Application of TRISOPLAST for lining of landfills

A.M. Weitz
D. Boels
H.J.J. Wiegers
J.J. Evers-Vermeer

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ABSTRACT


TRISOPLAST is a mixture of a special clay gel and sand with a high swelling potential and plasticity. The permeability coefficient for water ranges from $0.1-0.4 \times 10^{-10}$ m.s$^{-1}$ and is not affected by landfill leachate, fluids with pH 1.5-10, exposure to UV-light, air and elevated temperatures. Bi-lateral strain does not affect the permeability while considerable consolidation makes TRISOPLAST virtually complete impermeable. Diffusion of dissolved substances is not impeded by TRISOPLAST. Compared with standard sand bentonite liners, TRISOPLAST requires 60% less raw materials and additionally reduces leachate losses with 60-90%.

Key words: plasticity, compaction, permeability, adsorption, cation exchange capacity, temperature

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Preface

In 1992 General Industrial Developments of Kerkdriel commissioned DLO-Staring Centre to investigate TRISOPLAST applications in barrier structures to protect the soil. TRISOPLAST is the trade name of a mixture of bentonite, sand and a polymer. The polymer binds to the bentonite in this mixture.

The material was tested in accordance with the Richtlijnen onderafdichtings-constructies voor stort- en opslagplaatsen (Landfill and storage site liner design guidelines) from the Dutch Ministry of Housing, Physical Planning and Environment (VROM), under the supervision of NOVEM (Netherland Organisation for Energy and Environment), the Dutch Department of Public Works (Rijkswaterstaat) and the ministry.
Summary

Commissioned by General Industrial Developments Benelux B.V., DLO-Staring Centre has tested the suitability of a mixture of a special clay gel and sand for sealing landfills. The trade names under which these clay gels are used are TONPLAST and TRISOPLAST. The variant consisting of a layer of clay gel mixed with a filler is called TRISOPLAST. The clay gel used in the production of TRISOPLAST is bentonite, and a standard and a lean variant are obtained by using different percentages of bentonite.

Because TRISOPLAST is a new material, it must be demonstrated, in compliance with the VROM, 1993 requirements for applications in barriers in landfills, that it is at least as effective as the current sand-bentonite barriers. To this end, its compactability and water permeability in relation to the dry weight by volume were tested. The thermal, chemical and mechanical stability, the water retention characteristics, plasticity, adhesion, diffusion coefficient and adsorption capacity, swelling behaviour and cation exchange capacity (CEC) were tested for the standard TRISOPLAST.

Standard TRISOPLAST was compacted to 1690 kg/m$^3$ in a compaction test, and lean TRISOPLAST to 1720 kg/m$^3$. The guideline value for the compaction to be achieved for bentonite mixed with sand is 1700 kg/m$^3$, so TRISOPLAST meets this requirement.

The swelling capacity of TRISOPLAST is reversible. The water absorption rate of the dry clay gel (800% in 1 hour and 950% after 24 hours) is greater than required and exceeds the rate for standard activated European bentonite.

The plasticity index of TRISOPLAST is 180%, i.e. substantially higher than the required 35% and very much higher than that of sand-bentonite mixtures (approximately 12%).

No air enters the material when moisture is extraced from saturated TRISOPLAST; it shrinks. TRISOPLAST loses very little water and remains airtight when exposed to the suction tensions which can be expected to occur temporarily in a landfill cover. No requirements have been formulated for this. Natural mineral barriers have been found to be temporarily permeable to gas under the conditions to which landfill covers are exposed.

Water permeability was determined for variants with different densities. The permeability is lowest at the highest density for both variants. Compaction to more than 92% Proctor density does not produce a significantly lower permeability. The preparation procedure has a clear effect on the permeability. Mixing the components with a very low moisture content yields a less permeable liner than mixing at high moisture content.
The flux through a landfill cover is required not to exceed 0.0001 m/day at a gradient of 5, while the flux through a landfill liner has to be less than 0.000055 m/day at a gradient of 2.6. This means that the respective permeabilities must be less than $2.3 \times 10^{-10}$ and $2.4 \times 10^{-10}$ m/s. The values measured so far for all variants ($0.1-0.6 \times 10^{-10}$ m/s) are well below this limit, the measured permeability of the highly plastic variants (1000 to 1300 kg/m$^3$) is close to the limit. The permeability of the usual sand-bentonite mixtures is more than 10 times higher than that of TRISOPLAST. A test on a semi-field scale at the ‘De Spinder’ landfill in Tilburg showed that this very low permeability can also be achieved under practical conditions for both the standard and lean mixtures.

A TRISOPLAST layer of 0.05 m would suffice to meet the requirement that the flux through the barrier must be less than 0.0001 m/day. The density needed for this is at least 92% Proctor density. The standard, lean and ‘dry’ mixed TRISOPLAST variants are suitable for this purpose.

Landfill leachate has no adverse effect on the permeability, and in fact might have a beneficial effect, so that no extra safety margin is needed to take account of adverse effects due to contact with leachate.

Neither very low pH (1.5) nor very high pH (10.0) has any effect on the permeability of TRISOPLAST-sand mixtures.

The cation exchange capacity reveals that a significant portion of the potential capacity is occupied or blocked by the polymer, reducing the effect of polyvalent ions on the permeability. The cation exchange capacity of the clay gel corresponds to that of the clay mineral illite.

It can be deduced from the bromine diffusion coefficient that TRISOPLAST does not cause additional inhibition of the diffusion of solutes.

Soluble organic compounds such as toluene and ethylbenzene are not adsorbed by TRISOPLAST, while the adsorption of butylbenzene andacenaphthene by TRISOPLAST is the same as that by sand.

High temperature, UV radiation or long-term exposure to the air has no adverse effect on the permeability of TRISOPLAST. Long-term storage is more likely to be beneficial than deleterious.

The effect of deformation on the permeability of TRISOPLAST could not be determined because virtually complete impermeability was obtained as a result of consolidation during the measurement. This behaviour makes TRISOPLAST very suitable for application on substrates where large irregular subsidence is expected.

The processing of TRISOPLAST is not impeded at the moisture content remains below the plastic limit of 35%. In practice, TRISOPLAST will be processed at moisture contents well below 20%. Good mixing produces a very homogeneous material, whose permeability remains within a very narrow range.
The relative insensitivity to variations in density makes TRISOPLAST less susceptible to implementation errors than the current mineral barrier materials.

TRISOPLAST's advantages are its very low water permeability, its insensitivity to landfill leachate, its high plasticity, the reduced risk thanks to the bonding with the gel-forming polymer of the bentonite being washed out, the modest compaction required (making the quality of the barrier much less dependent on the implementation accuracy than that of equivalent mineral barrier materials) and the virtually complete impermeability at high loads, which makes TRISOPLAST very suitable for landfill liners.

The use of TRISOPLAST in accordance with the present guidelines results in a reduction of the environmental impact on the soil of 30-90% compared with the usual materials. The use of TRISOPLAST barriers according to current requirements may lead to a reduction of at least 50% in the amounts of construction materials used, compared with the present sand-bentonite barriers. The application of TRISOPLAST in both landfill liners and covers can yield an increase in the landfill volume of at least 4000 m$^3$ per hectare, if these barriers are designed in accordance with the current design criteria (maximum flux for given conditions). Because of its high plasticity, TRISOPLAST is particularly suitable as a liner material in areas susceptible to settlement and as a cover material for landfills where large irregular subsidence is expected. Consequently, the choice of locations for landfills can be increased.
1 Introduction

Commissioned by General Industrial Developments (GID) Benelux B.V., DLO-Staring Centre has tested the suitability of a special clay gel for environmental applications. The clay gel is a mixture of certain polymers and bentonite and it derives its properties from molecular bonds between the clay particles and the polymer. These bonds also prevent the bentonite from being washed out of barriers. The absorption of water by the clay gel is completely reversible. The clay gel can absorb many times its own weight in water when not subjected to pressure. This clay gel is a Hungarian invention, and a patent application has been filed. The trade names under which these clay gels are used are TONPLAST and TRISOPLAST. The variant in which the clay gel, mixed with sand, is processed in dry or semi-dry condition is called TRISOPLAST.

According to the ‘Richtlijnen onderafdichtingsconstructies voor stort- en opslagplaatsen’ [Landfill and storage site liner design guidelines] (Bulletin of Acts, Orders and Decrees 55, 20 January 1993) applications of new barrier materials in landfill covers and liners after 1 March 1993 require proof that such materials are ‘at least as effective as’ existing mineral barrier materials. The reference is a 0.25 m sand-bentonite barrier with a percolation rate of 0.0001 m per day for a water pressure of 50 mbar at the top and an underpressure of 50 mbar at the bottom. There are additional requirements in respect of the plasticity.

Research results serve to demonstrate the ‘equal effectiveness’ and provide the basis for a Protocol for the application, processing, testing and acceptance of TRISOPLAST barriers.

This report describes the requirements which mineral materials must meet for the purpose of application in barriers. The properties tested, the methods used and the results are presented in Chapter 4, while TRISOPLAST is compared with other suitable mineral barrier materials in Chapter 5.
2 Required properties of materials for application in liners

New mineral barrier materials must be at least as good as existing sand-bentonite mixtures. To that end the requirements given below must be met.

Water permeability
Landfill covers have to prevent leachate formation through the infiltration of rain into dumped waste, while landfill liners must prevent the discharge of leachate into the soil. Because mineral barriers are not completely watertight, the guidelines require the minimum permeability which can be achieved at a certain moment using the best of the known materials and techniques. The reference at this moment is a 0.25 m thick sand-bentonite layer, with a percolation rate not exceeding 0.0001 m/day for a water tension of 50 mbar at the top of the layer and an underpressure of 50 mbar at the bottom. Barriers made from other materials must perform equally well or better under these conditions. For landfill liners, the reference thickness is 0.5 m, with a percolation rate of less than 0.02 m per year for a water tension of 50 mbar at the top of the layer and an undepressure of 30 mbar on the underside of the barrier.

Mechanical stability
The material is subjected to dynamic loads and strains as the barrier is being installed. The shear resistance in the slopes of landfills must be sufficiently large to prevent shear failure at gradients up to 1:2. Landfill liners undergo static loads up to about 1 MPa.

A landfill cover may partially dry out during periods of dry weather. In order to prevent the escape of landfill gas, the barrier material is allowed to shrink as a result of moisture loss, but no air should enter into the pores. Upon re-moistening, the water absorption capacity must exceed the precipitation excess (temporarily). Both the (reversible) swelling capacity and the swelling rate are important here.

Thermal stability
The temperature in landfills can increase temporarily to 70°C when organic material is present, and consequently the temperature in the (liner) barriers will also increase. It is assumed that the liner will be at a temperature of 30-40°C for several years, and the properties of the barrier material should not deteriorate as a result.

Chemical stability
In landfill covers and during processing (some of) the material is exposed to oxygen. The polymer in the clay gel must not oxidize or be biodegraded. The material must also be resistant to (usually brief) periods of UV radiation. The material in landfill liners comes into contact with landfill leachate, while the material in landfill covers can come into contact with components from the leachate through the diffusion of solutes.
Biological stability
Conditions in barriers may be either aerobic (thin layer at the top of landfill covers) or anaerobic. Aerobic conditions in landfill liners will not occur, and they will probably not be found in landfill covers either, as long as no moisture is extracted from the barrier material by underpressure drawing down the pore water. If certain threshold values are exceeded air will enter the pores and conditions will become aerobic. Plant roots are able to exceed such threshold values, but penetration by plant roots is generally prevented by using a drainage layer with a relatively high density (porosity < 39%). The environment for organisms in a barrier is characterized by an acidity between pH 4.5 and 7.0, a temperature between 15 and 40°C and anaerobic conditions.

Installation of liners
The installation of liners is a continuous process, in which the mixing of the various materials determines the quality of the barrier layer. It is important that the equipment available produces good, homogeneous and reproducible mixing in a short space of time. The mixture must not adhere to equipment and tools or form lumps during mixing, transport and distribution. Because the mixture is often made at the optimal moisture content in order to achieve the required density, the mixture must not adhere or form lumps at its optimal moisture content. Problem free installation is generally achieved if the moisture content of the material to be processed is below the plastic limit.

Check on composition
The nature and composition of the materials are determined on the basis of random samples. This check can be carried out on site or during the production or transport of the material. The quality of the monomer used to prepare the polymer will have to be guaranteed by the manufacturer. Checks on the nature and quality of the bentonite used and the sand can be made according to recommendations yet to be made by CUR in Gouda.

Special provisions during installation of barriers
Barriers are usually installed in strips. The joins between the strips ("seams") must have the same properties as the rest of the material. The mixture at the joins will dry out (somewhat) during installation. The joins should merge through water absorption and swelling of the material. A generous plasticity index and swelling capacity of the material is important here in view of the need to cover the joins temporarily during installation.

Environmentally harmful components, toxicity
The barrier must not contain any leachable components which are environmentally harmful or which are toxic to humans or animals.
3 Exploratory examination

An exploratory examination of the pure clay gel studied the permeability to different liquids, the behaviour of the polymers added and the use of fillers.

**Permeability**
The permeability of pure Tonplast to water, landfill leachate, gasoline and diesel fuel was tested by Grondmechanica Delft (CO-312920/5, March 1990, Wst/Msk).

The tests were done at two different vertical downward loads (2 and 5 kN/m\(^2\)). The applied volume of the leachate and other liquids were insufficient to replace the pore volume entirely with the test liquid. The geometric mean of the permeabilities measured for different samples amounted to 8.9 \times 10^{-11} \text{ m/s} for water.

According to current requirements, the permeability of sand-bentonite mixtures must be less than 30 \times 10^{-11} \text{ m/s}.

**Added polymer**
The ‘Expert Opinion on Tonplast water sealing material’ (Bela Johan National Institute for Public Health, Budapest, October 2, 1990) relates to an investigation of the polymer.

The polymer was analyzed and evaluated for application as a sealing barrier in a main water reservoir. The permitted limit for the monomer in water (0.5 mg/m\(^3\)) was not exceeded. For safety reasons, its use in mains water reservoirs is not recommended for the time being, because there is no knowledge about the biodegradability of the polymer.

The opinion of the experts Dr G. Schraa, Microbiology Department, Wageningen Agricultural University, and Dr W.M.J. van Gelder, head of Non-food Processing, DLO-ATO, Wageningen is that the polymer can not be decomposed by microbiological activity.

The probability of biological degradation of the polymer under anaerobic conditions at pH 4.5-7.0 was assessed on the basis of information about the polymer in the patent application and of the confidential product information that was provided. The (preliminary) conclusion is that the polymer will very probably not degrade, or at least not to a measurable degree.

**Fillers**
Professor O. Libor, Lorand Eotvos University, Chemical Engineering Department, Budapest, conducted a study of the possibilities for fillers in Tonplast.

The objective of the study was to establish whether Tonplast retains a continuous structure if fillers such as cement, gypsum or gravel are used. The structure of Tonplast becomes crumbly if more than 1% cement is added. The addition of gravel
is possible, as long as more than 25-50% Tonplast is used. The permeability of the mixtures of clay gel and fillers was not measured.
4 Materials and testing methods

GID is planning to use TRISOPLAST in landfill liners and covers which must comply with IBC criteria. The advantage of TRISOPLAST compared with the usual mixtures of sand and bentonite is that probably no stringent requirements need to be set for the compaction, while the layers can probably be thinner, which implies a reduction in the quantity of barrier material needed. Because TRISOPLAST is a new material, the ‘Richtlijnen onderafdichtingen voor afval- en reststoffbergingen’ [Landfill and storage site liner design guidelines] (Dutch Bulletin of Acts, Orders and Decrees 1 March 1993) require proof that the material is ‘at least as effective as’ a 0.25 m sand-bentonite barrier, with a percolation rate not exceeding 0.0001 m per day for a water pressure of 50 mbar at the top of the layer and an underpressure of 50 mbar at the bottom. Additional tests were therefore carried out into:
- the permeability of TRISOPLAST in relation to the degree of compaction and the nature of the test liquid;
- the relation between UV irradiation and permeability, and between storage time under aerobic conditions and permeability;
- the relation between storage time at 30°C and permeability;
- the relation between strain and permeability;
- the moisture retention characteristics in the range of 0 to -150 mbar water tension and its relation with the air penetration value;
- the reversibility and extent of swelling and shrinkage;
- the plasticity index;
- the relation between moisture content and adhesion between TRISOPLAST and metals and plastics;
- the cation exchange capacity (adsorption);
- the capacity to adsorb some organic compounds;
- the diffusion coefficient of polar substances (using bromide as a tracer);
- the chemical and biological stability (durability) of the polymer;
(carried out and reported separately by DLO-ATO)
- the maximum gradient of a saturated layer of TRISOPLAST under a vertical downward load of 50 kPa (carried out and reported separately by Grondmechanica Delft, Delft).

4.1 Material

TRISOPLAST is a mixture of a clay mineral, a polymer and filler.

A sodium-enriched bentonite (pH-H2O 10.5) is the clay mineral and it is supplied as a powder. The polymer is supplied as a 5% aqueous solution (pH-H2O 7.8).

The filler used is washed, moist river sand (pH-H2O 7.6) of two size classes: coarse, designated as type ‘M4’ and less coarse, designated as type ‘M2’. The texture (particle size distribution) was determined by wet-sieving the sand fraction (Table 1).
Table 1  Granular composition of the sand used

<table>
<thead>
<tr>
<th>Class</th>
<th>Class size</th>
<th>Type ‘M4’</th>
<th>Type ‘M2’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay and silt</td>
<td>0- 50 µm</td>
<td>0.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Fine sand</td>
<td>50- 210 µm</td>
<td>3.8%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>210-2000 µm</td>
<td>69.7%</td>
<td>83.9%</td>
</tr>
<tr>
<td>Gravel</td>
<td>&gt; 2000 µm</td>
<td>26.0%</td>
<td>13.4%</td>
</tr>
</tbody>
</table>

Type ‘M4’ sand has almost twice as much gravel as type ‘M2’ sand.

4.2 Preparation of TRISOPLAST

The Hungarian developer of TONPLAST has specified the optimal proportions for the mixture of bentonite, polymer and sand. The mixtures can be made in two different ways:

a) mixing at very low moisture content.
   The moist sand is mixed with the polymer solution and bentonite in a prescribed way. The result is a crumbly, particulate material.

b) mixing at high moisture content.
   The bentonite powder is stirred mechanically with water to a ‘cream’, to which the polymer solution and sand are added. The result is a very plastic, compact mass.

A special mixing variant, in which a special dry mixture of the clay gel is mixed with moist sand, was investigated. The result was a homogeneous, loose and crumbly material.

Specific densities were obtained by weighing a quantity of material and then compacting to a preset volume.

4.3 Test design

The relation between compactability and moisture content (Proctor curve) was first determined for dry-mixed standard and lean TRISOPLAST. On the basis of this, different combinations of density and moisture were chosen for measuring the permeability to water and landfill leachate.

Samples of standard TRISOPLAST compacted to 92% Proctor density were used to investigate the relationship between permeability and UV exposure etc., the diffusion coefficient, moisture retention characteristics and shrinkage behaviour.

In addition to the water permeability of the special variant, the permeability of samples of mixtures with various proportions of sand and bentonite (without polymer) was also determined, for the purpose of comparison. The required density of these mixtures was determined using the Proctor method.
The plasticity index, adhesion and adsorption were determined for standard TRISOPLAST samples; the water absorption behaviour and cation exchange capacity were determined for clay gel without filler.

Table 2 gives an overview of the parameters investigated and the methods used.

Table 2 Properties tested and methods used

<table>
<thead>
<tr>
<th>Property</th>
<th>Type of mixture</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compactability</td>
<td>standard, lean, special variant</td>
<td>Proctor test</td>
</tr>
<tr>
<td>Permeability (water, leachate)</td>
<td>dry-mixed standard and lean prepared dry</td>
<td>falling head</td>
</tr>
<tr>
<td>Permeability (water)</td>
<td>wet-mixed standard and 'standard plus 4% bentonite' prepared wet</td>
<td>falling head</td>
</tr>
<tr>
<td>Permeability after susceptibility</td>
<td>standard</td>
<td>falling head and triaxial test</td>
</tr>
<tr>
<td>Moisture retention, shrinkage behaviour</td>
<td>standard</td>
<td>hanging water column &amp; shrink test</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>standard</td>
<td>plastic limit and liquid limit determination</td>
</tr>
<tr>
<td>Water absorption and drying behaviour</td>
<td>clay gel</td>
<td>Enslin method</td>
</tr>
<tr>
<td>Adhesion to metals and plastics</td>
<td>standard</td>
<td>adhesion test</td>
</tr>
<tr>
<td>Adsorption capacity (CEC) and cation content</td>
<td>clay gel</td>
<td>CEC and exchanged cations</td>
</tr>
<tr>
<td>Adsorption capacity of non-polar substances</td>
<td>lean</td>
<td>microcolumn system, HPLC technique</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
<td>standard</td>
<td>half-cell method</td>
</tr>
</tbody>
</table>

4.4 Methods

4.4.1 Proctor test

The compaction behaviour of the material is determined by its composition (texture, organic matter content etc.), the compaction energy and the moisture content. The maximum density and the associated optimal moisture content were determined using the Standard Proctor Test (Standard RAW, Determination, 1990, test 5.1). This density is referred to as the Proctor density. It has been found in practice that this density can be achieved using the techniques commonly applied in road building.

The Proctor test was carried out using an automated standard instrument, in which the material to be tested is compacted in a cylinder using a free-falling tamper. The
sample is built up from three 0.04 m layers, using 25 tamps per layer, with the tamps spread evenly over the surface of the sample. The sample is trimmed after which the weight by volume is determined by weighing. The contents of the cylinder are then dried at 105°C for 24 hours, after which the weight is determined again. The dry weight by volume and the moisture content (weight %) are calculated from these measurements. The test is repeated for different moisture contents, and the results are expressed in graphical form (the Proctor curve). The graph shows the maximum (Proctor) density and the corresponding moisture content.

4.4.2 Permeability

The saturated water permeability of TRISOPLAST was determined in the laboratory by means of the falling head method (Hoeks et al., 1990). The method entails introducing a sample in a stainless steel ring and mounting it in the measurement apparatus (Fig. 1). The sample is 0.025 m thick. The remaining volume of the ring is filled with washed, moist dune sand. The sample is saturated from below. The whole measurement system is filled with water prior to the measurement, so that water from the riser can flow through the sample to the discharge point. The quantity of water entering is determined from the movement of the meniscus in the riser. The quantity discharged is collected as a check. The permeability (K) is calculated according to:

\[
K = \frac{a \cdot d}{A \cdot \Delta t} \cdot \ln \frac{h(1)}{h(2)}
\]  

where:

- \(K\) = permeability (m/s)
- \(h(1)\) = water level in riser at time \(t(1)\) (m)
- \(h(2)\) = water level in riser at time \(t(2)\) (m)
- \(\Delta t\) = \(t(2) - t(1)\) (s)
- \(A\) = cross-sectional area of the sample (m²)
- \(a\) = cross-sectional area of the riser (m²)
- \(d\) = thickness of the sample (m)

The average hydraulic gradient (i) over the time interval \(\Delta t\) is calculated according to:

\[
i = \frac{h(1) - h(2)}{d} / \ln \frac{h(1)}{h(2)}
\]  

The measurements were first carried out with water, until the measured permeabilities remained constant at different gradients. Thereafter, landfill leachate was added and measurements were continued for 3 months. As an additional test, the landfill leachate was replaced for some samples by dilute hydrochloric acid (pH 1.5) or sodium hydroxide (pH 10), after which the permeability was measured again.
The permeability was verified in a field test. A test site was prepared at the 'Spinder' landfill in Tilburg, and the permeability was measured in situ and in undisturbed samples with a diameter of 0.3 m.

4.4.2.1 UV test

The effect of UV radiation on the permeability of standard TRISOPLAST was determined by exposing the test material to sunlight for a period corresponding to the UV load from a 5 day exposure in the summer. Current meteorological data were used to establish the UV load. The average summer load during the last ten years in Wageningen was used to set the desired UV load.

The test involved spreading the material out in a thin layer and exposing it to sunlight. Losses due to evaporation were made up every day. Over this period, the test material received a total of 720 J/cm². The water permeability was determined immediately afterwards (see 3.4.2).
4.4.2.2 Oxidation test

The effect of oxidation by air on the permeability of standard TRISOPLAST was determined by spreading it out in a thin layer and exposing it to the air. The mixture was placed in a humid environment in order to prevent it drying out. The test lasted 3 months, the same duration as the UV test, allowing any oxidation effects in the UV test to be eliminated. The water permeability was measured over a 3 months period after the end of the oxidation phase (see 3.4.2).

4.4.3 Strain test

The relation was determined between the deformation of standard TRISOPLAST with a known density and the water permeability. A sample was deformed by directed pressure without changing its density. The permeability before and after deformation was measured using the falling head method.

The test used a triaxial apparatus according to Boels (1977), in which a sample is compressed in a cylinder to the desired density. After removal from the cylinder the sample was sheathed in a latex membrane, its top and bottom were covered with ceramic filters and it was placed in a triaxial cell. The latex membrane provided a watertight and gastight barrier between the permeability measurement system and the liquid in the pressure chamber. The pressure cell was filled with water and kept at a pressure of about 3 bar, which is comparable with the conditions at the bottom of a landfill. After the sample had become saturated, the permeability was determined using the falling head method. Immediately thereafter the sample was deformed and the permeability was measured again. This procedure was repeated a number of times in order to determine the relationship between bi-axial strain and permeability.

4.4.4 Water retention and shrinkage characteristics

The gas-tightness of the material was derived from the water retention properties. The water retention function describes the capacity of material to retain water in the pores against an underpressure in the pore water. The air penetration value is determined to establish the water content at which the material just becomes permeable to air. Plant roots will only grow in a porous material if air is present as well as water, while landfill gas can escape if at least some of the pores are filled with air.

The water retention of porous material is determined by means of the hanging water column method. TRISOPLAST was compressed to the desired density in a metal cylinder, placed on a ceramic plate and saturated. During the measurements, the underpressure was lowered stepwise and the change in the moisture content of the sample was measured.

TRISOPLAST displayed marked swelling properties. The absorption of water was accompanied by a volume increase. When moisture was removed from this swollen
material, the sample shrank. After a shrinkage phase, in which the water loss is directly proportional to the volume change, the water removed is replaced by air. The moisture content at which air first enters the material (the air penetration value) was determined by means of a shrinkage experiment, in which the swollen material was wrapped in Saran film. This film is permeable to water vapour, but not to liquid water. The changes in the volume of the samples were determined through underwater weighing. Air enters the material as soon as evaporation losses and shrinkage volumes are no longer equal.

4.4.5 Enslin test

The water absorption behaviour of TRISOPLAST was determined using the Enslin test. This test was carried out with pure clay gel, because sand has no water absorption properties.

The clay gel from standard TRISOPLAST was spread in a thin layer on the porous ceramic plate of the Enslin apparatus. The porous plate was connected to a horizontal capillary, from which water could be absorbed at a water tension of 0 mbar. The quantity of water absorbed by the test material was measured at different moments. The test series was stopped after 72 hours. The material was then air-dried, powdered and spread once again in a thin layer on the ceramic plate, and the test was repeated, in order to test the reversible behaviour.

4.4.6 Plasticity index

The plasticity index is defined as the difference in water content between the plastic limit and the liquid limit, and is calculated as a percentage of the dry weight. This percentage characterizes the range of moisture contents within which the material displays plastic behaviour. The determinations were made using standard TRISOPLAST.

4.4.6.1 Plastic limit

The plastic limit is defined as the minimum water content of a material at which it can still be rolled out by hand on a porous stone plate to form a roll of about 0.003 m diameter without cracking. The moisture content is determined by drying the test material for 24 hours in a drying oven at 105°C. The plastic limit test was repeated 10 times.
4.4.6.2 Liquid limit

The liquid limit is defined as the water content at which the plastic state of the material changes to a liquid state, and is determined using the Cassagrande apparatus. A spatula is used to create a groove with a width of 0.002 m and a depth of 0.012 m in a test sample. The sample is then subjected to a type of standard fall test in the apparatus. The liquid limit is reached when the groove fills up within 10 to 12 seconds. The corresponding moisture content is determined by drying and weighing.

4.4.7 Adhesion

The adhesion between TRISOPLAST and metals and plastics determines the material’s practical applications. The adhesion was determined by bringing samples of TRISOPLAST with different moisture contents into contact with the materials and determining how much material adhered. The moisture contents were accurately determined directly afterwards by weighing and drying.

4.4.8 Adsorption capacity (CEC) and cation content

The adsorption capacity of TRISOPLAST is a measure of the number of electrochemical bonding sites for cations. The cation content is always lower than the total adsorption capacity of a mineral material, because hydrogen ions are also bound. The cation content of a clay mineral determines its physical and chemical properties.

The cation content of the clay gel was determined by exchanging all cations present (aluminium, iron, manganese, calcium, magnesium, sodium and potassium) with barium ions. The ion concentrations were determined using an ICP-AES (Induction Coupled Plasma - Atom Emission Spectrophotometer). All the bound barium ions were then exchanged with magnesium ions in a second step. The adsorption capacity was determined by measuring the quantity of magnesium ions used for this exchange.

4.4.9 Adsorption process

The kinetics of organic micro-contaminants sorption to TRISOPLAST was determined using a microcolumn system according to Velthorst (1990). In this test, an eluent, containing certain model substances, is forced through a column (length 25 cm, diameter 4.6 mm) filled with the TRISOPLAST sample at a constant flux of 0.1 ml/minute. The concentrations of the model substances in the inflowing and outflowing liquid (eluent and effluent) are measured simultaneously. The total adsorption is the difference between the quantity of solute flowing into the column and the quantity flowing out. HPLC (High Pressure Liquid Chromatography) is used to detect the model substances.

The breakthrough curve (showing the time course of the concentration in the effluent) reveals the delayed transport of the model substances through the column as a result
of the adsorption processes. The total adsorption of a particular substance is measured by determining the adsorption and desorption. The time course of the concentration of the substance in the effluent is determined in both tests and is plotted graphically against the volume of liquid that has flowed through. The adsorption curve rises steadily and reaches a maximum, while the desorption curve declines steadily to reach a minimum. The breakthrough volume is derived from the point where the two curves intersect. The total adsorption is equal to the total amount of substance in the breakthrough volume. The effective porosity of the test column is determined from the adsorption and desorption curves of a nitrate solution. Since nitrate is not adsorbed, the effective pore volume can be derived from the intersection of the two curves.

Toluene, ethylbutene, acenaphthene and butylbenzene were selected as characteristic model substances. Since the permeability of the lean TRISOPLAST was lower than the value required for this method, an extra-lean TRISOPLAST with a very low bentonite content was used. The same test was also carried out using pure sand. The adsorption capacity of standard TRISOPLAST was calculated from the two breakthrough curves.

4.4.10 Diffusion

Diffusion is the movement of substances in a material as a result of molecular movement in the absence of mass flow. Diffusion is characterized by the diffusion coefficient, which is independent of the concentration of the substance, but depends on the nature of the substance, the porosity and the geometry of the pore system. The ratio between the diffusion coefficients of different substances in porous media equals the ratio of their diffusion coefficients in water. Bromide ions were used for the determination of the diffusion coefficient.

The diffusion coefficient of bromide ions in standard TRISOPLAST was determined using the half-cell method (Yong et al., 1992). Two identical stainless steel rings are filled with standard TRISOPLAST samples of equal density. A potassium bromide solution is introduced into one of the cells. After saturation with water, both cells are combined, ensuring close contact between the two samples. In the saturated sample, bromide ions diffuse through the interface, going from the cell with the high concentration to the cell with the low concentration, until the bromide concentrations in both cells are the same. The bromide distribution was determined for different samples at different times, and the results we used to calculate the diffusion coefficient of bromide in TRISOPLAST.
4.5 Results

4.5.1 Proctor test

The values measured in the Proctor tests on standard and lean TRISOPLAST are given in Table 3, and the Proctor curves and densities in figure 3. A complete Proctor curve for the 'M4' sand type was prepared for both the mixtures tested. Three Proctor values were determined for each mixture of the 'M2' sand type and compared with those of the 'M4' type.

It can be seen from Table 3 that the type of sand has no effect on the density obtained. Therefore one Proctor value was considered sufficient in the further tests. All subsequent tests in this study were carried out with 'M2' sand type. The Proctor density of standard TRISOPLAST is 1680 kg/m\(^3\) at a moisture content of 16% while that of lean TRISOPLAST is 1720 kg/m\(^3\) at 16% by weight.

According to the guidelines, it must be possible to compact barrier material with filler to at least a dry weight by volume of 1700 kg/m\(^3\) in order to achieve a sufficiently low permeability. With a Proctor density of 1680 kg/m\(^3\), standard TRISOPLAST is just below this guideline, but the difference is negligible.

<table>
<thead>
<tr>
<th>Moisture (% by weight)</th>
<th>Standard TRISOPLAST</th>
<th>Lean TRISOPLAST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>'M2'</td>
<td>'M4'</td>
</tr>
<tr>
<td>9.5</td>
<td>1620</td>
<td>1620</td>
</tr>
<tr>
<td>11.4</td>
<td>1720</td>
<td>1720</td>
</tr>
<tr>
<td>12.3</td>
<td>1650</td>
<td>1700</td>
</tr>
<tr>
<td>12.4</td>
<td>1700</td>
<td>1710</td>
</tr>
<tr>
<td>14.4</td>
<td>1690</td>
<td>1700</td>
</tr>
<tr>
<td>15.0</td>
<td>1690</td>
<td>1720</td>
</tr>
<tr>
<td>15.3</td>
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<td>1670</td>
</tr>
<tr>
<td>15.8</td>
<td>1680</td>
<td>1670</td>
</tr>
<tr>
<td>16.3</td>
<td>1660</td>
<td>1660</td>
</tr>
<tr>
<td>17.0</td>
<td>1660</td>
<td>1670</td>
</tr>
<tr>
<td>17.3</td>
<td>1610</td>
<td>1610</td>
</tr>
<tr>
<td>19.2</td>
<td>1590</td>
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<tr>
<td>19.9</td>
<td>1550</td>
<td>1580</td>
</tr>
<tr>
<td>20.4</td>
<td>1500</td>
<td>1590</td>
</tr>
<tr>
<td>21.9</td>
<td>1450</td>
<td>1500</td>
</tr>
<tr>
<td>23.5</td>
<td>1370</td>
<td>1450</td>
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<tr>
<td>23.6</td>
<td>1360</td>
<td>1450</td>
</tr>
<tr>
<td>32.8</td>
<td>1270</td>
<td>1350</td>
</tr>
<tr>
<td>34.1</td>
<td>1270</td>
<td>1360</td>
</tr>
</tbody>
</table>
Fig. 2 Proctor curves of TRISOPLAST-sand mixtures

Lean TRISOPLAST, with a Proctor density of 1720 kg/m³, is just above the guideline value. The densities for all subsequent tests were selected on the basis of the results of the Proctor tests. Table 4 gives an overview of the test variants.

Permeability measurements were carried out with different test liquids at Proctor densities ranging from 59 to 100%.
4.5.2 Permeability

Table 4 describes the conditions under which the permeability of the different variants was measured (tests A to D) for water and landfill leachate. The results are given in Table 5. All measurements were made in duplicate. The table lists permeability values for each measurement cell for each test liquid, as well as the geometric mean for each variant. The duplicate measurements of all variants show good reproducibility. The maximum differences measured between the Tonplast-sand mixture duplicates are $2.0 \times 10^{-11}$ m/s for water and $2.4 \times 10^{-11}$ m/s for landfill leachate.

Table 4 Dry weight by volume of different samples used in the permeability tests

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Density (kg/m$^3$)</th>
<th>Moisture (%)</th>
<th>Proctor density (%)</th>
<th>Type of test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>1690</td>
<td>16</td>
<td>100.0</td>
<td>A, B</td>
</tr>
<tr>
<td>1680</td>
<td>20</td>
<td>99.4</td>
<td>A, B, C</td>
<td></td>
</tr>
<tr>
<td>1560</td>
<td>16</td>
<td>92.3</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>1560</td>
<td>25</td>
<td>92.3</td>
<td>A, B, C, D, E, F, G</td>
<td></td>
</tr>
<tr>
<td>1230</td>
<td>40</td>
<td>72.8</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>*) 1000</td>
<td>63</td>
<td>59.2</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>**) 1000</td>
<td>75</td>
<td>----</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>Lean</td>
<td>1720</td>
<td>16</td>
<td>100.0</td>
<td>A, B</td>
</tr>
<tr>
<td>1670</td>
<td>20</td>
<td>97.1</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>1570</td>
<td>25</td>
<td>91.3</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>1340</td>
<td>35</td>
<td>77.9</td>
<td>A, B</td>
<td></td>
</tr>
</tbody>
</table>

Explanation of symbols:

*) 'wet-mixed' material

**) 'wet-mixed' material with 4% higher bentonite content than the standard mixture

Explanation of types of test:

A = permeability to water

B = permeability to landfill leachate

C = permeability at different pHs

D = permeability to water subject to several influences

E = permeability related to bi-axial strain

F = water retention and shrinkage behaviour

G = bromide diffusion

The lowest water permeability was measured in the duplicates of standard TRISOPLAST with Proctor densities between 92 and 100%; an average of $4.3 \times 10^{-11}$ m/s.

The average permeability of the lean mixture at corresponding Proctor density values was $5.9 \times 10^{-11}$ m/s. Although the permeability of the lean TRISOPLAST is somewhat higher, the difference is small. The permeability of the least compacted samples (i.e. those with the highest prior moisture content) for the two 'dry-mixed' TRISOPLAST variants is $11 \times 10^{-11}$ m/s and $16 \times 10^{-11}$ m/s. This is about 2.5 times higher than that of the more compacted material. The permeability measured in the samples with a low degree of compaction is comparable with that of the 'wet-mixed' variants. The average water permeability of 'dry-mixed' samples with a low dry weight by volume is $14 \times 10^{-11}$ m/s, while that of the 'wet-mixed' samples is $19 \times 10^{-11}$ m/s.
The average permeability of standard TRISOPLAST (1560 kg/m³) prepared with less water than is needed for a maximum density is 6.9*10⁻¹¹ m/s, which is higher than the value for the material prepared with more water (average 4.3*10⁻¹¹ m/s).

It can be seen from Table 5 that the permeability of all variants to landfill leachate is substantially lower than that to water. The difference for lean TRISOPLAST is generally larger than that for comparable variants of standard TRISOPLAST. The permeability of the more compacted variants (92-100% Proctor density) is an average of 2.5*10⁻¹¹ m/s lower for landfill leachate than for water, while comparable variants of the lean mixture show an average difference of 3.2*10⁻¹¹ m/s. A more marked reduction of the permeability was found for the less compacted 'dry'-mixed variants and the 'wet-mixed' variants with decreases ranging from 5.0*10⁻¹¹ m/s to 7.0*10⁻¹¹ m/s.

The measurements show a clear relation between the dry weight by volume and the permeability (Fig. 3). This relation applies for both water and landfill leachate as test liquids, but it is slightly less pronounced in the case of leachate. Since for all mixtures the samples with a high dry weight by volume have the lowest permeability, or at least a clearly lower permeability than the 'wet-mixed' variants, it can be concluded that a high degree of compaction of the material is important. However, Proctor densities higher than 92% have no significant effect on the permeability.

For the sake of comparison, figure 3 shows the water permeability of a sand-bentonite mixture without added polymer. This variant had a density of 1560 kg/m³ and had

---

**Table 5 Permeability results for water and landfill leachate**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Density (kg/m³)</th>
<th>K measured for water (m/s)</th>
<th>Geometric mean of K</th>
<th>K measured for leachate (m/s)</th>
<th>Geometric mean of K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>1690</td>
<td>5.5*10⁻¹¹</td>
<td>4.8*10⁻¹¹</td>
<td>1.8*10⁻¹¹</td>
<td>2.7*10⁻¹¹</td>
</tr>
<tr>
<td></td>
<td>1680</td>
<td>4.2*10⁻¹¹</td>
<td>3.7*10⁻¹¹</td>
<td>4.2*10⁻¹¹</td>
<td>1.0*10⁻¹¹</td>
</tr>
<tr>
<td></td>
<td>1560</td>
<td>3.9*10⁻¹¹</td>
<td>4.7*10⁻¹¹</td>
<td>2.5*10⁻¹¹</td>
<td>1.8*10⁻¹¹</td>
</tr>
<tr>
<td>l.m.</td>
<td>1560</td>
<td>6.9*10⁻¹¹</td>
<td>4.3*10⁻¹¹</td>
<td>2.8*10⁻¹¹</td>
<td>1.6*10⁻¹¹</td>
</tr>
<tr>
<td></td>
<td>1230</td>
<td>7.0*10⁻¹¹</td>
<td>6.9*10⁻¹¹</td>
<td>3.0*10⁻¹¹</td>
<td>2.9*10⁻¹¹</td>
</tr>
<tr>
<td>w.m.</td>
<td>1000</td>
<td>1.1*10⁻¹⁶</td>
<td>1.1*10⁻¹⁰</td>
<td>1.1*10⁻¹⁰</td>
<td>1.2*10⁻¹⁰</td>
</tr>
<tr>
<td></td>
<td>1720</td>
<td>1.7*10⁻¹⁶</td>
<td>1.8*10⁻¹⁰</td>
<td>1.3*10⁻¹⁰</td>
<td>1.3*10⁻¹⁰</td>
</tr>
<tr>
<td>w.m.4%</td>
<td>1000</td>
<td>2.0*10⁻¹⁶</td>
<td>1.9*10⁻¹⁰</td>
<td>1.2*10⁻¹⁰</td>
<td>1.2*10⁻¹⁰</td>
</tr>
<tr>
<td>Lean</td>
<td>1670</td>
<td>5.8*10⁻¹¹</td>
<td>5.5*10⁻¹¹</td>
<td>2.4*10⁻¹¹</td>
<td>2.4*10⁻¹¹</td>
</tr>
<tr>
<td></td>
<td>1570</td>
<td>5.7*10⁻¹¹</td>
<td>5.7*10⁻¹¹</td>
<td>2.3*10⁻¹¹</td>
<td>2.3*10⁻¹¹</td>
</tr>
<tr>
<td></td>
<td>1340</td>
<td>6.5*10⁻¹¹</td>
<td>6.3*10⁻¹¹</td>
<td>3.0*10⁻¹¹</td>
<td>3.1*10⁻¹¹</td>
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<tr>
<td></td>
<td>1.6*10⁻¹⁶</td>
<td>1.6*10⁻¹⁰</td>
<td>9.5*10⁻¹ⁱ</td>
<td>9.3*10⁻¹¹</td>
<td>9.4*10⁻¹¹</td>
</tr>
</tbody>
</table>

l.m. less than optimal moisture content after preparation
w.m. 'wet-mixed', otherwise like standard mixture
w.m.4% 'wet-mixed' like standard mixture plus 4% bentonite

The measurements show a clear relation between the dry weight by volume and the permeability (Fig. 3). This relation applies for both water and landfill leachate as test liquids, but it is slightly less pronounced in the case of leachate. Since for all mixtures the samples with a high dry weight by volume have the lowest permeability, or at least a clearly lower permeability than the 'wet-mixed' variants, it can be concluded that a high degree of compaction of the material is important. However, Proctor densities higher than 92% have no significant effect on the permeability.
been prepared with a moisture content of 25%. The average permeability of the sand-bentonite mixture is $9.5 \times 10^{-11}$ m/s, i.e. more than twice as high as that of TRISOPLAST.

Fig. 3 Relation between dry weight by volume and permeability to water and landfill leachate.
According to Hoeks et al. (1990) a flux of less than 0.0001 m/day at a gradient (i) of 5 is required for a 0.25 m landfill cover and a flux of less than 0.000055 m/day at a gradient of 2.6 for a 0.5 m landfill liner. This means a permeability of less than 23*10^{-11} m/s. The measured permeabilities of all variants to water and landfill leachate easily meet this requirement. The permeability values of the highly plastic mixtures (1000-1300 kg/m^3), using water as the test liquid, are close to the limit (see Table 5). The water permeability of the sand-bentonite mixture without polymer is also below the limit.

### 4.5.2.1 UV test

After exposure to the dose of UV radiation, the sample was mounted in the measurement cells and the saturated permeability for water was measured over a period of 3 months. The measurements were made in triplicate (Table 6). The permeability of the material exposed to UV radiation is 0.59*10^{-11} m/s, which is clearly lower than prior to the UV load.

<table>
<thead>
<tr>
<th>Test</th>
<th>Density (kg/m^3)</th>
<th>Permeability (m/s)</th>
<th>Geometric mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability of unaffected material</td>
<td>1560</td>
<td>3.9*10^{-11}</td>
<td>4.3*10^{-11}</td>
</tr>
<tr>
<td>UV test</td>
<td>1560</td>
<td>4.7*10^{-11}</td>
<td></td>
</tr>
<tr>
<td>Oxidation test</td>
<td>1560</td>
<td>5.7*10^{-12}</td>
<td>5.9*10^{-12}</td>
</tr>
<tr>
<td>Temperature test*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_{uat}</td>
<td>1560</td>
<td>4.1*10^{-11}</td>
<td>4.2*10^{-11}</td>
</tr>
<tr>
<td>K_{30}</td>
<td>1560</td>
<td>4.4*10^{-11}</td>
<td>4.2*10^{-11}</td>
</tr>
</tbody>
</table>

* K_{uat} = K measured at 20°C laboratory temperature
  K_{30} = permeability at 30°C, converted to 20°C

All the results of the permeability measurements are shown in figure 3. This allows the average permeability of standard TRISOPLAST exposed to UV to be compared with that of the other variants with the same dry weight by volume. The measured values are on the vertical dotted line. The sample exposed to UV radiation has the lowest measured values. It seems unlikely that this effect is due to the UV radiation. There was probably an influence of the duration of the 'pretreatment', which involves a slow binding process between bentonite and polymer.
4.5.2.2 Oxidation test

The duration of the oxidation test was three months, i.e. the same as the UV test. After being exposed to the air, the material was mounted in the permeability measurement cells and the saturated permeability to water was measured over a period of 3 months. The measurements were carried out in triplicate and the results are given in Table 6. The permeability of the material prior to the oxidation test (average $7.7 \times 10^{-11}$ m/s) is higher than that after the test ($3.5 \times 10^{-11}$ m/s). The permeability of the material exposed to air was the same as the permeability after the UV load. Long-term exposure to the air probably has no effect on the permeability, and the reduced permeability is probably due to other processes.

4.5.2.3 Temperature test

The temperature test was carried out in triplicate. First the water permeability was determined at an ambient temperature of approximately 20°C ($K_{\text{start}}$). The measurement cells were then placed in a heated cabinet and kept continuously at an average of 30°C. The permeability ($K_{30}$) was measured several times during the 100 day test period and converted to the permeability at 20°C (Table 6). The time-course of the permeability over the test period is depicted in figure 4, which shows that the permeability correlates with the temperature. The average measured $K_{\text{start}}$ is $4.2 \times 10^{-11}$ m/s, comparable with the permeability of material not subjected to any influences ($4.3 \times 10^{-11}$ m/s). After the ambient temperature of the measurement cells has been increased, a new average level of $1.4 \times 10^{-11}$ m/s at 30°C is established within about 20 days, corresponding to $1.2 \times 10^{-11}$ m/s when converted to 20°C. When corrected for viscosity, $K_{30}$ is found to be lower than the permeability prior to exposure to raised temperature. No cause for this effect could be established in this test. If air is inclosed in the material, it may expand at raised temperatures and restrict the effective flow area, as a result of which the permeability decreases (Hopmans & Dane, 1986). It is also possible that a change in the bonding between polymer and clay in the TRISOPLAST reduces the water permeability.

4.5.2.4 Permeability values for the special variant

The ‘special variant’ (Section 4.1) was prepared by mixing dry clay gel with moist sand. Mixtures containing 5% and 10% clay gel were made and the Proctor density was determined at the moisture content at which the material will be processed in practice. The results of the Proctor tests and the permeability measurements are given in Table 7. The Proctor test was carried out for each mixture. For the sake of comparison, the permeability of lean TRISOPLAST made with minimum and optimal moisture contents was also determined.
Table 7: Proctor values and permeability of 'special variants'  

<table>
<thead>
<tr>
<th>Variant</th>
<th>Density (kg/m³)</th>
<th>Moisture (weight %)</th>
<th>Permeability *10⁻¹¹ (m/s)</th>
<th>Geometric mean *10⁻¹¹ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% clay gel</td>
<td>1670</td>
<td>5.7</td>
<td>8.1</td>
<td>7.2</td>
</tr>
<tr>
<td>10% clay gel</td>
<td>1690</td>
<td>6.1</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Lean TRISOPLAST</td>
<td>1710</td>
<td>6.4</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Lean TRISOPLAST</td>
<td>1670</td>
<td>20.0</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

It can be seen from Table 7 that the permeability of the dry-mixed variant with 10% clay gel does not differ significantly from that of lean TRISOPLAST. The moisture content at which lean TRISOPLAST was prepared was found to have no effect on the permeability.

4.5.2.5 Effect of the pH of the test solution

The effect of the pH on the permeability was determined for standard TRISOPLAST at densities of 1680 and 1560 kg/m³ (results after 320 days, Table 8, Appendix). It can be seen from Table 8 that neither a high nor a low pH had any effect on the permeability for the duration of the test period. There are several possible explanations: a) the crystal lattice is affected, but the residues are bound by the polymer, b) the crystal lattice is affected, but the residues behave as an amorphous, clay-like material and are not washed out, c) the polymer prevents the clay crystal lattice being affected.
Table 8 Effect of acidity on TRISOPLAST permeability (*10^-11 m/s)

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Dilute HCl</th>
<th>Water</th>
<th>Leachate</th>
<th>Dilute NaOH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH 1.5</td>
<td>pH 3</td>
<td>pH 5</td>
<td>pH 7</td>
</tr>
<tr>
<td>1680</td>
<td>0.89</td>
<td>n.d.</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td>1560</td>
<td>1.23</td>
<td>1.48</td>
<td>4.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

n.d. = not determined

4.5.2.6 Field trial

The practical test involved two test sites, where liners were installed, one with a standard clay polymer content (site 1), the other with two-thirds of the standard content (site 2). Infiltration measurements were carried out over a five-month period at a pressure level of 0.5 m water column on the infiltration side.

The barrier layer was not saturated with water at the beginning of the infiltration test. In order to determine the hydraulic gradient, the soil moisture tension was measured at different depths in the barrier layer using tensiometers which are also able to measure underpressures. This latter was necessary because initially the barrier layer was not saturated with water, producing an underpressure in the capillary water.

The average infiltration rate at site 1 was initially 0.08 mm per day at a gradient of 27 (permeability 3.3*10^-11 m/s). The infiltration rate decreased in the subsequent months to 0.03 mm/day as a result of the decreasing gradient.

The average infiltration rate at site 2 was initially 0.06 mm per day at a gradient of 35 (permeability 2*10^-11 m/s) and decreased to 0.02 mm/day.

It can be deduced from these measurements that the permeability achieved in the field corresponds with that of samples prepared in the laboratory.

4.5.3 Strain test

The sample in the triaxial test was subjected to an ambient pressure of 3 atmospheres. The sample was consolidated at the beginning of the test, as a result of which water flowed out of the sample. The flow rates through the top and bottom of the sample were measured. During the first month of the test there was also a flow of gas, probably air, from the sample.

After about a month the flow direction reversed and the permeability could be measured. The measurement was continued for a month in order to make sure that no further consolidation occurred. The triaxial method yielded a water permeability of 3.2*10^-11 m/s, a value which deviates by approximately 1.1*10^-11 m/s from the permeability measured using the falling head method, and is about 0.7*10^-11 m/s lower than the lowest value obtained with the falling head measurement.
The sample in the triaxial test was deformed through an imposed length reduction of 3 mm, leaving the sample volume unchanged. No permeability could be measured after the deformation because the intervention immediately led to a substantial discharge of gas from both sides of the sample. A high concentration of CO₂ was found in the gas, indicating degradation of organic matter. Tests by ATO-DLO show that it is the organic matter in the river sand (approximately 0.5%) which was responsible for this, and not the polymer.

The test was started again with a test liquid containing a bactericide. The permeability after consolidation was below the limit of detection (<< 10⁻¹² m/s). The permeability remained below the detection limit even after the imposed deformation.

4.5.4 Water retention and shrinkage characteristics

The retention and shrinkage characteristics of standard TRISOPLAST (1560 kg/m³) were determined in duplicate. The results of both tests are depicted in figure 5. The moisture retention characteristic is the relation between the quantity of moisture which can be retained and the suction tensions in the pore water. The shrinkage characteristic is the relation between the volume of a quantity of TRISOPLAST and its moisture content.

The shrinkage characteristic (upper graph) and moisture retention characteristic (lower graph) are shown in figure 5. The shrinkage characteristic is described as the relation between the moisture ratio (volume of moisture per unit volume of solid phase) and the pore ratio (pore volume per unit volume of solid phase). The moisture ratio can increase through water absorption as a result of the swelling properties of TRISOPLAST. If the material contains no air (saturated condition), the pore ratio increases in direct proportion to the moisture ratio. The moisture ratio decreases when moisture is extracted from swollen material. The pore ratio will also decrease at the same rate as long as no air enters the material. It is only when air penetrates into the material during continued moisture extraction that the pore ratio decreases at a lower rate than the moisture ratio.

The air entry value of standard TRISOPLAST is reached at a moisture ratio of 1.2.

The shrinkage characteristic was determined for suction tensions up to 150 mB. At a suction tension of 0 mbar the material is saturated, while at higher tensions it is considered to be unsaturated even if no water can be extracted from it. TRISOPLAST loses 2.8% moisture, relative to the saturation level, under the influence of a suction tension of 150 mB. This loss of moisture causes the material to shrink only, and no air was able to enter. The vertical dotted line in figure 5 shows the moisture ratio at which air penetrates the material. It is very likely that this will only happen at suction tensions much higher than 150 mbar.
Fig. 5 Shrinkage and water retention characteristics of a standard TRISOPLAST mixture

4.5.5 Enslin test

The Enslin test is used to determine the maximum swelling capacity. The test was carried out in two series, each with three repeats. The results are depicted in figure 6. The a(1) series relates to freshly prepared material, while the tests in the a(2) series were conducted on material from test a(1) which had first been allowed to swell, and was then air-dried, ground to a powder and mounted the Enslin apparatus again. The same procedure was followed for the a(3) series, but after execution of the a(2) series.

The water absorption rate of freshly prepared clay gel clearly differs from that of dried clay gel. The rapid water absorption by dried clay gel is probably caused by the much better contact with the ceramic plate than in the case of freshly mixed clay gel. Moreover, it would appear that the bonding between polymer and bentonite in the freshly mixed clay gel inhibits rapid water absorption or swelling. When air-dried clay gel in powder form was put on the Enslin apparatus, it absorbed almost all the absorbable quantity of water in the first hour.
Fig. 6 Water absorption by clay gel in the Enslin test
A - pre-dried mixed standard TRISOPLAST
B - previously dried TRISOPLAST
The Enslin test was continued with samples of TRISOPLAST with different initial densities and in the absence of vertical load. Figure 7 shows that the absorption of water is relatively slow, but it continues for a very long time (more than 200 days).

### 4.5.6 Plasticity index

The plasticity index PI is calculated from the moisture content at the liquid limit V and the plastic limit U according to:

\[ PI = V - U \]

The plastic limit of the standard TRISOPLAST is 36% and the liquid limit 179%. The plasticity index is 143%, which is well above the required 35%. The high plasticity of TRISOPLAST is caused by the binding properties of the polymer, which allow water absorption but inhibit to reach the liquid limit. The high PI value of the standard mixture characterizes the very wide range of water contents at which the material shows plastic behaviour. High plasticity is generally considered to be advantageous because pressure will only deform the material, without cracking it. Plastic material displays liquid behaviour under pressure. The plasticity and the density determine the strength of the material and the maximum gradients of the slopes which can be constructed from it.
4.5.7 Adhesion test

The adhesion between TRISOPLAST and different materials was tested at different moisture contents of the standard mixture. The materials selected were smooth HDPE film, rough HDPE film, PVC, untreated steel and surface-hardened steel. The results are depicted in figure 8.

The test showed that TRISOPLAST does not adhere to other materials at a moisture content below the plastic limit (36 weight %). TRISOPLAST adheres least to smooth HDPE film and smooth, surface-hardened steel. The greatest adhesion is found to rough steel, particularly at high moisture contents. TRISOPLAST adheres to almost all materials if pressure is exerted, especially to rough steel.

It can be concluded from this test that equipment with 'smooth' surfaces should be selected for processing and handling TRISOPLAST and that processing techniques which grind or rub can give rise to problems. No processing problems are expected because the material will certainly be processed at moisture contents below 20%, in other words well below the plastic limit. Processing in rainy weather is not to be recommended, however.

4.5.8 Adsorption capacity and cation content

The adsorption capacity of TRISOPLAST is its capacity to bind cations exchangeably (CEC, cation exchange capacity). Cation content is defined as the adsorbed quantity of each positively charged ion. The adsorption capacity and cation content are expressed in milliequivalents per kg dry matter (meq+/kg).

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>HDPE film</th>
<th>PVC</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>smooth</td>
<td>rough</td>
<td>smooth</td>
</tr>
<tr>
<td>20-30 (n=7)</td>
<td>- - -</td>
<td>- - -</td>
<td>- - -</td>
</tr>
<tr>
<td>31-50 (n=5)</td>
<td>+ - +</td>
<td>+ - +</td>
<td>- - +</td>
</tr>
<tr>
<td>51-70 (n=3)</td>
<td>- - +</td>
<td>+ - +</td>
<td>- - +</td>
</tr>
<tr>
<td>71-90 (n=3)</td>
<td>- - -</td>
<td>- - +</td>
<td>- - +</td>
</tr>
<tr>
<td>91-110 (n=2)</td>
<td>- - -</td>
<td>- - +</td>
<td>- - +</td>
</tr>
<tr>
<td>111-130 (n=1)</td>
<td>- - -</td>
<td>- + +</td>
<td>- - +</td>
</tr>
</tbody>
</table>

s stab p push r rub - no adhesion + traces adhering # obvious adhesion

Fig. 8 Adhesion test
The adsorption capacity of the clay gel in TRISOPLAST is 450 meq+/kg. The CEC for pure bentonite is 800-1200 meq+/kg (Hoeks et al., 1991). The polymer added appears to occupy a major proportion of the binding sites, halving the cation exchange capacity. As a result, the clay gel resembles the clay mineral illite, which has a relatively low CEC. Because of the use of sodium-enriched bentonite, the cation content of the clay gel is clearly dominated by sodium (1272 meq+/kg). Calcium (214 meq+/kg), magnesium (65 meq+/kg) and potassium (32 meq+/kg) ions are also present. Aluminium, iron and manganese ions were not found; their concentrations were below the detection limit.

4.5.9 Adsorption

The microcolumns were filled with sand and with a mixture of sand and clay gel. The effective porosity was determined on the basis of the breakthrough curves of a nitrate solution (Fig. 9).

The adsorption and desorption behaviour of acenaphthene and butylbenzene is shown in figure 10.

The dimensions of column (volume 4.155 ml) and the nitrate breakthrough curve were used to deduce that the pore volume is 0.40 m.m$^3$. The dry weight by volume is approximately 1565 kg/m$^3$. It can be seen from figure 10 that the intersection of the butylbenzene adsorption and desorption curves occurs at a volume flow of 6.1 ml for the sand column and 6.4 ml for the TRISOPLAST column, or in other words

Fig. 9 Breakthrough curves for nitrate solution, 10 mg/l, in a TRISOPLAST column. In this case the breakthrough volume, 1.7 ml, is the total pore volume
3.58 and 3.77 times the pore volume respectively. The curves for acenaphthene intersect at 10.2 ml, i.e. about 6.0 times the pore volume.

The so-called retardation factor, \( R_d \), is an important factor in adsorption-desorption. This factor represents the ratio between the rate of movement/transport rate of dissolved substances in the soil which are not adsorbed and that of dissolved substances which are adsorbed. This ratio is dependent on the dry weight by volume, \( \rho \), the porosity, \( \varepsilon \), and the distribution coefficient, \( K_d \), (= ratio between the quantity of adsorbed substance per unit mass of dry soil and the concentration of the substance in the soil solution).

The distribution factor is calculated from:

\[
K_d = \frac{V_d - \varepsilon}{V_t} \frac{\varepsilon}{\rho}
\]

and the retardation factor from:

\[
R_d = 1 + \frac{\rho}{\varepsilon} K_d
\]

The distribution coefficients of the polar butylbenzene are \( 6.83 \times 10^{-4} \) m\(^3\)/kg (sand) and \( 7.29 \times 10^{-4} \) m\(^3\)/kg (TRISOPLAST). This is not significantly different, because the variation in the dry weight by volume in the columns amounts to about 10%. The adsorption of butylbenzene is therefore not significantly influenced by the polymer. The average retardation factor in sand and TRISOPLAST is 3.8. The distribution coefficient of the non-polar acenaphthene in sand and TRISOPLAST is \( 13.1 \times 10^{-4} \) m\(^3\)/kg and the retardation factor is 6.1. No significant extra adsorption capacity in TRISOPLAST was found for this substance either.

The non-polar toluene and ethylbenzene behave in the same way as the nitrate, in that they are not adsorbed by sand or TRISOPLAST.

### 4.5.10 Diffusion coefficient

In addition to adsorption, the diffusion coefficient is an important material property which determines the transport capacity for the dissolved contaminants through barrier layers. The diffusion coefficient of bromide in standard TRISOPLAST with a density of 1560 kg/m\(^3\) was measured using the half cell method. The coefficient was calculated according to the method of Beuving and Boels (1992), based on the time-course of the concentration of bromide in the compartments of the half cells. The diffusion coefficient tends to decrease with time. The average value is approximately \( 4.0 \times 10^{-10} \) m\(^2\)/s. The diffusion coefficient for chloride varies from 1 to \( 8 \times 10^{-10} \) m\(^2\)/s (Beuving and Boels, 1992).
Fig. 10 Breakthrough curves for butylbenzene andacenaphthene. Influent concentration of butylbenzene 0.6 mg/l, acenaphthene 0.4 mg/l
5 Evaluation of TRISOPLAST relative to other mineral barrier materials

Permeability
Table 9 gives an overview of suitable natural mineral barrier materials (Boels, 1993). It can be seen from this table that only pottery clay comes close to TRISOPLAST’s permeability. The permeability of the normal sand-bentonite mixtures is a factor 10 higher than that of TRISOPLAST.

<table>
<thead>
<tr>
<th>Material</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderately heavy to very heavy clay</td>
<td>&gt; 35</td>
<td>&lt; 12</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Light clay</td>
<td>28-35</td>
<td>&lt; 35</td>
<td>1.0-10.0</td>
</tr>
<tr>
<td>Loess</td>
<td>&gt; 70</td>
<td>0-100</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Boulder clay</td>
<td>50-70</td>
<td>5.0-10.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>&lt; 50</td>
<td>&gt; 10.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Tegel clay</td>
<td>50</td>
<td>&lt; 12</td>
<td>0.5</td>
</tr>
<tr>
<td>Reuver clay</td>
<td>38</td>
<td>1.5</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Pottery clay</td>
<td>74-80</td>
<td>0.1</td>
<td>0.1-0.4</td>
</tr>
<tr>
<td>Boom clay</td>
<td>38-62</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Sand-bentonite</td>
<td>5</td>
<td>5.0</td>
<td>0.1-0.4</td>
</tr>
<tr>
<td>Sand-bentonite</td>
<td>7</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Sand-bentonite</td>
<td>10</td>
<td>1.5</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>Standard TRISOPLAST</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Lean TRISOPLAST</td>
<td></td>
<td>&lt; 0.6</td>
<td></td>
</tr>
<tr>
<td>Dry-mixed, lean TRISOPLAST</td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
</tbody>
</table>

Melchior et al. (1993) recently demonstrated in a 5 year experiment that the permeability of natural sandy clay (17% clay, 26% silt, 52% sand and 5% gravel, PI 8.9%, density 1950 kg/m$^3$) increases substantially, probably through structure formation as a result of repeated limited loss and absorption of moisture, with the material even losing its barrier function completely. The use of natural clays as landfill covers is currently discouraged, as long as the cause of this phenomenon has not been found and a remedy has not been developed. Sand-bentonite, on the other hand, does retain its barrier function (Boels and Wiebing, 1990). In view of the great similarity between sand-bentonite and TRISOPLAST, it can be expected that the latter will also retain its function in the long term.

The effect of density on the permeability of TRISOPLAST ceases above Proctor densities of 92%. It is only at Proctor densities of about 60% that the permeability of TRISOPLAST increases to the permeability of the usual sand-bentonite mixtures.

Landfill leachate is more likely to have a positive than a negative effect on the permeability of TRISOPLAST.
The polymer can withstand UV radiation and is insensitive to long-term exposure to the air. Extended storage of the finished product is more likely to have a positive than a negative effect on the barrier function.

A raised temperature appears to enhance the barrier function and at the very least has no deleterious effect.

**Strain**
During the deformation test the permeability of TRISOPLAST became too low to measure, as a result of consolidation. Deformation had no effect whatsoever on this. This relationship is unknown for other mineral barrier materials.

**Water retention and shrinkage characteristics**
TRISOPLAST has a large reversible swelling and shrinkage capacity. Suction tensions up to more than 150 mbar cause the extraction of about 3% moisture, whereby the material shrinks but no air penetrates. This property has not been determined for other mineral materials. Figuera and Stegmann (1991) showed that landfill covers made from natural mineral materials are not always gas tight. Because in the case of landfill covers suction tensions on the barrier layers will not exceed 100 mbar, TRISOPLAST will always remain airtight. This makes the material very suitable for covering landfills from which landfill gas is being extracted. The escape of landfill gas to the atmosphere is prevented, but at the same time air will not be drawn in during forced extraction, so that oxidation of methane in the landfill will be avoided.

**Plasticity index**
The required plasticity index is 35%, whereas the value for TRISOPLAST is approximately 180%, which is very high compared with the plasticity index of Boom clay 38-52% (Koenis and Loovers, 1991) and certainly compared with the usual sand-bentonite mixtures, i.e. approximately 12% (Onstenk, 1992). Cracks may arise in the barrier layer if there is very rapid uneven irregular subsidence, as is the case for clay and sand-bentonite barriers. Such cracks are sealed again as a result of the swelling capacity of the mineral barriers. In such situations, the dry weight by volume of the barrier layer close to the cracks normally decreases. The dry weight by volume of TRISOPLAST may drop to 1000 kg/m$^3$, as a result of which the permeability increases to $1.3\times10^{-10}$ m/s. In theory this means that a crack volume of 60% in the original barrier layer will be re-sealed without loss of the barrier layer's performance.

Slow, irregular subsidence will lead to slow deformation and stretching of the barrier, whereby the dry weight by volume and the permeability do not change. The thickness of a TRISOPLAST landfill cover could in theory decrease to about 0.03 m before the required barrier function no longer complies with the landfill cover Guideline. This means that the irregular subsidence must not exceed about 4.5 m per m for an original layer thickness of 0.15 m, or about 2.0 m per m for an original layer thickness of 0.08 m. Such extreme uneven settlement is very unlikely, as a value of 0.3 m per m is already considered to be extreme. This property makes TRISOPLAST more suitable than the other materials for barriers on substrates where major differences in subsidence, are expected.
**Enslin value**
The bentonite in sand-bentonite mixtures is required to have an Enslin value (= fraction of water absorbed per unit mass of dry matter, expressed as a percentage) of at least 400% after one hour and more than 700% after 24 hours. Because of the presence of the bound polymer, the clay gel in TRISOPLAST cannot be directly compared with bentonite. The dry clay gel absorbs approximately 800% water within one hour, and some 950% in 24 hours, so it more than meets the requirements. For the normal activated European bentonite these values are about 500% and 850% respectively (Onstenk, 1992).

**Adhesion**
TRISOPLAST adheres to steel and plastics at moisture contents above the plastic limit of 35%. In practice the moisture content during processing will be less than 20%, so no problems need be expected in the mixing step or the processing. Continuing to work in rainy weather is not recommended however. Sand-bentonite mixtures are processed at a moisture content of about 13% and these do not present any problems either. Other natural mineral barriers generally have to be processed at moisture contents below the plastic limit.

**Cation exchange capacity**
The cation exchange capacity of the clay gel is lower than that of pure bentonite because the polymer appears to block or occupy a proportion of the potential cation exchange capacity. The exchange capacity corresponds to that of the clay mineral illite. Experiments with landfill leachate, which showed that the permeability is more likely to decrease than increase, allow the conclusion that the clay gel is less sensitive to polyvalent ions than pure bentonite, which reacts by developing a thinner dielectric double layer and consequently shows increased permeability.

**Adsorption**
There are relatively few organic microcontaminants in waste substances. If the adsorption capacity of a landfill liner is greater than the total quantity of contamination, no emission to the soil will occur. The clay gel does not adsorb toluene or ethylbenzene, while its adsorption capacity for butylbenzene and acenaphthene depends on the concentration in the solution. The ratio between the quantity of adsorbed substance per unit mass of the soil material and the concentration of that substance in the soil solution is called the distribution coefficient. This coefficient is about $7.1 \times 10^{-4} \text{ m}^3/\text{kg}$ for butylbenzene and $13.1 \times 10^{-4} \text{ m}^3/\text{kg}$ for acenaphthene for sand and TRISOPLAST. TRISOPLAST does not significantly increase the adsorption capacity for these substances.

This property cannot be compared with that for other mineral materials because the required data is lacking.

**Diffusion**
The average diffusion coefficient of bromide in TRISOPLAST is $4.0 \times 10^{-10} \text{ m}^2/\text{s}$. It can be concluded that the polymer does not increase the apparent path length for ions. TRISOPLAST does not differ from the normal sand-bentonite mixtures in this regard.
Environmental benefit

The environmental benefit of using TRISOPLAST derives from the possibility of reducing the material requirements (raw materials), limiting the environmental impact on the soil, increasing the waste volume that can be dumped and expanding the choice of locations for tipping waste.

It is currently assumed that the use of foil on a sand-bentonite barrier leads to a leakage loss of 5-10 mm per year. Leakage losses will mainly be local, resulting from tears in the foil. The application of TRISOPLAST therefore has the advantage that the material is insensitive to leachate and fully retains its effectiveness as a barrier. If TRISOPLAST is used in accordance with the current guidelines, an additional reduction of leachate losses from 30-90% compared with the usual materials will be achieved.

Compared with ordinary materials, the use of TRISOPLAST can lead to at least a 50% reduction in construction materials, if the barrier layers are designed in accordance with the current criteria (maximum flux under given conditions).

The use of TRISOPLAST as both a landfill cover and liner can yield an extra landfill volume of at least 4000 m$^3$ per hectare, if the barrier is designed according to the current design criteria.

Although areas prone to subsidence are basically unsuitable for landfills, there may be reasons of a social or political nature why such sites are nevertheless selected. The design and the materials used in the construction of the mineral barriers and the building materials determine the extent to which the soil is protected. In such cases TRISOPLAST is particularly suitable as landfill liner and cover material on account of its high plasticity.
References


Unpublished sources

Boels, D., 1977. Bodemvervorming door sleuflooswerkende draineermachines en de invloed daarvan op de drainafstand (Soil deformation as a result of trenchless draining machines and the influence thereof on drain distance). Note 999, ICW Wageningen.


Annex 1 Effect of composition and moisture content on permeability

Effect of composition on permeability
Permeability ($10^{-10} m\cdot s^{-1}$)

- 5% clay gel
- 10%
- 16%

Effect of initial moisture content on permeability
Permeability ($10^{-10} m\cdot s^{-1}$)

- 1719 kg m$^{-3}$/ 6.4% moisture
- 1670 kg m$^{-3}$/ 20% moisture

Day number
Annex 2 Effect of pH on permeability

Effect of pH on permeability
Permeability ($10^{-9}$ m·s$^{-1}$)

- pH 1.5
- pH 1.5 duplicate

Effect of pH on permeability
Permeability ($10^{-9}$ m·s$^{-1}$)

- pH 3.0
- pH 3.0 duplicate

Day number
Effect of pH on permeability

Permeability ($10^{-9} \text{m} \cdot \text{s}^{-1}$)

- pH 5.0
- pH 5.0 duplicate

Day number

Effect of pH on permeability

Permeability ($10^{-9} \text{m} \cdot \text{s}^{-1}$)

- 1680 kg \cdot m^{-1} / pH 10.0
- 1560 kg \cdot m^{-1} / pH 10.0

Day number
Effect of pH on permeability

Permeability ($10^{-9}$ m·s$^{-1}$)

![Graph showing the effect of pH on permeability. The graph plots permeability ($10^{-9}$ m·s$^{-1}$) against pH, with a peak at pH 5.5.]