3)	Dry Bulk Density (kg/l)
15	Gravel						
15	Gravel/sand						
0.2	Geotextile						
14	Trisoplast				rep. 1	0.491	1.322
					rep. 2	0.472	1.372
					rep. 3	0.484	1.355
					rep. 4	0.485	1.343
					rep. 5	0.461	1.400
					Average	0.478	1.358
>	Subsoil						

Braambergen Almere
Location 1 (ALM4)

Thickness (cm)	Layer	Sub-layer (cm - cm)	Sample code	Moisture content (%, by weight)		MC (m^3/m^3)	Dry Bulk Density (kg/l)
10	Topsoil						
60	Recultivation layer I						
40	Recultivation layer II						
-	Geotextile						
30	drainage layer						
6 +/- 0.5	Trisoplast	0-1	4/18	22.0	rep. 1	0.341	1.636
		1-2	4/19	21.6	rep. 2	0.345	1.659
		2-3	4/20	22.1	rep. 3	0.354	1.627
		3-4	4/21	22.6	rep. 4	0.339	1.644
		4-5	4/22	22.7	rep. 5	0.347	1.624
		5-6	4/23	22.4	Average	0.345	1.638
-	Geotextile						
>	S+B32ubgrade						

Braambergen Almere
Location 2 (ALM5)

Thickness (cm)	Layer	Sub-layer (cm - cm)	Sample code	Moisture content (%, by weight)		MC (m^3/m^3)	Dry Bulk Density (kg/l)
20	Topsoil						
70	Recultivation layer						
-	Geotextile						
30	Drainage layer						
8.5 +/- 2.5	Trisoplast	0-1	5/9	22.3	rep. 1	0.363	1.598
		1-2	5/10	22.4	rep. 2	0.364	1.599
		2-3	5/11	22.6	rep. 3	0.366	1.573
		3-4	5/12	22.8	rep. 4	0.365	1.567
		4-5	5/13	22.9	rep. 5	0.367	1.573
		5-6	5/14	23.5	Average	0.365	1.582
		6-7	5/15	24.6			
	Geotextile						

Tammer Soesterberg (SOE6)

Thickness (cm)	Layer	Sub-layer (cm - cm)	Sample code	Moisture content (%, by weight)		MC (m^3/m^3)	Dry Bulk Density (kg/l)
40	Topsoil						
55	recultivation layer						
-	Geotextile						
25	recultivation layer						
1	Geodrain						
0.2	Geomembrane (HDPE)						
9	Trisoplast	0-1	6/10	10.3	rep. 1	0.161	1.550
		1-2	6/11	10.9	rep. 2	0.164	1.582
		2-3	6/12	10.8	rep. 3	0.167	1.568
		3-4	6/13	10.8	rep. 4	0.159	1.552
		4-5	6/14	10.7	rep. 5	0.163	1.619
		5-6	6/15	10.4	Average	0.163	1.574
		6-7	6/16	10.4			
		7-8	6/17	10.5			
		8-9	6/18	10.7			
>	Subgrade			9.0			

3.4 Soil water retention

The soil water retention characteristics have been determined for the Trisoplast barriers and some of the adjoining layers and topsoils. The data were measured by dewatering the samples without load. The method used does not account for any swelling or shrinkage of the samples during the experiment. Table 4 and the figures in appendix 5 show the results.

Table 6 Soil water retention data

Layer and site	Water content at matrix suction head				
	3 hPa	60 hPa	300 hPa	1000 hPa	15000 hPa
Topsoil EUR 2	44.3	37.0	33.1	28.9	16.4
Drainage layer EUR 1	39.0	21.3	8.1	5.3	n.d.
Drainage layer ALM 4	34.3	15.3	9.3	7.6	1.0
Trisoplast EUR 1	42.3	41.1	38.7	35.3	15.7
Trisoplast EUR 2	46.7	43.7	37.5	33.6	15.9
Trisoplast VOP 3	49.7	48.4	46.4	43.9	14.3
Trisoplast ALM 4	38.2	36.4	37.1	35.3	12.6
Trisoplast ALM 5	39.6	36.8	36.7	34.3	11.1
Trisoplast SOE 6	49.7	46.8	45.0	41.2	15.1
Subgrade ALM 4	41.1	24.7	9.1	4.9	1.2
Subgrade SOE 6	30.1	23.7	22.4	20.4	8.0

The data for the topsoil of profile EUR 2 does show typical data for a sandy loam. The air capacity (pore volume between saturation and field capacity at 60 hPa) is high. The capacity for plant available water (pore volume between field capacity,60 hPa, and permanent wilting point, 15000 hPa) amounts to approximately 20 % by volume and is also rather high. However, due to the shallow depth of the topsoil the actual storage capacity for plant available water at the profiles EUR 1 and EUR 2 is very low (40 - 60 mm) and the vegetation very likely suffers from desiccation during dry summer periods.

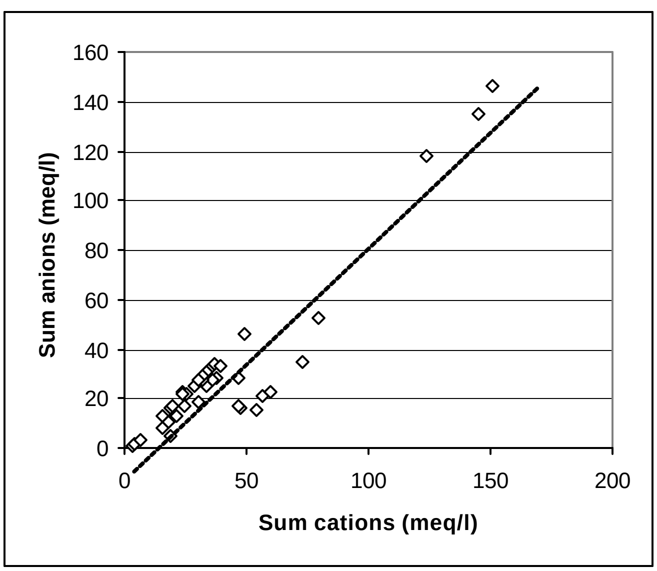
The sandy drainage layers are dominated by coarse pores, but still offer around 15 % by volume plant available water.

The retention characteristics of Trisoplast are quite similar, showing a significant decrease of water content between matrix suction heads of 1000 hPa and 3000 hPa, in effect the medium pores. The volume of fine pores is around 15 %. The barriers at EUR 1, ALM 4 and ALM 5 contain slightly more than 20 % medium pores and only very few percent of coarse pores (total porosities around 40 %). At EUR 2, VOP 3 and SOE 6 total pore volume is significantly higher (around 50 %). The higher pore volume at EUR 2 compared to EUR 1 might be the effect of plant root penetration into the barrier at EUR 2.

3.5 Pore water composition and permeability

3.5.1 Pore water composition

The chemical composition of pore water (macro-parameters only) in different layers is presented in Annex 2. We assume that the S-concentration in general reflects sulphate. Following this assumption, the data show that the sum of cations equals in general the sum of anions (fig. 7). It can be concluded that in the majority of cases sulphate, and to a limited extend also chloride are the major negatively charged constituents of the pore water solution.



Figuur 7 *Sum of anions compared to sum of cations obtained from chemical analysis of pore water in the Trisoplast layers*

The sum of anion and cation concentration (= “total concentration”) of the pore water in Trisoplast is usually about 60 meq/l. Compared to this average to the observed total concentration at the VBM-Maasavlakte location 1 and 2 (~ 250 meq/l) is rather high and a relatively low concentration is observed at the VOPAK-Rotterdam location (~ 30 meq/l). No explanations could be found for these deviations.

The total concentration of dissolved substances and the SAR-value (reflecting the ratio of mono-valent over the bi-valent cations) derived from the chemical composition of pore water are given in figure 8 and 9.

Figure 8 suggests that no significant displacement of dissolved substances occurred in the Trisoplast layers at the VMB-Maasvlakte location 1 and the Soesterberg site. At these locations, Trisoplast is covered with an HDPE geomembrane. The total salt concentration gradient at the Almere location 1 is very weak, which suggests a strongly limited migration of dissolved substances. A significant gradient of the total salt-concentration is found at VBM-Maasvlakte location 2.

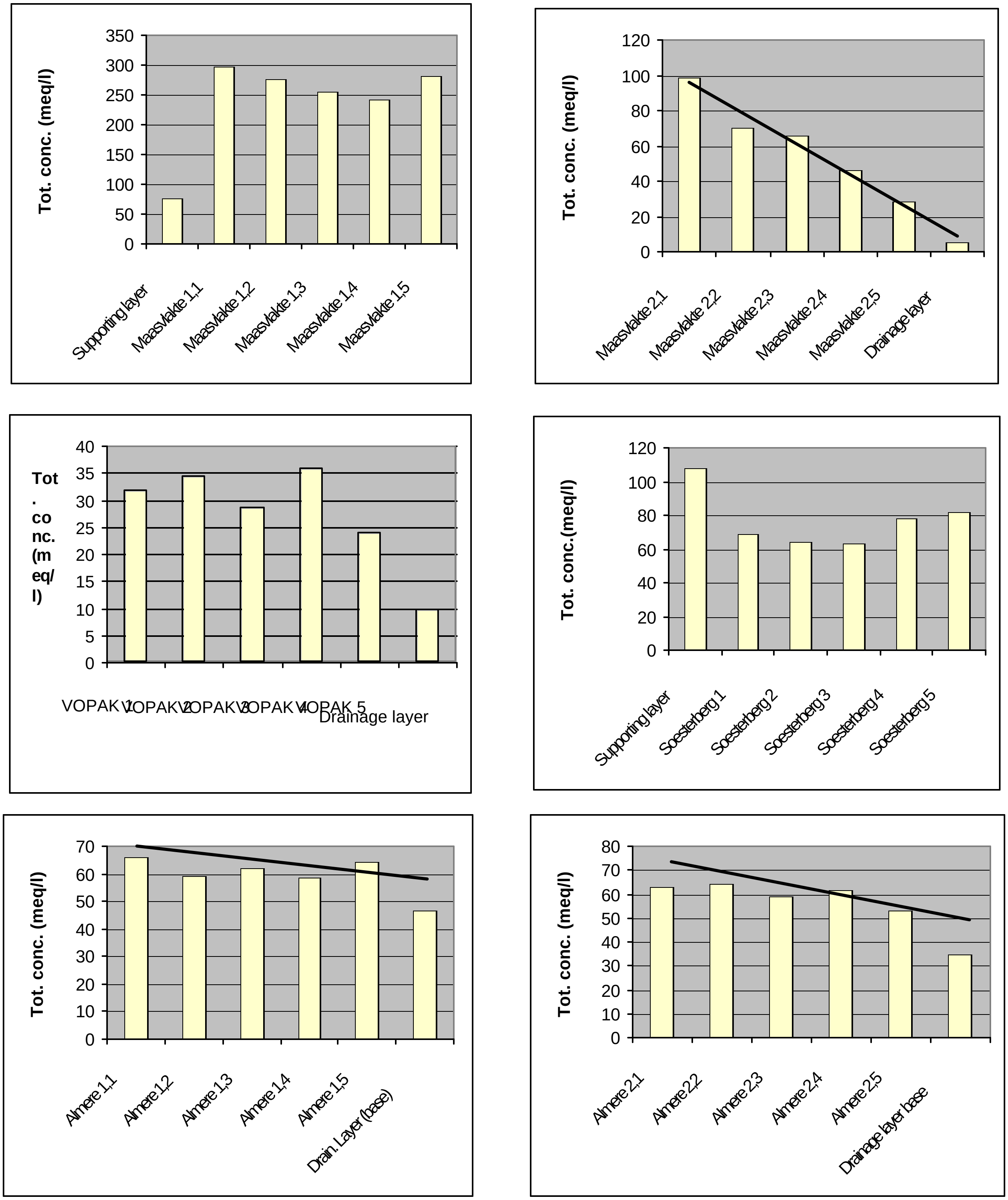
These gradients suggest leaching of salt from the Trisoplast layer. The expected annual infiltration rate at sites without a geomembrane is calculated according to leaching theories of conservative dissolved substances. Table 7 shows the calculated infiltration rates.

Table 7 Calculated annual infiltration rate at sites without a geomembrane, ignoring the contribution of molecular diffusion to transport of dissolved salts.

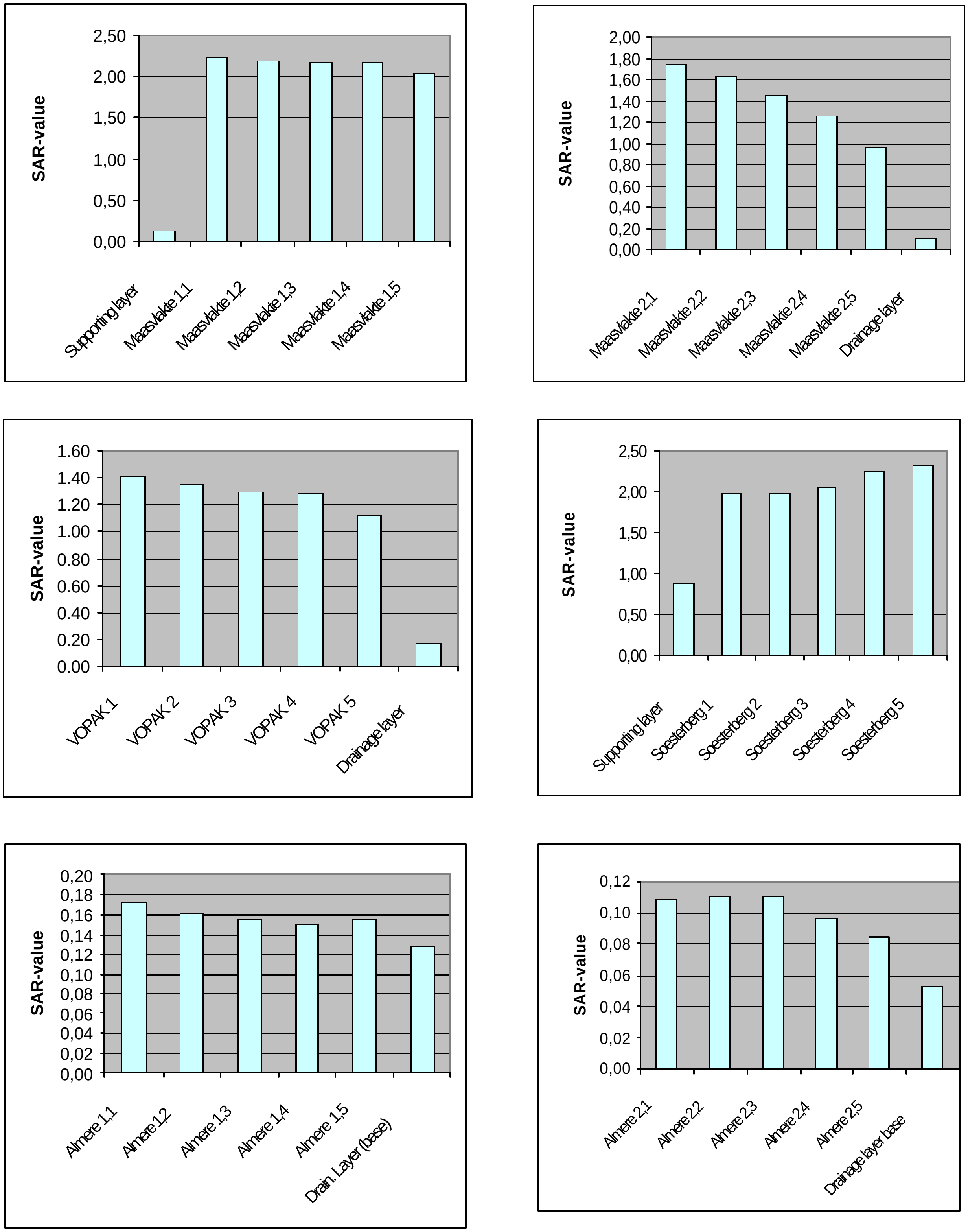
Site	Location	Infiltration rate (mm/y)
EuropoortVBM-maasvlakte	EUR2	1.5
VOPAK	VOP3	1.3
Almere	ALM4	0.2
	ALM5	0.7

The infiltration rates calculated from the water balance of Trisoplast amounted for the VBM Maasvlakte location 2 about 1 mm annually, which is close to the infiltration rate calculated according to this theory. The calculated infiltration rate for the Almere locations is much less than the minimum of 1.6 mm annually derived from the water balance. This analysis, however, shows that the actual infiltration rates are significantly less than the rates used for designing barrier dimensions. The limited infiltration rate is attributed to (1) the relative low permeability of Trisoplast, which is less than the required value; (2) the favourable drainage conditions at the slopes of the VBM Maasvlakte and Almere locations, (3) the coarse grainded texture of the subgrade, which limits the hydraulic gradients (Boels et al., 1993)

The SAR-values (fig. 9) show a clear gradient at the VBM-Maasvlakte location 2, where leaching has taken place. On the Almere locations a slight gradient seems present, so a certain leaching has probably occurred. At the Soesterberg location the SAR-gradient suggest a probable diffusion towards the supporting layer, but at a rather low pace.



Figuur. 8 Overview of total concentration in pore water solution in different sub layers in Trisoplast and the adjacent layers. Each sampled layer has a thickness of about 1-2 cm, depending on the total thickness of the Trisoplast layer



Figuur 9 *Overview of SAR-values (sodium adsorption ratio) of pore water solution in different sub layers in the Trisoplast layer*

The observed total concentration and SAR-value profiles suggest limited infiltration rates (< 2 mm annually) and displacement of dissolved substances through molecular diffusion.

3.5.2 Permeability

The permeability of Trisoplast, Ksat (= flux/gradient), is determined in a test where constant head conditions have repetitively been changed with falling head conditions. during a period of maximum 64 days. Annex 6 shows the observations. The average permeability of the Trisoplast barrier, Ksat (obs.), the fraction of bentonite determined according to the sedimentation method, the chemical pore water composition of the barrier, the sum of anions and cations, the sodium adsorption ration (SAR), and the average relative permeability of Trisoplast, K/Kref, calculated with the empirical relationship according Boels and Breen, 2001, are shown in table 8. Kref refers to the permeability measured with tap water. The parameters in the relationship between K/Kref and sum anions plus cations and SAR, were empirically determined from measured permeability of Trisoplast for liquids of different chemical composition (NaCl and $CaCl_2$).

Table 8 Permeability and other related parameters

Site	location	DBD (kg/m^3)	% bentonite (sedimen-tation method)	Sum anions + cations (meq/l)	SAR	K/Kref (calc.)	Ksat (obs.) (x 10^{-11} m/s)
VBM (+HDPE)	EUR1	1560	7.6	268	2.16	1.95	2.6
	EUR2	1490 – 1560	7.6	61.6	1.43	1.46	1.3
VOPAK	VOP3	1360	9.1	29.6	1.3	1.39	1.6
Almere	ALM4	1640	5.7	62.1	0.16	2.71	1.5
	ALM5	1580	5.7	60.3	0.1	2.78	4.3
Soesterb. (+HDPE)	SOE6	1570	6.9	71.2	2.11	1.07	2.1

The permeability of the Trisoplast, measured just before installation fell according to information of “Trisoplast Mineral Liners” in the range of 2.0– 3.3 10^{-11} $m.s^{-1}$. Compared to the recent observed data, the deviations are not significant. Because the absence of significance, the observed variation of the permeability cannot be attributed to variations of dry bulk density or the percentage of bentonite. Weak relationship exists between the observed permeability and the calculated ratio of actual permeability over the initial one (fig. 10, table 9). This suggests that the permeability of Trisoplast is hardly affected by the composition of the pore water in the observed range of salt concentration (29.6 – 268 meq/l) and SAR (0.1 – 2.16). This complies well with recent findings (Boels et al., 2002).

Table 9 Summarised chemical data and calculated K/Kref ratio after Boels and Breen, 2001:
${}^{10}Log(K/Kref) = 0.381511 + 0.001398*Tot.\ conc. - 0.21751*SAR$ ($R^2 = 0.94$)

Site	Sample location	Layercode acc. fig. 1	Tot. conc. (meq/l)	SAR	K/Kref	
Supporting layer	EUR1	7	75.37	0.13	2.87	
Maasvlakte 1,1	EUR1	1	297.34	2.23	2.05	
Maasvlakte 1,2	EUR1	2	276.31	2.19	1.96	
Maasvlakte 1,3	EUR1	3	254.72	2.18	1.84	Average:
Maasvlakte 1,4	EUR1	4	242.34	2.18	1.77	1.95
Maasvlakte 1,5	EUR1	5	280.59	2.05	2.13	
Drainage layer	EUR1	6		0.04	2.36	
Supporting layer	EUR2	7	41.92	0.07	2.66	
Maasvlakte 2,1	EUR2	1	99.05	1.74	1.38	
Maasvlakte 2,2	EUR2	2	70.28	1.63	1.33	
Maasvlakte 2,3	EUR2	3	65.92	1.45	1.44	Average:
Maasvlakte 2,4	EUR2	4	46.34	1.26	1.49	1.46
Maasvlakte 2,5	EUR2	5	28.63	0.96	1.63	
Drainage layer	EUR2	6	5.37	0.10	2.33	
Supporting layer	VOP3	7	23.32	0.34	2.19	
VOPAK 1	VOP3	1	32.02	1.41	1.31	
VOPAK 2	VOP3	2	34.35	1.36	1.36	
VOPAK 3	VOP3	3	28.60	1.30	1.38	
VOPAK 4	VOP3	4	35.97	1.29	1.42	Average:
VOPAK 5	VOP3	5	24.02	1.12	1.48	1.39
Drainage layer	VOP3	6	9.72	0.17	2.28	
Supporting layer	ALM4	7	34.90	0.15	2.50	
Almere 1,1	ALM4	1	66.00	0.17	2.73	
Almere 1,2	ALM4	2	59.19	0.16	2.69	
Almere 1,3	ALM4	3	62.25	0.16	2.72	
Almere 1,4	ALM4	4	58.89	0.15	2.70	Average:
Almere 1,5	ALM4	5	64.04	0.16	2.74	2.71
Drain. layer (lower half)	ALM4	6	46.57	0.13	2.62	
Drain. layer (upper half)	ALM4	6 top	45.59	0.03	2.75	
Supporting layer	ALM5	7	57.88	0.12	2.73	
Almere 2,1	ALM5	1	62.78	0.11	2.79	
Almere 2,2	ALM5	2	64.27	0.11	2.80	
Almere 2,3	ALM5	3	59.32	0.11	2.76	
Almere 2,4	ALM5	4	61.63	0.10	2.80	Average:
Almere 2,5	ALM5	5	53.34	0.08	2.74	2.78
Drain. layer (lower half)	ALM5	6	34.83	0.05	2.62	
Drain. layer (upper half)	ALM5	6 top	36.96	0.01	2.69	
Soesterberg 60 -90		recultiv. layer I	132.49	0.02	3.65	
Soesterberg 90 - 115		recultiv. layer II	72.70	0.01	3.02	
Supporting layer		7	108.11	0.88	2.19	
Soesterberg 1		1	68.65	1.97	1.12	
Soesterberg 2		2	64.10	1.97	1.10	
Soesterberg 3		3	63.42	2.05	1.06	
Soesterberg 4		4	77.89	2.26	1.00	Average:
Soesterberg 5		5	81.96	2.33	0.98	1.05
Drainage layer		6	48.96	0.01	2.80	

To check whether the Trisoplast barrier still meets the requirements of the Dutch legislation for barriers in caps of landfills, the actual safety factor of the Trisoplast barrier is calculated according to:

$$Safety\ factor = \frac{(\frac{1.0}{d_{leg}} + 1)\,K_{leg}}{(\frac{1.0}{d_{act}} + 1)\,K_{act}}$$

Where:

D_{leg} 0.075 m, legally accepted thickness in The Netherlands

K_{leg} 8.075 x 10^{-11} m.s^{-1} , legally maximum acceptable permeability for 0.075 m layer thickness

act actual value of parameter

The results are listed in table 10. A safety factor of 1 complies with the legal requirements. The higher this factor the better the sealing capacity of the barrier.

Table 10 Evaluation of actual performance of Trisoplast at different sites

Site	location	Thickness Trisoplast barrier (cm)	Ksat, obs. (x 10^{-11} m.s^{-1})	Actual safety factor
Europoort Rotterdam / VBM-Maasvlakte +HDPE	EUR1	8.0	2.6	3.3
VBM	EUR2	13.0	1.3	10.2
VOPAK	VOP3	14.0	1.6	8.9
Almere	ALM4	6.0	1.5	4.4
	ALM5	8.5	4.3	2.1
Soesterberg +HDPE	SOE6	9.0	2.1	4.6

The safety factors in table 10 are at all sites significant above the minimum of 1, so Trisoplast performs better than strictly required by the Dutch legislation. The estimated safety factor when Trisoplast was installed most probably varied between 2.0 and 7.1 for a minimum thickness of 6 cm and a highest permeability of 3.3 x 10^{-11} m.s^{-1} and a maximum thickness of 14 cm and a lowest permeability of 2.0 x 10^{-11} m.s^{-1}.

In the future probably the permeability will change due to a slow migration of dissolved salts from layer adjacent to Trisoplast, followed by exchange of cations. The worst case situation is when the pore water composition of Trisoplast becomes the same as the actual one of the adjacent layer which controls the quality: in systems without geomembrane that is the , in composite barriers with geomembrane this is the subgrade below the barrier. The expected change is calculated according to Boels and Breen, 2001. The followed procedure is that the future ratio of the future permeability over the initial permeability (measured with tap water), K/Kref, is calculated for the worst case situation and divided by the calculated actual ratio of K/Kref for the actual pore water composition in Trisoplast. The result is multiplied by the actual observed permeability and the (worst case) safety factor is again calculated (table 11)

Table 11 Calculated worst case safety factor at different sites

Site	Location	K/Kref		Safety factor	
		Actual	Worst case	Actual	Worst case
Europoort /VBM-Maasvlakte +HDPE	EUR1	1.95	2.87	3.3	2.2
VBM	EUR2	1.46	2.33	10.2	6.4
VOPAK	VOP3	1.39	2.28	8.9	5.4
Almere	ALM4	2.71	2.75	4.4	4.3
	ALM5	2.78	2.69	2.1	2.2
Soesterberg +HDPE	SOE6	1.05	2.19	4.6	2.2

The calculated worst case safety factor shows that the values are all above the lower limit of 1 (one), which means that also in the future Trisoplast will perform significantly better than required by the Dutch legislation. For these sites, Trisoplast is sustainable.

3.6 Precipitation of iron oxides and hydroxides in drainage layers

At the Almere site significant precipitation of iron oxides and hydroxides has been observed within the drainage layer forming rusty coloured coatings on the surface of the sand particles (see photos 43 and 44). Probably the iron originated from the topsoil, has been mobilised as Fe^{2+} before precipitation within the drainage layer as Fe^{3+}. Appendix 7 includes some laboratory data on pH, total concentrations and sequential extraction of Fe, Mn and Al.

The amount of Fe, which is extractable with the oxalat complex, contains the amorphous Fe, which can easily be mobilised. The Fe-content extractable with dithionit additionally contains the Fe, which is bound in pedogenetic Fe-oxides and hydroxides. Both fractions as well as the total iron content are much higher within the rusty coloured areas of the drainage layer at Almere than in the other drainage layers. Photos 7 and 8 of appendix 3 show the distribution of the iron coatings on the sand particles. The topsoil of profile 2 at the Europoort Rotterdam site also contains high concentrations of total and soluble iron.

3.7 Micromorphology of Trisoplast barriers

Appendix 3 contains several photos from thin sections through Trisoplast, which all prove that the mix of sand and the bentonite/polymer component is very homogeneous. The electron mircroscopical scans in appendix 4 give a very comprehensive impression of the microstructure of Trisoplast. The bentonite/polymer component settles within the pores between the sand fraction and sort of “glues together” these larger particles by forming “strings” which connect to the sand grains.

4 Conclusions

The results from the excavation of the six profiles at four locations allow some clear conclusions:

(1) Visual aspects

Trisoplast barriers were inspected under cover layers with different properties and thicknesses. In two profiles the Trisoplast barriers were covered by geomembranes. All six barriers appeared very homogeneous in colour, water content, bulk density, thickness, plasticity and structure. No indications for desiccation, crack formation or other ageing processes were found. Only under the thin cover (0.55 m) at profile EUR 2 plant roots had penetrated the barrier. This plant root penetration, however, has not yet caused any visually detectable damage to the barrier. The fact that Trisoplast has not formed any desiccation cracks even after being exposed for six years to the very severe boundary conditions under the thin cover of EUR 2 proves that Trisoplast is extremely unsensitive to desiccation. Under less severe or similar boundary conditions other mineral barriers and geosynthetic clay liners have failed completely and irreversibly in less time (Melchior 2001 and 2002). The observed plasticity of the excavated Trisoplast barriers furthermore indicates that no harmful ageing of the polymer component has taken place up to now.

(2) Micromophology of Trisoplast barriers

Thin sections and electron microscopical scans show that the microstructure of the inspected Trisoplast barriers and the distribution of the fine components, which are responsible for the sealing effect, are very homogeneous.

(3) Moisture content

The water content of the barriers has been sampled in depth intervals of 1 cm.

At the profiles EUR 1 and SOE 6 the Trisoplast barriers are covered by geomembranes. In both barriers the water content is totally homogeneous, 21 % by volume at EUR 1, 16 % by volume at SOE 6. This means that the water content has homogeneously increased within the barrier of EUR 1 by 6.5 % (by 5.4 % at the profile SOE 6). The reason for this increase of water content can only be water uptake from the supporting layers underneath the barriers, probably enhanced by thermally induced water transport. The measured water contents show that the barriers covered by geomembranes are still strongly unsaturated, the soil matric suction head probably being around 3000 hPa (EUR 1) and appr. 10000 hPa (SOE 6) when calculated on the base of the measured water retention characteristics.

The barriers at the profiles in Almere were much wetter (35 % by volume, suction head appr. 1000 hPa), the barrier at VOPAK was saturated.

At the profile EUR 2 with also no geomembrane on top of the Trisoplast barrier, the lower part of the barrier had similar water contents as underneath the geomembrane in profil EUR 1, the upper part was much wetter with the upmost cm being almost saturated. From this data it can be concluded that the infiltration of water from the drainage layer is extremely low and amounts to 1 to 2 mm per year.

(4) Pore water composition and permeability
The measured data on the chemical composition within the pore water of the Trisoplast barriers support the conclusions drawn from the water content measurements. Calculations based on the measured total ion concentrations and the sodium adsorption ratios result in annual infiltration rates of water from the drainage layers between 0.2 and 1.5 mm/a.
Measurements of the water conductivity of the barriers in the laboratory show saturated water conductivities between 1.3 and 4.3 x 10^{-11} m/s. Compared to the data measured with the same method after the placement of the barriers (2.0 to 3.3 x 10^{-11} m/s) no increase of permeability has been found.
Based on the measured ion concentrations and the permeability data safety factors for the performance of the barriers with respect to Dutch regulations were calculated. These factors show that the barriers– also in the future and even under worst case assumptions –will perform significantly better than required. Therefore the barrier can be regarded as sustainable.

References

AG Boden, 1994: Bodenkundliche Kartieranleitung. 4. Auflage, Hannover, p.p. 292

Anonymus. "Aanbeveling 33; Granulaire afdichtingslagen op basis van zandbentoniet al dan niet in combinatie met kunststof geomembranen". The netherlands, Gouda, Stichting CUR.

Boels, D., H. te Beest, H. Zweers, P. Groenendijk, 2002. "Investigation of the functional lifetime of TRISOPLAST". Wageningen, Alterra, Report 528, p.p. 40

Boels, D., 2001. Comparing performance of TRISOPLAST with different mineral barrier materials. In: Barriers, waste mechanics and groundwater pollution. Proceedings Volume III,. 8th International Waste Management and Landfill Symposium, 1-5 Oct, Sardinia, Italy, page 45 – 55.

Boels, D. and J. Breen, 2001. "Functional lifetime of mineral barriers and geomembrane in cap constructions of landfills". The netherlands, Wageningen, Alterra, Rapport 290, ISSN 1566-7197, p.p. 125 (Dutch)

Boels, D. en G.J.Veerman. 1996. "Doorlatendheid van Trisoplast voor verschillende vloeistoffen. Wageningen, DLO-Staring Centrum, Rapport 487

Boels, D. and K. van der Wal, 1999. Trisoplast® : New developments in soil protection. Proceedings Sardinia 99, seventh Intern. Waste management and landfill symposium, 4-8 October, 1999, page 77 - 84

Boels, D., P. Groenendijk, A.G. Hengeveld and M. M. Nass, 1993. Dispersion of polluting substances from landfills related to the quality of cap barriers. Wageningen, Winand Staring centre, Rapport 246 (Dutch)

Hoeks, J., H. P. van Oostrom, D. Boels, J. F. M. Borsten, K. Strijbis and W. ter Hoeven, 1990. "Richtlijn voor ontwerp en konstruktie van eindafdekkingen van afval- en reststofbergingen". Wageningen, Staring Centrum, Rapport 91.

Locher, W. P. and H. De Bakker (eds.), 1987. Bodemkunde van nederland; deel 1, Algemene Bodemkunde. The netherlands, Wageningen, Stichting voor Bodemkartering; Malmberg 's-Hertogenbosch.

Melchior, S., B. Steinert and O. Flöter, 2001. A comparison of traditional clay barriers and the polymer modified material trisoplast in landfill covers. In: Barriers, waste mechanics and groundwater pollution. Proceedings Volume III,. 8th International Waste Management and Landfill Symposium, 1-5 Oct, Sardinia, Italy, page 55 – 65.

MELCHIOR, S.,2001. Performance and design of cappings for contaminated sites and landfills. In. SARSBY, R.W. & T. MEGGYES (Hrsg.): The exploitation of natural resources and the consequences.Thomas Telford Publishing, London, S. 95-106.

MELCHIOR, S., 2002. Field studies and excavations of geosynthetic clay barriers in landfill covers. In: Zanzinger, H., R. M. Koerner & E. Gartung (eds.): Clay Geosynthetic Barriers, A.A. Balkema Publ., Lisse, Abingdon, Exton (PA), Tokyo, p. 321- 330.

Munsell Color Company Inc., 1994. Soil Color Charts. Baltimore, MN, USA

Weitz, A.M., D. Boels, H.J.J. Wiegers en J.J. Evers-Vermeer, 1994. “Toepassingsmogelijkheden van Trisoplast voor de afdichting van afval- en reststofbergingen”. Wageningen,DLO-Staring Centrum, Rapport 300