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NEW DEVELOPMENTS IN RESEARCH AND INSTALLATION TECHNIQUES OF TRISOPLAST, THE INNOVATIVE POLYMER-ENHANCED MINERAL BARRIER

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ABSTRACT: Trisoplast is a special mineral liner that consists of a bentonite-polymer, mixed with sand and water. It is extremely impermeable and has many advantages over traditional liners. In common practice Trisoplast is installed horizontally, up to slopes of 1:1.5. in open air on dry surfaces. In this paper it is shown that it is also possible to install the layer vertically or under water. Besides that, the most recent tests and investigations on the specific performances of water-saturated Trisoplast are presented. The investigation and analyses on the slope stability and research on the sustainability of Trisoplast regarding differential settlements have confirmed that Trisoplast can be installed on very steep slopes and is able to sustain high strains without losing its integrity and impermeability. All together this opens up a whole set of new possibilities in which Trisoplast can be of use for clients that seek the highest level of environmental protection through isolation.

Keywords: Mineral liners, environmental protection, bottom liners, capping, sealing, vertical screen, steep slopes, stability, isolation, differential settlements, installation techniques, underwater.

1. INTRODUCTION

Mineral liners, such like Trisoplast play an important role in the protection of our environment. They are commonly used as a bottom liner under, or a capping on landfills preventing leachate from contaminating the groundwater and landfill gas from emitting to the atmosphere. Trisoplast consists of a special bentonite-polymer component mixed with sand and water, resulting in an extremely impermeable liner for dumpsites or landfills. Trisoplast has many advantages over traditional liners and has a long reference list of over 400 landfill projects worldwide since its introduction some 25 years ago. Earlier publications and presentations at the Sardinia landfill symposium were taken as opportunities to present Trisoplast to the market [Boels et al., 1999, Boels, 2001, Melchior et al., 2001, Melchior 2003, Naismith et al., 2003, Guyonnet et al., 2009]. These describe the durability and performance of Trisoplast and the advantages it has over other traditional mineral barriers. In particular the high resistance of Trisoplast towards desiccation and cation exchange processes are reported. Recent research confirms the unique quality of Trisoplast and shows that this easy molding and self-healing material can be used for various other application.

As a result of its performance combined with further ongoing research Trisoplast is now used in landfill constructions, contaminated land isolation, mining (under and on top of tailing dams, leaching ponds and other protective applications), industry (tank farms, water tight floor protection), infrastructure and construction as well as landscaping projects within Europe, Asia and an increasing number of other countries around the world. The main reason for its widespread application is that Trisoplast raises the level of soil and groundwater protection significantly higher than the level required by the individual national regulations which often fail to keep up with the actual state of the art.

In this paper the latest developments around Trisoplast are described. New installation techniques are introduced, such like installation in vertical underground screens, or underwater installation directly on water bottoms. Besides that, the most recent tests and investigations on the specific performances of Trisoplast are presented, as experiments and analyses on the slope stability and the research on the sustainability of Trisoplast regarding differential settlements.

2. NEW INSTALLATION TECHNIQUES

2.1 Standard installation

In common practice Trisoplast is installed horizontally, up to slopes of 1:1.5. in open air on dry surfaces in layer thicknesses of 5 to 10 cm (depending on the site specific requirements and the objective of the layer). After mixing the separate components in a (mobile) dedicated mixing plant, the Trisoplast mixture is spread out by an excavator and compacted with a lightweight compactor, a larger vibrating plate or a single drum roller operated by an excavator. There is no need for specialized equipment during the installation.

Prior to the installation of Trisoplast, the subgrade only needs to be leveled. There is no need for removal of larger and/or sharp objects from the surface, since the thickness of the Trisoplast layer and its self-healing capabilities ensure a qualitative high standard isolation layer. Due to its simplicity, the installation works can usually completely be performed by a local contractor.

After installation, the Trisoplast layer is covered with a ballast layer (usually a drainage layer plus a top soil layer) providing confining pressure to keep the pore volume low. Trisoplast layers have a typical compaction rate of >90% and a typical permeability smaller than $3x10^{-11}$ m/s. These kinds of installation and properties are particularly suitable for making landfill liners, basins for tank storage terminals or ponds.

During its 25 years of existence, numerous other applications of Trisoplast have been invented, tested and applied. Proven technical applications that are ready for usage in projects worldwide are Trisoplast installed vertically in underground screens and the underwater installation of Trisoplast, directly on water bottoms. Trisoplast even appears to be applicable when pile foundations are installed through the layer afterwards.

2.1 Trisoplast in vertical underground screens

In several projects there is a need for vertical isolation solutions. To utilize the properties of Trisoplast in these cases as well, two specific installation techniques were developed:

- On-situ, in which the installation is performed above the ground level;
- In-situ, in which the installation takes place below ground level.

2.1.1 On-situ vertical installation

In a road construction project, the Trisoplast layer was installed vertically, on-situ. The elevated road was constructed on top of a foundation layer of bottom ash from waste incineration. The ash replaces the use of large amounts of natural sand that otherwise were needed to elevate the road. However, this ash contains contaminants that can pollute the groundwater. Therefore, Dutch legislation obliges isolation of this ash by a suitable cap that will function for at least 100 years. Trisoplast is officially accepted as such capping layer.

The space for the road construction was very limited and therefore a reinforced retaining wall using geogrids was designed. This vertical retaining wall was built against a temporary formwork of wooden plates. The on-situ vertical Trisoplast layer was integrated in the vertical wall construction by installing successive 30 cm high ridges, using a 2.5 m long and 10 cm wide mold (see figure 2.1a). In this mold the loose material was pre-compacted, resulting in a solid vertical layer (figure 2.1a/b). After several ridges were installed, the sides were filled with granular material to build up the construction. The clean granular material was placed around the Trisoplast ridge and the bottom ash at the inner side of the construction. Afterwards the Trisoplast layer was compacted with a vibrating plate (figure 2.1b/c). This results in a layer with compaction rate of approximately 90%. After compaction the layer was reinforced by geogrids to provide sufficient stability for the total vertical wall (see figure 2.1c).

Figure 2.1. The overview of the on-situ installation of a Trisoplast liner

By repeating this process of ridges, compaction and backfilling, a 340 m long and 13 m high impermeable (k-value <$3x10^{-11}$m/s) retaining construction with integrated Trisoplast liner was constructed.

2.1.2 In-situ vertical installation

In the search for more simple installation techniques an in-situ variant was developed. The in-situ vertical Trisoplast liner was installed using a specially adapted chain digger (figure 2.2). With the chain digger the Trisoplast could be installed several meters below ground level in a vertical screen with a wall thickness of 15 cm. The depth is mainly depending on the size of the chain digger. Experiments showed that installation up to at least 6 meters below ground level is possible. Excavation at the location showed that the installed vertical liner had a uniform solid structure and width (see figure 2.3) Samples from the layer have been tested in the laboratory. The results confirmed that the installed layer had a high density (~90%) and a k-value smaller than $3x10^{-11}$ m/s.

The vertical screens are unlimited in length and can be applied for example as an impermeable layer around landfills, as cut-off walls or in dykes to prevent seepage or piping.

Figure 2.2 In-situ installation of a Trisoplast vertical underground screen

Figure 2.3. Visual inspection of an in-situ vertical underground screen of Trisoplast

2.2 Installation under water

Installing under water is sometimes needed to isolate waste or sludge at the bottom of a lake or to improve the impermeability of the lake/canal bottom.

For this purpose, we setup an experiment in a controlled environment. For this a basin was filled with a foundations layer of approximately 30 cm built from material from the river moose. In this layer a drainage pipe was installed and connected to a flange at the bottom (figure 2.4). The basin was then filled with water. The Trisoplast layer was installed under water lever via a specially adapted hopper on with a surface of 1 x 1.2 m (~1m^2) (figure 2.5).

The hopper was filled batch-wise and after every batch the place is moved 0.8 m to create an overlap of 0.2 m (figure 2.6).

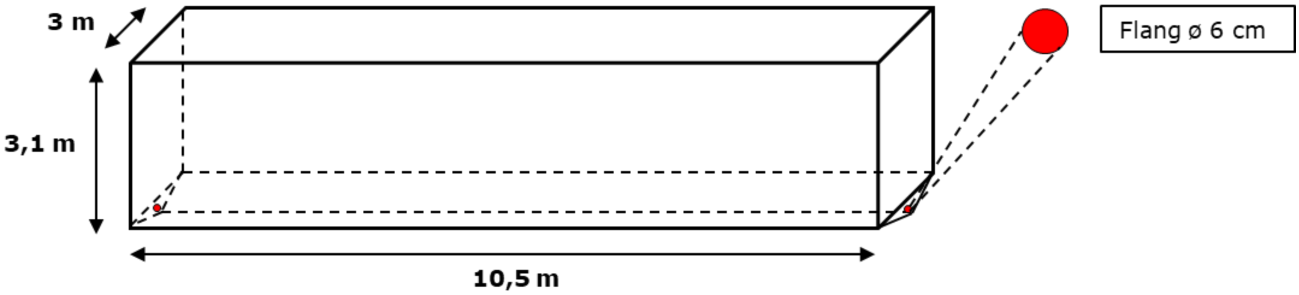

Figure 2.4: Schematic drawing of the basin and flange.

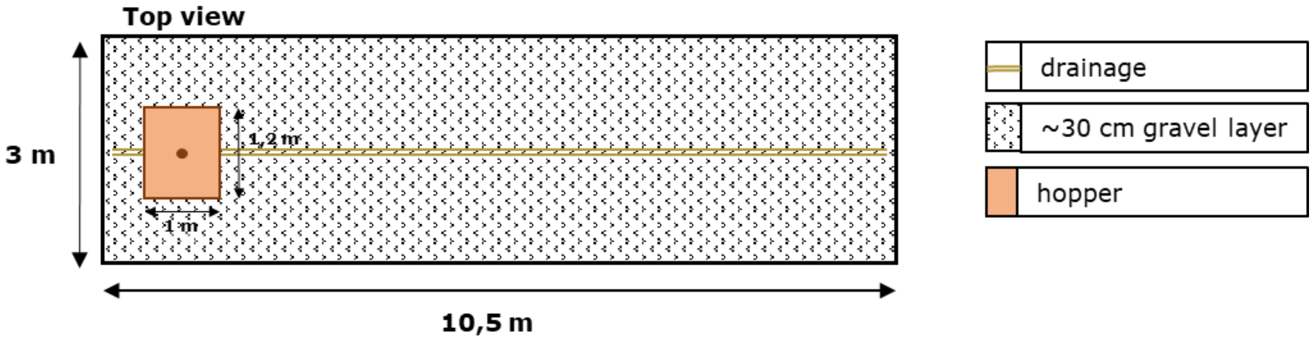

Figure 2.5: Top view of the basin with hopper before adding the Trisoplast.

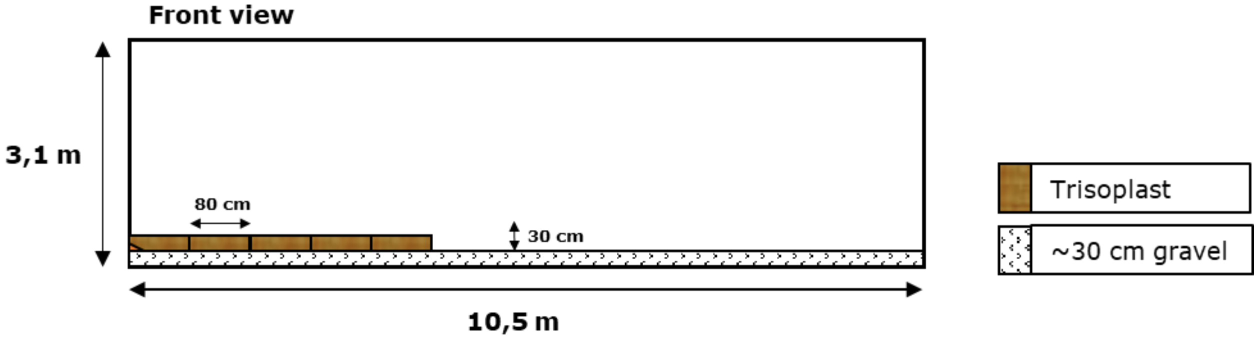

Figure 2.6: Front view of the installed Trisoplast layer.

The Trisoplast layer was covered with approximately 40 cm of granular material for protection and necessary confining pressure.

During several weeks the water flow through the open flange was measured. This flow remained rather constant over time and resulted in a k-value of around 3x10^{-10} m/s. After 3 weeks when the water was removed, the layer was examined on thickness, density and permeability.

The layer appeared to be uniform (figure 2.7). No segregation of smaller from larger particles was observed.

Figure 2.7: excavated underwater installed Trisoplast layer.

Over a length of 7 meter, the layer thickness was measured every 30 cm (figure 2.8). The average thickness was 26 cm and varied from 21 to 32 cm. the relatively large variation was expected as installation was performed in an overlapping strategy.

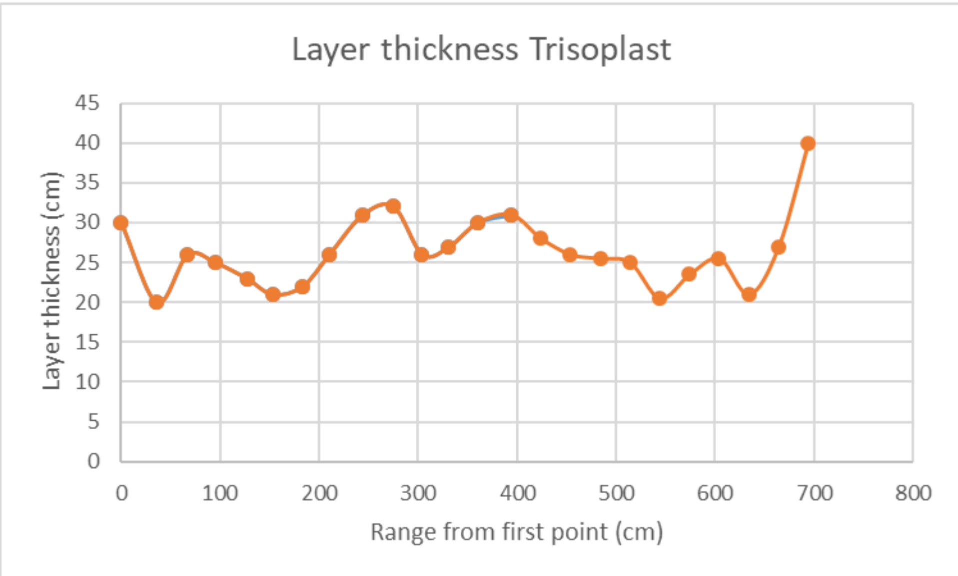

Figure 2.8: layer thickness of the underwater installed Trisoplast layer.

The moisture content of the layer was relatively high and the density was rather low compared to compacted layers on dry surfaces. This could be expected from the installation method underwater (figure 2.10).

From larger undisturbed samples the k-value was measured in the laboratory. These results show slightly better k-values ($9x10^{-11}$ m/s) than realtime meausured waterflows from the flang ($3x10^{-10}$ m/s).

From this experiment it can be concluded that an effective, uniform, robust and impermeable Trisoplast layer can be installed underwater. This layer can be applied to isolate sludge at a the bottom of a lake or to improve the impermeability of lake bottoms. It is especially adequate to improve the impermeability near constructions in canals or lakes, such as quay walls, buildings, bridge pile foundations etc.

2.3 Self-Healing effect: pile foundations installed through a Trisoplast layer

The self-healing effect in case of puncturing a Trisoplast layer is known for many years and is amongst the specific properties that make Trisoplast a preferred option for mineral lining. The self-healing properties of Trisoplast were further confirmed and investigated in a full-scale test with a pile foundation construction of the "Directorate-General for Public Works and Water Management" ("Rijkswaterstaat") in The Netherlands.

2.3.1 Introduction

In the Netherlands, highways are often built on a foundation layer of bottom ash, remaining from the incineration of solid wastes. This prevents the use of primary mineral sources like sand and is widely accepted as a more circular and sustainable way of working. The bottom ash is likely to be polluted and needs to be isolated from the environment. Therefore, legislation prescribes a suitable capping with a functional lifetime of more than 100 years. Trisoplast meets these requirements and has been used in these circumstances frequently.

A specific aspect of road constructions are poles: light poles, sign posts and bigger frames above the road with information panels for road users. All these objects are usually founded on piles that perforate the road foundation, including the isolation layers that separate the bottom ash from the environment. For most liner systems this will be "catastrophic" for the functionality.

For this particular case the capping excisted of a 2 mm HDPE membrane. For the areas where the piles had to be installed the capping was reinforced by a Trisoplast layer. In this full scale research, the integrity and functionality of the Trisoplast layer was investigated, while the complete layer (membrane and Trisoplast) was perforated with steel piles.

2.3.2. Materials and methods

For the testing, two different situations were created on top of a foundation layer of bottom ash:

1. A 2 mm HDPE membrane put on the foundation layer with a 25 cm thick layer of Trisoplast on top of it
2. A second set-up in which the HDPE membrane was captured in two 25 cm thick layers of Trisoplast

In both set ups, two types of open steel tubelar piles were tested. One with a diameter of 32 cm and the other with a diameter of 71 cm (see figure 2.9). Both pile types were 10 m long and had a wall thickness of 12.5 mm. The piles were driven through the full-scale constructions of sand-Trisoplast-incineration ash. Two installation methods were tested:

- Vibrating, using a Resonance Free Vibratory Hammer
- traditional pile driving, using a Junttan HHK-5a Hydraulic block (see figure 2.10).

Figure 2.9: Overview of the steel piles.

Figure 2.10: Junttan HHK-5a Hydraulic block with steel pipe.

2.3.3. Results

After installation of the piles, the top layer of sand was removed to visually inspect the connection between the Trisoplast layer and the outside pile walls.

- Effect of the installation technique:
  When using the vibrating method, the Trisoplast kept its form but particles of sand were transported downwards along the side of the pile, creating a thin sandy layer between the side of the pile and the Trisoplast layer, thus creating a pathway for leaks. This method is therefore not suitable to create an impermeable construction.
  When using the pile driving method on the 71 cm pile the Trisoplast was slightly dented at the

surface of the layer, but was not affected. The sand transport phenomena did not occur and the layer remained connected to the pile wall, regardless whether the membrane was situated under or in between the Trisoplast layers. (See figure 2.11)

Figure 2.11 Trisoplast connection to the side of the pile (71 cm)

- Effect of pile diameters:
  When using the larger diameter pile, the connection remained seamlessly tight. When using the smaller diameter pile there was a small disturbance of sand particles observed in the first centimeters of the connection, furthermore the connection remained seamlessly tight as with the larger pile. Most probably the disturbance is caused by the horizontal movements a smaller pile can make, when pile driven.

- Effect of the membrane:
  For the connection of the Trisoplast layer to the pile wall it does not make a difference if the membrane is situated below or in between the Trisoplast layer. As expected, the membrane itself does not have a tight connection to the side of the pile in any of the experiments.

2.3.4. Conclusion

The test set ups delivered additional and new insights in the way Trisoplast can be used in situations where pile foundations have to be installed through isolating constructions. Excavation afterwards proved that Trisoplast remained connected to the pile walls, despite the destructive effect of the perforation and the high pressures involved. Trisoplast kept its form and functionality, the total construction kept its impermeability and remained functional.

3. RECENT RESEARCH AND DEVELOPMENTS

After intensive independent research and testing, Trisoplast has become the preferred mineral barrier for landfill applications in the Netherlands. Ongoing investigations have confirmed moreover that the clay gel offers improved properties compared to traditionally used mineral barriers. Some of latest recent studies are described here.

3.1 Slope Stability

Slope stability is a major issue when designing waterproof isolation systems for landfills, tank parks and ponds. In Trisoplast, the sandy structure gives high friction angles. The bentonite-polymer component on the other hand provides the material with cohesion. In the period between 1994 and 2021 extensive lab research was conducted, in which the strength properties of Trisoplast were studied on both saturated and non-saturated samples. Since the saturated state appeared normative in most cases, new tests and calculations have solely been performed on saturated samples. The values and conclusions referred to in this latest research serve as exploratory information and do not replace project-specific laboratory investigations

This research provides a general overview of the strength parameters of saturated Trisoplast. The testing and calculation method for these parameters are described and analyzed. Subsequently, some practical applications of Trisoplast are assessed, to prove the potential of the product in constructions for landfills, tank parks and ponds.

3.1.1. Testing materials and methods

Two types of studies were performed: (1) studies on the internal shear strength of Trisoplast and (2) studies on shear strength between Trisoplast and a membrane or geotextile. Two methods were used to determine the angle of internal friction (φ') and cohesion (c') / adhesion (a') of the material and interface surface:

- Triaxial tests (CU), where the sample (50 mm in diameter and 100 mm in height) is built-in and subsequently consolidated at a specific initial stress. These tests were performed at the laboratory of Fugro in The Netherlands.
- Direct Shear (DS) tests, where a sample (20 to 40 mm in height) is placed in a square container of 10 x 10 cm^2. These tests were performed at the laboratory of the “Institut für Geotechnik at the Leibniz Universität Hannover” Germany.

When only a one test is conducted the value of the effective angle of internal friction φ' can be determined, when the effective cohesion c' is assumed zero. In that case, the value for the angle of internal friction is indicated as the secant φ' - value (φ'_{secant}).

When a φ'_{secant} approach is assumed, the characteristic value of φ'_{secant} will be dependent on the vertical effective stress σ'_v according to the relation:

$$\varphi'_{secant} = \arctan\left(\frac{c' + \sigma'_v \times \tan(\varphi')}{\sigma'_v}\right)$$

All the tests were performed on a typical mixture of Trisoplast. This mixture was composed with river sand from the Netherlands (D_{50} 255 µm) and a standard amount of bentonite-polymer.

3.2.2. Results of the internal shear strength tests

Two strength parameters were determined in the lab tests: the effective angle of internal friction φ' and the effective cohesion c'. Table 3.1 provides a summary of the internal shear test results for similar types of sand.

The average and the variation coefficient of a test series were determined based on the individual values of such test series. According the Dutch normative document NEN9997-1, the characteristic value can be deduced on the basis of these two measurements.This characteristic value was determined for four parameters: the effective angle of internal friction φ', the cohesion c' and the φ'_{secant} at vertical stress of 7.5 kPa and 15 kPa. All these values were deduced based on the raw data of the test results.

By deducing the characteristic value, a restriction of the variation coefficient up to 10 % was considered for the φ' and φ'_{secant} and up to 20 % for the c'. When the variation coefficient is restricted, the restricted value is shown between brackets () in table 3.1.

Tabel 3.1: results of the internal shear strength tests on Trisoplast

Experiment nr	N	Test	Density	Water content	Bento-nite	D50	φ' [^{0}]	c' kPa	φ'	c' kPa	φ' [^{0}]	c' kPa	φ'$_{secant}$ [^{0}] 7.5 kPa	φ'$_{secant}$ [^{0}] 15 kPa	φ'$_{secant}$ [^{0}] 7.5 kPa	φ'$_{secant}$ [^{0}] 15 kPa	φ'$_{secant}$ [^{0}] 7.5 kPa	φ'$_{secant}$ [^{0}] 15 kPa
			kN/m3	% (m/m)	% (m/m)	µm	Average		Variation coefficient		Characteristic		Average		Variation coefficient [%]		Characteristic	
TP-2017-01[a]	4	CU-2%	14.2	27	12	255	32.0	5.8	13 (10)	43 (20)	28.2	4.4	53.9	45.2	10	6	48.3	39.7
TP-2018-04[a]	3	DS-3 mm	≈ 15	29	13	255	32.2	5.4	8	29 (20)	27.8	3.6	53.3	44.6	6	3	48.3	42.7
TP-2018-04[a]	3	DS-10 mm	≈ 15	29	13	255	37.9	8.2	9	33 (20)	31.9	5.5	61.7	53.0	6	3	55.8	50.1
TP-2017-01[a] TP-2018-04[a]	7	CU-2% DS-3 mm	≈ 15	28	12	255	32.1	5.6	10	36 (20)	29.7	4.8	53.6	45.0	8	5	50.6	43.4

a These tests were performed on samples of the same composition

A comparison of the results of DS tests at 3 mm strain (Hannover 2019) and the CU tests (Fugro) at 2 % strain (TP-2017-01) on the same samples shows that the results are virtually similar. Both DS and CU testing methods are applicable for the determination of the shear strength parameters.

Based on the raw data of the individual tests Fugro concluded that the approach with the secant friction angle φ'_{secant} is the preferred method for design calculations in practical applications.

The characteristic φ'_{secant} value in this latest research ranges from 48.3 degrees to 55.8 degrees (at 7.5 kPa) and from 39.7 degrees to 50.1 degrees (at 15 kPa). These values give an indication for the values that can be used in Trisoplast slope designs. Of course, each design shall be calculated based on site specific materials and thus parameters.

3.1.3. Results of shear strength properties at the interface Trisoplast- membrane/geotextile

For testing the shear strength between a membrane and Trisoplast a structured membrane (AGRU MST+/MSB) was used. The less structured MSB side was in contact with the Trisoplast layer. For testing the geotextile, the geotextile from a drainage mat (fildrain 7D(D)/NW8) was in contact with the Trisoplast. All tests were conducted with a Direct Shear (DS) device. The strength of the interaction along the shear surface is expressed in an interaction friction angle δ' and an adhesion a'. This is determined at a 10 mm horizontal deformation. Similar to the approach with the internal parameters of Trisoplast, the δ'_{secant} values were also determined at 7.5 kPa and 15 kPa vertical effective stress. A summary of the results with characteristic values is shown in table 3.2.

Table 3.2: Results of shear parameters of the interface of Trisoplast and a membrane/geotextile.

Document	Test	N	Den-sity	Water content	δ' [^{0}]	a' kPa	δ'	a'	δ' [^{0}]	a' kPa	δ'secant [^{0}] 7.5 kPa	δ'secant [^{0}] 15 kPa	δ'secant [^{0}] 7.5 kPa	δ'secant [^{0}] 15 kPa	δ'secant [^{0}] 7.5 kPa	δ'secant [^{0}] 15 kPa
			kN/m^3	%	Average		Variation coefficient		Characteristic		average		Variation coefficient [%]		Characteristic	
TP-2018-02 & TP-2020-02	AGRU MST+/MSB (structured)	6	≈ 15	25	27.2	2.0	7	31 (20)	25.6	1.6	37.9	32.9	5	4	36.3	31.8
TP-2018-03 & TP-2020-01	Geotextile from Fildrain 7DD/NW8 and 7D/NW8	6	≈ 15	25	38.1	1.6	8	72 (20)	35.0	1.4	45.4	41.8	**6**	**3**	43.3	40.8

The friction along a structured (rough surface) membrane (average, δ'_{secant} alues) is lower than along a geotextile.

Based on the raw data of the individual tests Fugro concluded that the approach with the secant friction angle δ'_{secant} is again the preferred method. In the calculations that follow in chapter 3.1.4, the δ'_{secant} [^{0}] values are therefore used again. to use for the calculation of the practical applications.

The characteristic δ'_{secant} value of geotextile and Trisoplast in this latest research ranges from 36.3 degrees (at 7.5 kPa) to 31.8 degrees (at 15 kPa). The characteristic δ'_{secant} of Trisoplast and a structured membrane was between 43.3 degrees (at 7.5 kPa) and 40.8 degrees (at 15 kPa). These values give an indication for the values that can be used in Trisoplast slope designs. Of course, each design shall be calculated based on site specific materials and thus parameters.

3.1.4. Stability of the cover layer

The calculation of the safety level against shearing at a slope is performed by Fugro according to the Edelman-Joustra method. This method has an infinite slope as the starting principle. The underlying assumption here is that the toe of the slope does not contribute to the resistance against shearing. This method is a reasonable approach for shallow sliding surfaces. The method of Edelman-Joustra can be used for every layer boundary in the cross-section of a cover layer on the slope. The layer boundary with the lowest safety factor is the determining factor for the stability of the cover layer on the slope. The slope inclination varies between 15 degrees (v:h = 1:3.7) and 40 degrees (v:h = 1:1.2).

Three examples of Trisoplast being applied in slopes are:

- landfills/waste disposal sites,
- emergency facilities at storage tanks and tank farms,
- ponds.

These three examples are schematized as in figure 3.1, 3.2 and 3.3.

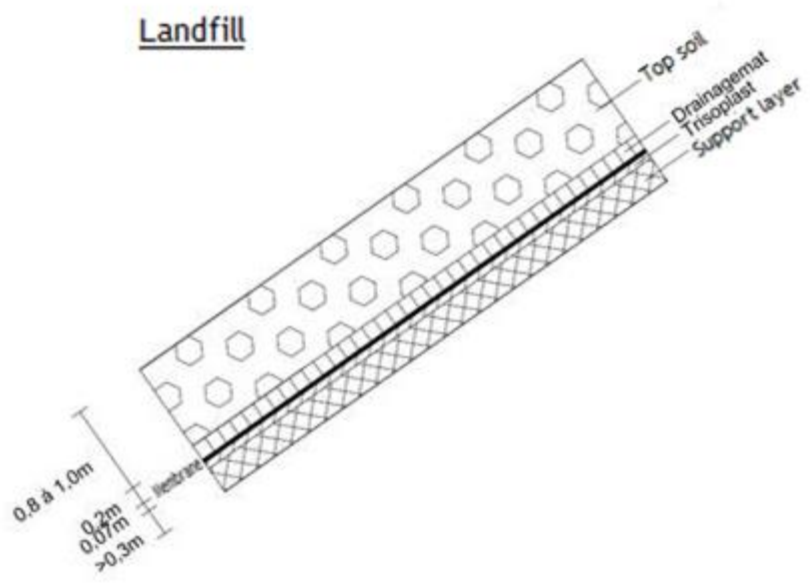

Figure 3.1 Cross section of a slope with Trisoplast at a landfill.

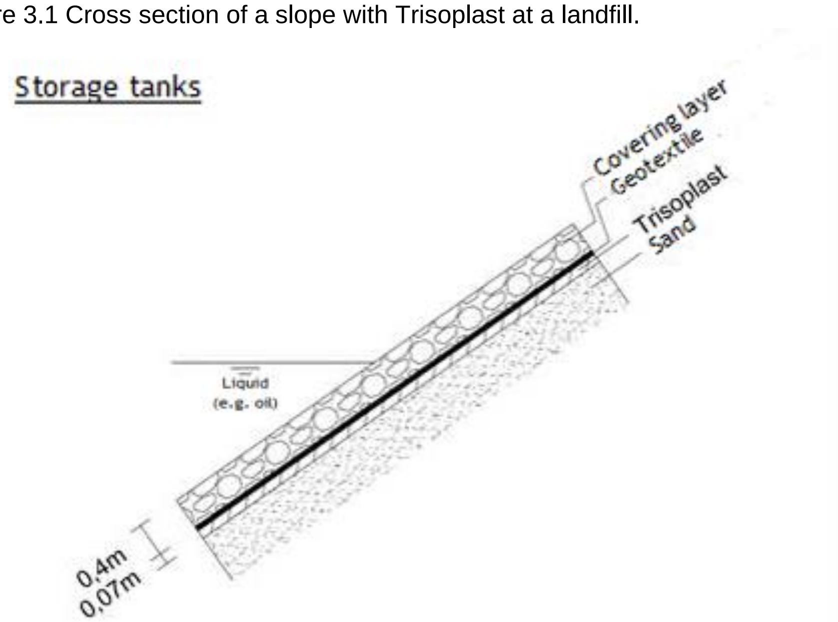

Figure 3.2 Cross section of a slope with Trisoplast for a storage tank.

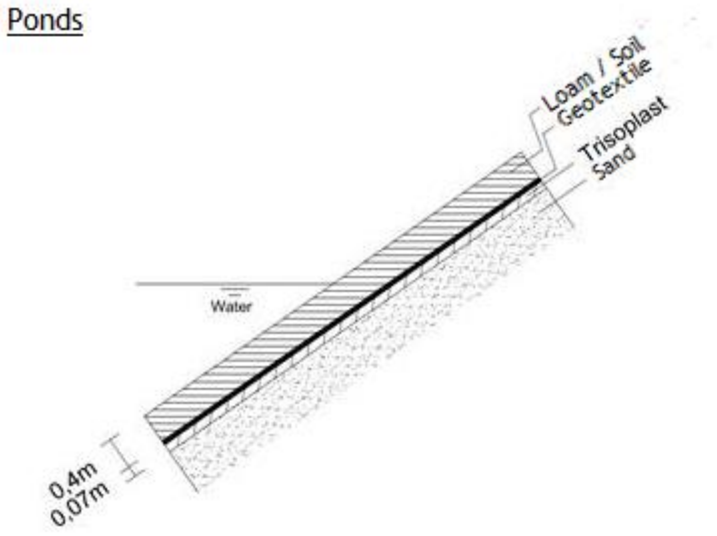

Figure 3.3 Cross section of a slope with Trisoplast at a pond.

For the assessment of the slopes described above, the characteristic parameters were used, as indicated in tables 3.1 and 3.2. For the other materials assumptions were drawn in accordance with national and international literature

According to the Dutch geotechnical standard NEN 9997-1 (A), the characteristic values for (the tangent of) the effective friction angle/interface friction angle and the effective cohesion/adhesion must still be divided by a partial material factor to achieve the design values. The material factors depend on the Consequence Class CC, which reflects the interest in terms of victims and economic damage when the construction fails (CC1 – insignificant, CC2 – significant, CC3 – very significant).

In all tested examples Trisoplast is not the critical layer for the stability of the slope. When a membrane is part of the construction it is mostly the normative element in terms of slope stability. . If no membrane is present, , the interface between Trisoplast and the underlying sand layer, is the determining factor. The interface of the Trisoplast and the sand is determined by the lowest value of the angle of internal friction. Lab tests of Trisoplast (table 3.1) show that a higher friction for Trisoplast may be taken into account. The angle of internal friction of sand is therefore the determining factor.

3.2 Coping with differential settlements

The performance of Trisoplast subjected to continuous differential settlements was realistically evaluated using a large beam centrifuge. The study was performed by the Indian Institute of Technology Bombay. Continuous differential settlements were induced during centrifuge test using a motor based differential settlement simulator set-up.

3.2.1 Scope and Objectives of the study

The main aim of the study was to understand the behavior of Trisoplast based landfill covers subjected to the continuous differential settlements through centrifuge model tests. Figure 3.4 shows the schematic of the non-uniformly deformed Trisoplast barrier at 20 gravities. In the research an attempt was made to evaluate the influence of thickness, pre-saturation, settlement rate and self-healing effect on the deformation behavior of Trisoplast - based landfill covers through series of centrifuge model tests. In addition, results of Trisoplast barrier were compared with Clay - based landfill covers subjected to differential settlements.

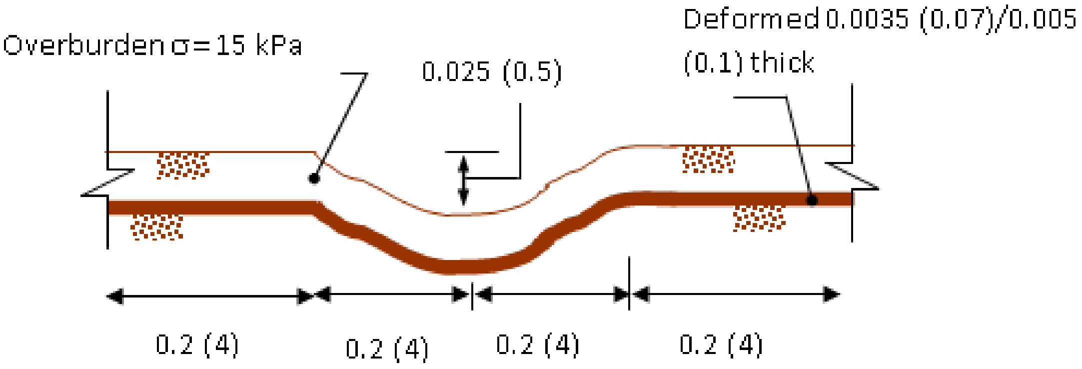

Fig. 3.4 Schematic of the non-uniformly deformed Trisoplast barrier at 20 gravities (dimensions in m)

3.2.2. Material properties

Centrifuge model testing involves the study of geotechnical events using small–scale models subjected to acceleration fields that provide a magnitude of many times the earth's gravity (g). Centrifuge modelling plays a major role in resolving geotechnical issues related to waste containment systems. A special feature of geotechnical modelling is the necessity to reproduce the soil behavior in terms of both strength and stiffness. According to Taylor (1995) with the application of centrifuge modelling technique, self-weight stresses and gravity dependent processes are correctly reproduced and observations from small–scale models can be related to the full-scale prototype situations using well-established scaling laws. centrifuge model tests have proven to be particularly valuable in revealing the mechanisms of soil deformation and collapse and in providing data for validating numerical analyses.

A large beam centrifuge was used in this study (figure 3.5). The large beam centrifuge of IIT Bombay is used for studying numbers of problems in geotechnical and geo-environmental engineering. A 450 kW DC motor housed in a motor room located below the ground level powers the centrifuge. The centrifuge capacity is 2500 g-kN with a maximum payload of 25 kN at 100 g and at higher acceleration of 200 g the allowable load is 6.25 kN.

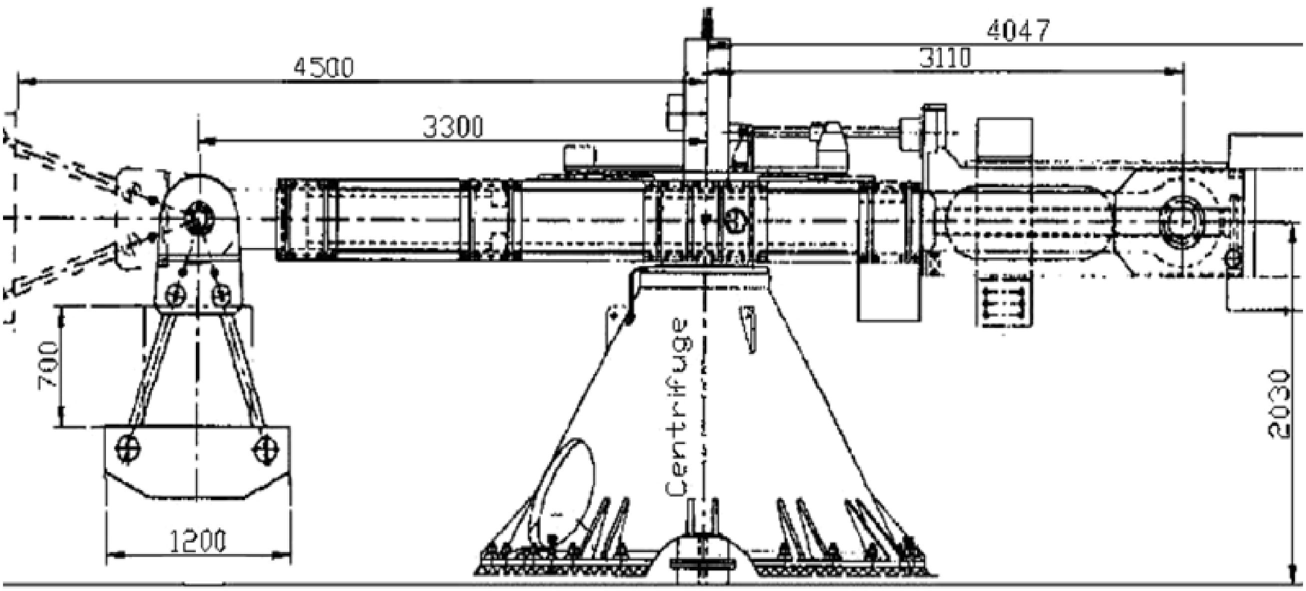

Figure 3.5 Cross section of a large beam centrifuge NGCF (dimensions mm) [After Chandrasekaran, 2001]

3.2.3 Centrifuge model tests

The centrifuge tests were conducted by maintaining a desired constant angular velocity (for example 93 revolutions per minute (rpm) for 40 gravities) so that desired gravity level was 4 maintained within the barrier. A waiting period of 10 minutes was maintained before starting the motor of MDSS system at a desired gravity level and thereafter it was set to a desired speed to induce differential settlements. The speed of the motor of MDSS was maintained as 13.5rpm by using a digital controller to lower the trapdoor settlement plate vertically at a settlement rate of 1mm/min in model dimensions. The value of settlement at the centre of the surface of the barrier is termed as central settlement, *a*. A maximum central settlement of 25mm was induced at a settlement rate of 1mm/min in model dimensions. Based on scaling considerations, the settlement rate (settlement over time) in the field Srp is 1/N times settlement rate in the centrifuge model S*rm* ($S_{rp} = S_{rm}/N$) with $t_m/t_p = 1/N^2$. This implies that a settlement rate S_{rm} of 1 mm/min at 40 g is equivalent to 36 mm/day in the field.

The performance of Trisoplast barriers was studied at the onset of continuous differential settlements was studied using a centrifuge modeling technique. In total, 12 (Twelve) centrifuge model tests were carried-out (excluding two pilot tests). Controlled deformations were induced by lowering central trap-door settlement unit. Two types of barrier materials, namely Trisoplast barrier material and Clay barrier material, were used. The details of the centrifuge tests conducted are summarised in Table 3.3. All these tests were categorized to study: a) Influence of thickness, b) Influence of pre-saturation, c) Influence of settlement rate, and d) Influence of self-healing effect. For all the tests, an overburden pressure equivalent to 15 kPa (except for model TL1) was applied before the test in the form of sand and water.

Centrifuge models CT1b, CT1c, TL1 and CT3 are grouped for studying the effect of thickness of the barrier, named as Series-A. Series-B consists of centrifuge models CT1b, CT2, CT1c, TL3 and CT1d to study the effect of pre-saturation of the moist-compacted Trisoplast barrier. Centrifuge models CT1e and CT1f are grouped in Series-C for studying the effect of settlement rate on the deformation behaviour of Trisoplast barriers. Finally, Series-D consists of centrifuge models TL2, TL2a, CT2, and CT2a for studying the effect of healing on the deformed Trisoplast barriers.

For all models with and without pre-saturation, a seating load of 6.25 kPa was applied for about 6 hours after completion of preparation of the barrier.

Table 3.3. Details of centrifuge model tests performed.

dTest No.	Test legend	N	Barrier soil	Thickness of barrier	σo [kN/m2]	wo [%]	γ [kN/m3]	Pre-Saturation
1	[e]TL1	40	TB	2.5mm [100 mm][a]	0	9.9[f]	19	No
2	TL2	40	TB	2.5mm [100 mm]	15	8[f]	19	No
3	TL2a	40	TB	2.5mm [100 mm]	15	45.95[h]	-[b]	[c]90 hrs at 1g
4	TL3	40	TB	2.5mm [100 mm]	15	8[f]	19	72 hrs at 1g
5	CT1b	20	TB	2.5mm [100 mm]	15	8[f]	19	No
6	CT2	20	TB	2.5mm [100 mm]	15	37.24[h]	19	72 hrs at 1g
7	CT2a	20	TB	2.5mm [100 mm]	15	27[g]	-[b]	[c]23 hrs at 1g
8	CT3	20	CB	2.5mm [100 mm]	15	8[f]	18.04	No
9	CT1c	20	TB	2.5mm [100 mm]	15	8[f]	19	No
10	CT1d	20	TB	2.5mm [100 mm]	15	8[f]	19	97 hrs at 1g
11	CT1e	25	TB	2.5mm [100 mm]	15	8[f]	19	No

12	CT1f	25	TB	2.5mm [100 mm]	15	8^f	19	No

TB: Trisoplast barrier; CB: Clay Barier; σ_o - overburden pressure; [a] prototype dimensions within the parenthesis; -[b] not relevant/not used; [c]Allowed to heal at 1g on the basket after inducing maximum central settlement a_{max}.[d]For all models with and without pre-saturation, a seating load of 6.25 kPa was applied for about 6 hours after completion of preparation of the barrier; [e] Initially test legends were given as TL and afterwards changed to CT and it is maintained for convenience; [f]In all these model tests, initial molding water content shown in this column was maintained; [g]In the case of model CT3 with clay barrier material, it was compacted towards wet side of optimum; [h]For model tests TL2a and CT2a, the initial molding water content was in the range of 8 to 9% and no-pre saturation before centrifuge test. After inducing maximum central settlement, these models were pre-saturated at normal gravity. σ_0 = Overburden pressure; w_o = Molding water content; γ = Bulk unit weight; S_{rm} = Settlement rate in model dimensions.

3.2.4 Centrifuge model results and conclusions

Figures 3.6 and 3.7 depict the status of the model Trisoplast barrier after centrifuge test. The results show crack-free Trisoplast barrier event after subjecting to a maximum central settlement of 0.5.

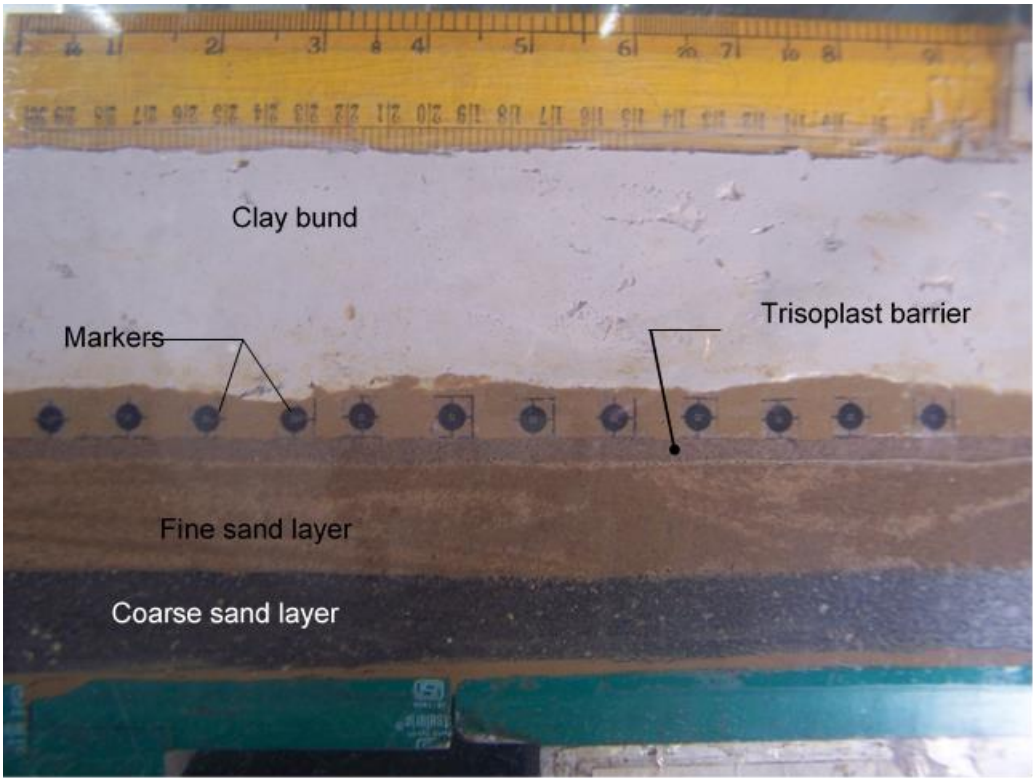

Figure 3.6 Before centrifuge test

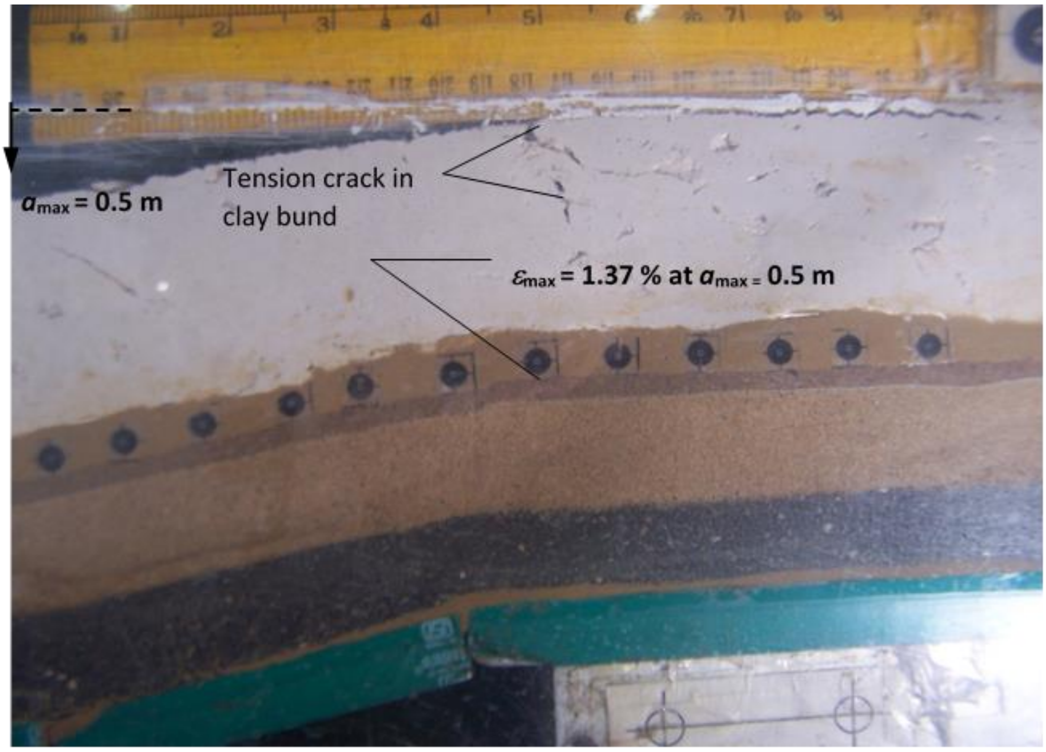

Figure 3.7 After centrifuge test

Based on the analysis and interpretation of centrifuge model test results, the following conclusions can be drawn:

The entire series of centrifuge tests were sub-divided into four series namely: Series – A, Series – B, Series – C, and Series –D.

In series-A, effect of thickness of moist-compacted Trisoplast barrier on the differential settlement behavior was studied. Both the Trisoplast barriers having thickness of 70 mm and 100 mm having an overburden equivalent to 15 kPa were able to withstand induced continuous differential settlements without any water breakthrough. Performance of 100 mm thick Trisoplast barrier was found to be superior to 70 mm thick Trisoplast barrier in having better sealing efficiency. The performance of 70 mm and 100 mm thick Trisoplast barrier was found much superior than 0.6 m clay barrier. At the onset of limiting settlement ratio, clay barrier was observed to experience a wide and full-depth crack at the zone of maximum curvature. In comparison, Trisoplast barriers were observed to have indentations extending to very shallow depths at the zone of maximum curvature. No clear formation of cracks was noticed.

In series-B, the effect of pre-saturation of Trisoplast barriers was studied on the differential settlement behavior of Trisoplast barriers. Significant influence of pre-saturation on the sealing efficiency of Trisoplast barrier can be noted. Very negligible variations were noted and about 90% of water stored on the surface of the barrier could be collected after the completion of centrifuge test. As mentioned earlier, no clear formation of crack was noticed, except indentations at the zone of curvature. This phenomenon was further studied through SEM testing of samples collected at the zone of maximum curvature and away from the zone of maximum curvature.

SEM of Trisoplast soil samples reveal gel type matrix development coating and connecting sand grains along with bentonite. This explains the observed behavior of leak proofness at the onset of differential settlements to Trisoplast barrier based landfill covers.

In Series-C, the effect of settling rate on the differential settlement behavior of Trisoplast barriers was studied. It is found that the settlement rate is not having any influence on the integrity of the tested barriers. In both the models, sealing efficiency of tested Trisoplast barriers was found to be excellent during all stages of centrifuge tests.

In Series-D, the self-healing ability of Trisoplast barriers was studied. After inducing a maximum central settlement of 0.5 m, Trisoplast barriers were allowed to heal at normal gravity. After elapsing the desired waiting period, it was noted that the deformed barrier material was found to have excellent sealing characteristics without any leakage. This shows that the Trisoplast barrier material can exhibit excellent sealing characteristics even under deformed conditions.

At the onset of differential settlements, strain experienced by the Trisoplast barrier was observed to be 4 to 4.5 times lower than the clay barrier having 0.6 m thickness at a settlement ratio of 0.6 (i.e. a central settlement of 0.3 m). Maximum strain values induced in the present study are of the order of 1.4 to 1.5 % to the Trisoplast barrier at the zone of maximum curvature. Trisoplast barrier material is able to sustain strains up to 1.4 to 1.5 % without losing its sealing efficiency. In comparison, barriers constructed with normal soils could able to sustain strains up to 0.1 – 0.2% only. This shows that the efficiency of thin barrier which has got inherent mineral properties to ensure sealing efficiency at the onset of differential settlements. The analysis and interpretation of this centrifuge test reveals that the performance of 70 mm and 100 mm thick Trisoplast layers was superior compared to a 0.6 m clay layer.

4. SUMMARY

Recent research and practical testing have confirmed the unique properties and quality of Trisoplast as mineral lining material. It can be installed on very steep slopes and is able to sustain high strains without losing its integrity and impermeability. Next to the common practice of horizontal installation it can also be installed vertically. Even installation under water is possible. This opens up a whole set of new possibilities in which Trisoplast can be of use for clients that seek the highest level of environmental protection through isolation.

It is evident that Trisoplast can be used for more applications than landfills only. It has been successfully installed in the mining and tank storage industry but also in infrastructural works where ground or groundwater needs protection. Furthermore, it is very suitable to be used in hydraulic engineering when impermeable layers are needed in dams, channels, canals, ponds or lagoons.

Future investigations

The search for even more applications and increased sustainability of Trisoplast continues. To help reducing the demand for natural resources, the sand skeleton of Trisoplast has already been replaced by alternatives. Molding or foundry sand appeared to be an excellent alternative as well as residual sand from soil remediation processes. Several landfills in the Netherlands have been capped with these alternatives of Trisoplast already.

Incineration ashes, mining residues or bentonite containing soil have also been considered as alternative for sand. Future research will prove the suitability of these materials.

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REFERENCES

Boels, D., van der Wal, K., 1999. Trisoplast: New developments in soil protection. Proceeding Sardina 99, seventh international waste management and landfill symposium International.

Boels, D., 2001. Comparing performance of Trisoplast with different mineral liner materials. Proceedings Sardina 2001, eighth international waste management and landfill symposium.

Melchior, S., Steinert, B., Flöter, O., 2001. The risk of desiccation and crack formation in cohesive soil barriers of landfill covers: A comparison of traditional clay barriers and the polymer-modified material Trisoplast. Proceedings Sardinia 2001, eight international waste management and landfill symposium.

Melchior, S., 2003. Desiccation of cohesive soil barriers in landfill covers: Experimental results, hydrological processes and important boundary conditions. Proceedings Sardina 2003, ninth international waste management and landfill symposium.

Naismith, M., Wammes, J., Timmermans, E., Behrens, W., 2003. Latest research regarding durability and performance on the polymer-enhanced mineral barrier Trisoplast. Proceedings Sardina 2003, ninth international waste management and landfill symposium.

Guyonnet, D., Cazaux, D., Vigier-Gailhanou, H., Chevrier, B., 2009. Effect of cation exchange on the hydraulic conductivity in a sand-bentonite-polymer mixture. Proceedings Sardinia 2007, twelfth international waste management and landfill symposium.