# Construction of Very Tight Clay Liners: The Högbytorp Case

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## Abstract

A large landfill for incinerated organic waste is under construction at Ragn-Sell's waste handling and deposition plant Högbytorp, northwest of Stockholm. Here, older stabilized ash forms the base of additional waste to be filled over it. The two will be separated by a clay liner for delaying and minimizing inflow and percolation of the older waste fill. The design principle and construction of the liner are described in the paper.
The clay liner is made of expanding clay with relatively high water content and a large span of particle size. The construction technique was originally planned for the forthcoming "near-surface" repository for low-level radioactive waste in Lithuania with the aim of providing very good tightness of liners at low cost.

**Keywords:** Ash, clay, hydraulic conductivity, ion diffusivity, liner, swelling pressure, smectite, waste

## 1   Background

Top covers of waste piles conventionally contain an erosion-protective drain layer over a low-permeable clay liner of smectitic clay. The rate of percolation of the liner, which may require tens of years or more to become water-saturated, determines the downward transport of ions released from the underlying waste to the underground. The percolation rate is controlled by the composition and density of the liner, which should be as tight as possible for minimizing the transmissivity. A high density yields a high swelling pressure and risk of expansion and softening and the density must hence be selected such that this pressure does not exceed the effective overburden pressure. After placement of the waste pile, which can be 20 m high, the clay liner will serve as barrier by sorbing cations from the waste. This can raise the percolation rate and degrade the clay by chemical attack.
Since the required time for isolation of hazardous waste is limited, presently 300 years according to EU directives, the clay liners do not have to be permanently tight but composed and constructed so that the amount of hazardous ions does not exceed certain

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values for the prescribed period of time. The essential parameters for the clay liners are: 1) water transmissivity, 2) expandability, 3) physical stability 4) constructability, and 5) cost.

The Swedish waste-handling company Ragn-Sell AB owns and operates a plant for waste processing and disposal at Högbytorp north of Stockholm. Organic waste is incinerated and the ash mixed with puzzolanic properties and placed and compacted on site, yielding a concrete of considerable strength and negligible compressibility under own weight and several meters of overburden. Old deposits are successively covered by newly prepared waste but separated from them by engineered barriers consisting of clay. The present paper describes the design, construction and predicted performance of the clay component.

## 2   Introduction

### 2.1 Site description

A 50 x 120 $m^2$ area has recently been completed for a 3 m thick stabilized landfill of incinerated organic waste (ash) in an area that is being used for landfill wastes by the company Ragn-Sell AB since late 1990. The most recent fill is being placed on top of earlier filled stabilized ash and separated from it by an about 0.5 m thick clay layer covered by a geotextile on which there is a 0.5 m layer of crushed and compacted rock serving as drainage. This layer is in turn covered by 0.3 m stabilized ash of incinerated waste classified that is classified as non-hazardous. The entire landfill has been licensed by the Swedish Environmental Agency. The present report describes the construction of the clay layer. Figure 1 illustrates the composition of the landfill and its interaction with earlier placed waste of cement-stabilized ash.

### 2.2 Hydration and Permeation of Clay Liners

#### 2.2.1 General

The amount of water that is infiltrated into the top liner of a waste pile and penetrates the waste mass and the bottom clay liner per time unit depends primarily on the water pressure exerted on the liner. The hydration of it is very complex since it depends on the access to water from the overlying drain layer, the water pressure and the relative humidity of the air in the voids of the layer. Taking the clay to consist of smectitic clay, like bentonite, and assuming that access to water from the overlying drain layer is unlimited, one can assume that hydration of the clay takes place by diffusive migration of water [1,2]. The time for saturation of the clay liner is very long as illustrated by the fact that a 20 mm thick layer of smectite clay with a dry density (ratio of solids and total volume) of 1300 $kg/m^3$ is almost completely saturated in about 12 days by one-sided wetting if the diffusion coefficient is $3x10^{-10}$ $m^2/s$, which is typical for dense smectite-rich clay. Considering that rain- and snowfall and hence access to water for uptake by the clay are intermittent and that draught will occur in periods, the actual time for complete saturation will be several tens of years and even more for a few decimetre thick smectite clay layer.
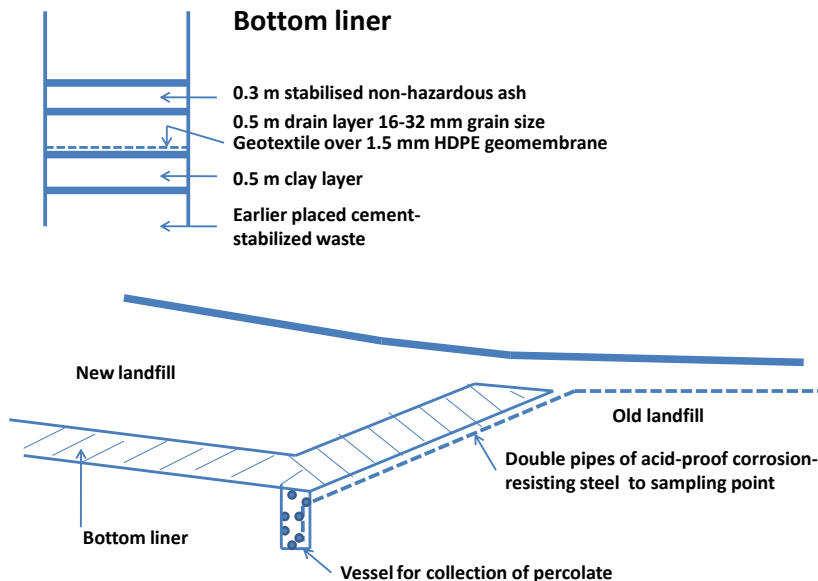
**Bottom liner**

0.3 m stabilised non-hazardous ash

0.5 m drain layer 16-32 mm grain size
Geotextile over 1.5 mm HDPE geomembrane

0.5 m clay layer

Earlier placed cement-
stabilized waste

New landfill

Old landfill

Double pipes of acid-proof corrosion-
resisting steel  to sampling point

Bottom liner

Vessel for collection of percolate

Figure 1: Schematic section of the landfill construction.

After water saturation of the top liner it will be percolated under the hydraulic gradient that is produced when a pressure head develops in the overlying drain layer. Prediction of the percolation rate is trivial, while definition of pressure heads and their persistence requires estimation of the water balance based on statistical precipitation data. As a very conservative case one can assume that the water level in the drain layer on top of the upper clay liner is maintained at a height over the clay liner that corresponds to 100 % of the annual precipitation, which is taken here as 1 m.   Using Darcy's law the percolation rate is:

$$v = K \times i \tag{1}$$

where: $v$=flow rate in m/s, $K$=hydraulic conductivity in m/s, $i$=hydraulic gradient (m/m). Taking $K$ as $10^{-11}$ m/s, which is achievable by using smectitic clay with a density of about 2000 kg/m$^3$ at water saturation and a thickness of the clay layer of 1 m one has $i$=1 and $v$=$10^{-11}$ m/s, which means that a flow-transported water molecule moves by about 10 mm in 300 days and that it would take 100 years for it to migrate through a 1 m thick clay layer.

Steady-state flow of water into the waste mass takes place when the top liner has become water saturated. Water is then entering the waste mass at a rate that is determined by the hydraulic gradient and hydraulic conductivity. Percolation of the mass is heterogeneous to begin with and some water can reach the bottom liner locally rather early. If it has the same hydraulic conductivity as the top liner and both are tighter than the waste mass, steady state through-flow will not take place until the waste mass has been completely water saturated. The electrolyte content of the porewater of the waste will increase

successively and this can increase the hydraulic conductivity of the bottom liner. The flow through it will still not increase since it is controlled by the flow through the top liner. Chemically induced microstructural changes of the bottom liner can lead to local softening, piping and erosion, which can strongly reduce its sealing potential.

### 2.2.2 Influence of ion exchange on the transport of contaminants

The cation exchange capacity of a bottom clay liner that is rich in Na smectite is about 100 meq/100 g, while it is about 40 meq/100 g for less smectic clay, like Friedland clay, which will be in focus here. The initially sorbed Na will be replaced by cations released from the waste according to the following replacing order: $Li < Na < Cd < K < Ca < NH_4 < Co < Cu < Hg < Fe$ (Pusch & Yong, 2006). For typical ashes of incinerated organic material the average concentration of heavy metals like cadmium in porewater that arrives at the lower clay liner can be up to 6 meq per liter and most of them will be sorbed by replacing the original sodium ions since they have a lower replacing capacity than the heavy metals.

The amount of water that passes through a 1 m thick bottom liner in a certain period of time is the product of the average flow rate, the cross section area (1 $m^2$) and the time. Taking the liner of Friedland clay to be 1 m thick, to have a density of 1950 kg/$m^3$ at water sarturation and a hydraulic conductivity of E-11 m/s, and assuming the hydraulic gradient to be 20 for a fully water-saturated waste pile of 20 m height, the annual percolated amount of water is 6 liters carrying with them 36 meq of heavy metals. This means that 0.9 kg of solid clay per cubic meter of clay is theoretically required for sorbing the amount of heavy metals every year. For a dry density of 1500 kg/$m^3$ at water saturation, its sorption capacity will be used up in somewhat less than 1700 years, after which the transport of metal cations will proceed at a constant rate. Thus, when the bottom liner has finally become water saturated, the leakage through it will be around 36 meq of metal ions per year, which for cadmium would correspond to an annual amount of 4.2 grams per square meter horizontal base area of the lower clay liner. This estimate neglects the flow-controlling function of the upper liner: since the percolated amount through this liner can in fact be much smaller than what is passing through the bottom liner it may take thousands of years before significant amounts of flow-transported heavy metals appear below the lower clay liner.

One concludes that while sorption by cation-exchange will significantly delay massive transport of heavy metals through the bottom liner the most effective barrier in the system is a very tight top liner because it retards water saturation of the waste mass and controls the permeation of the bottom liner.

## 2.3 Construction of the bottom Liner at Högbytorp

### 2.3.1 Criteria

The performance analysis of the waste mass made by the Ragn-Sells company that owns and runs the plant had led to the criterion that the liner, operating as a top seal, should have a higher hydraulic conductivity equal to or lower than 2E-11 m/s. The swelling pressure should not exceed a few hundred kPa but this would not be required until waste has been filled over the liner and starts to be permeated.

### 2.3.2 The principle of wet placement and compaction techniques

Experience from full-scale testing of compaction of raw material excavated from a thick clay bed of Triassic age in Lithuania [3] and stock-piled for drying in open air for one year for reducing the water content to 19-20 % (Figure 2), had shown that a dry density of about 1650 kg/m$^3$, corresponding to about 2000 kg/m$^3$ at water saturation, could be reached by rather moderate compaction, i.e. 420 kg vibrating plate on 11 cm layers, and 7 t vibratory roller on 17 cm layers[4]. The mineral composition is, in this order: 1) Fe-rich chlorite, 2) IS-mixed layer minerals (illite/smectite), 3) well- to poorly ordered illite, 4) kaolinite (2 types), feldspar, quartz and traces of calcite. The percentage of illitic layers in the IS varies between 40 and 85 % indicating that the content of expanding components was relatively small, i.e. 15-25 %. A density of 2000 kg/m$^3$ at water saturation, corresponding to a water content of about 29 %, would give the clay a hydraulic conductivity of 6.0E-11 m/s at percolation with low-electrolyte water, representing the conditions for a top liner.



Figure 2: Stockpiled Lithuanian clay.

### 2.3.3 Construction of the Högbytorp liner

Background: The principle of using slightly dried raw clay material with a large grain size spectrum for the Lithuanian case was further investigated and applied in the construction of the bottom liner at Högbytorp. Friedland clay is a very thick and homogeneous sediment mass of Tertiary age in northeastern Germany. It was selected because of the comprehensive experience from German landfill construction projects and systematic laboratory testing of this clay in Sweden. The content of clay-sized particles is about 90%. They consist of irregularly stacked muscovite-montmorillonite with about 30-40% expandables.

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[4]Chunks bigger than about 50 mm were removed

The required density was derived from a series of oedometer tests giving values of the hydraulic conductivity related to the density for various porewater compositions (Figure 3), [2]. One finds from the diagram in Figure 3 that the hydraulic conductivity for electrolyte-poor water is about 2E-11 m/s for a density at saturation of 1950 kg/m$^3$. For a density of slightly more than 2000 kg/m$^3$ percolation by strongly salt water (3.5 % CaCl$_2$ solution) will not raise the conductivity significantly beyond this figure. The tests were made at room temperature, which overrates the conductivity and considering also that the hydraulic gradient will be lower in practice than in the oedometer tests (roughly 50 %) the decision was taken to compact the liner of Friedland clay to a dry density of at least 1610 kg/m$^3$, corresponding to a density at water saturation of 2000 kg/m$^3$.

A particularly valuable property of Friedland clay is that the density obtained by compaction is not significantly affected by the water content (Figure 4), which means that the material does not require processing like drying, wetting etc, for reaching maximum density. The optimal water content is not well defined and untreated raw material can hence be used as long as the water content is below the figure representing complete water saturation, i.e. about 22 % for this clay. For reaching a high degree of homogeneity of the compacted clay large chunks should be removed in conjunction with placing and distributing the soil as in the Lithuanian case.
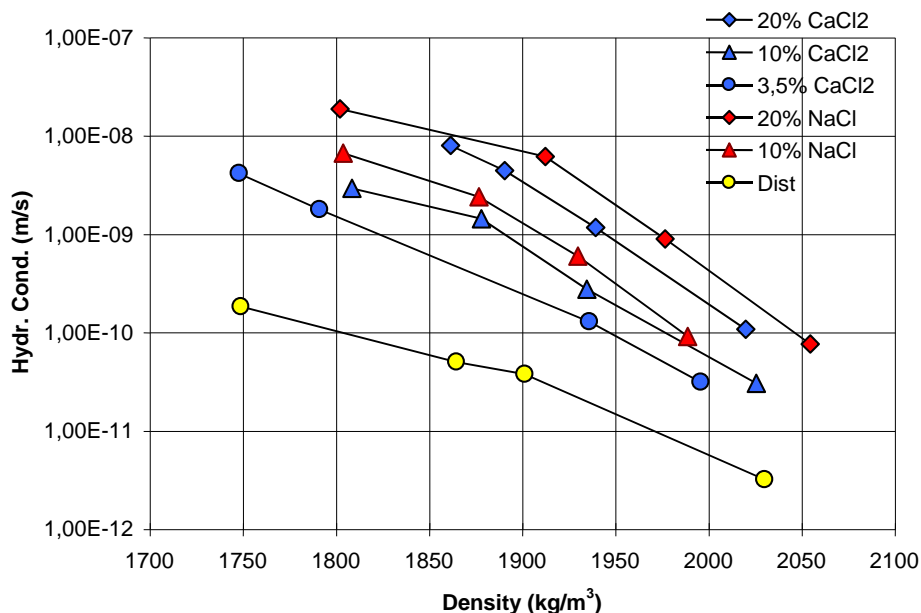


Figure 3: Hydraulic conductivity of Friedland clay as a function of the electrolyte content (After Clay Technology AB).

Analysis of samples taken in the course of compaction on site: The clay was placed in 25 cm layers that were compacted by 6 runs in one direction and another 6 runs in the perpendicular direction using a 19 t vibratory padfoot roller. The upper surface was then evened out by a few additional runs of a smooth roller. Samples of different size were taken systematically and representative results are summarized in Table 1. The placement and compaction were made under dry weather conditions and the completed surfaces sealed by HDPE geomembrane for preventing wetting in the construction phase.
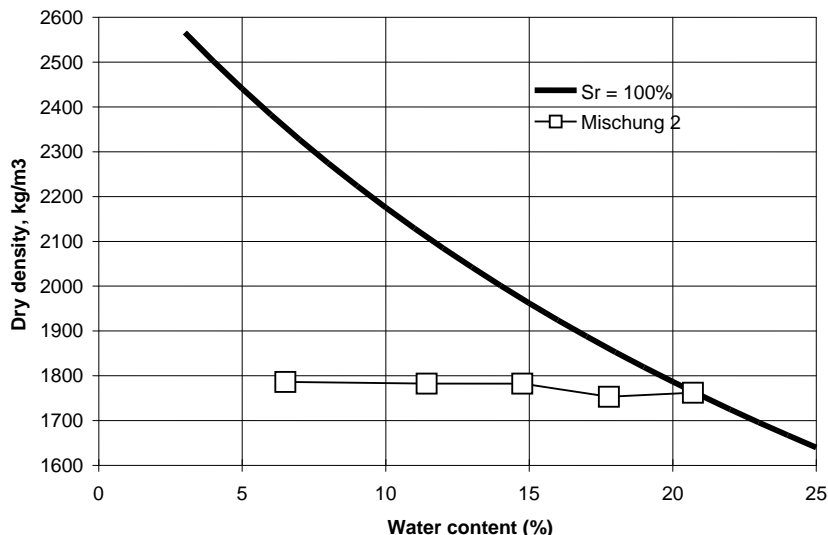
Figure 4: Compaction tests ("Mischung 2" represents the grain size distribution in the table). The full line represents the theoretical maximum density (no voids).

Table 1: Data from analysis of samples

| Layer | Volume, dm$^3$ | Water content, % | Density of clay kg/m$^3$ | Dry density kg/m$^3$ | Calculated density at water saturation kg/m$^3$ | n, porosity % | $S_r$, Degree of water saturation |
|---|---|---|---|---|---|---|---|
| 1 (first) | 1.178 | 22.55 | 1950 | 1612 | 2016 | 58 | 70 |
| 1 (first) | 1.178 | 22.19 | 1970 | 1615 | 2010 | 64 | 71 |
| 2 (second) | 1.178 | 22.79 | 1990 | 1615 | 2022 | 58 | 87 |
| 3 (third) | 1.178 | 19.16 | 1970 | 1655 | 2003 | 60 | 71 |
| 3 (third) | 1.178 | 23.03 | 1980 | 1612 | 2001 | 59 | 80 |

The results were interpreted as follows:
- The three layers have approximately the same density, meaning that the compaction energy provided to the upper layer was sufficient to give the same density as for the bottom layer,
- The average density at water saturation is 2010 kg/m$^3$, i.e. over the design value,
- The average degree of water saturation was 76 %, meaning that further compaction would not have been significant.

Figures 5-7 illustrate the compaction and condition of the clay.

Figure 5: Padfoot compaction with 19 t roller.



Figure 6: Appearance of padfoot-compacted Friedland clay. The wet surface indicates that the clay was compacted to nearly complete water saturation. It was perfectly homogeneous and no grains or chunks can be seen.

Figure 7: Sampling for determination of water content and density. Notice the homogeneity of the clay.



Figure 8: Smoothening of the upper surface for providing an even surface for the HDPE membrane.

## 3   Discussion and Conclusions

### 3.1 What is the Physical Stability of the Clay Liner?

The clay liner, serving temporarily as a top cover and as bottom liner after placing up to 20 m of waste consisting of stabilized ash, will be exposed to an effective pressure of up to 600 kPa after completing the waste fill operation. For physical stability it is required

that this pressure is balanced by the swelling pressure of the clay. Other criteria are that it must sustain vibrations caused by seismic events and that slope stability must be guaranteed. The latter implies that effective lateral support must be provided by tight dikes.

### 3.1.1 Swelling pressure

The swelling pressure of Friedland clay measured in conjunction with oedometer tests is illustrated in Figure 9. One concludes that the pressure at a density at water saturation of 2000 kg/m$^3$ can be up to 900 kPa for very electrolyte-poor porewater and down to about 500 kPa for very salt porewater. Analyses of porewater extracted from earlier placed waste have indicated that the clay can be saturated with water that is chemically equivalent to 3.5 % $CaCl_2$ solution, which roughly corresponds to 600 kPa swelling pressure, hence fulfilling the pressure criterion.

### 3.1.2 Seismic resistivity

For eliminating the risk of liquefaction or triggering of slope failure by earthquakes it is required that the density of the clay is sufficiently high. For a density at water saturation of more than about 1800 kg/m$^3$ (dry density 1270 kg/m$^3$), earthquakes of Richter magnitudes up to 5 will not cause damage [4].

### 3.1.3 Slope stability

Near the edges of the waste fill the clay liner is inclined by about 15$^o$, which means that one needs to consider the risk of slope failure. In contrast to smectite-rich soils Friedland clay does not exhibit any obvious creep potential but resembles silt in this respect. This makes it perform as a friction material with an angle of internal friction of at least about 25$^o$, which gives a safety factor with respect to slope stability of tan25/tan15=1.7.

## 3.2 What is the Chemical Stability of the Clay Liner?

An immediate reaction of the bottom liner clay to infiltration of percolate from the overburden of waste is exchange of the initially sorbed Na ions in the clay. This will change the hydraulic conductivity and swelling pressure as described in the preceding text but not very significantly. The impact of pH must be considered as well but it is concluded from testing of water from earlier placed waste that pH will not exceed 8 or be lower than 6 and will therefore not have any significant impact on the chemical stability of the clay material [2].
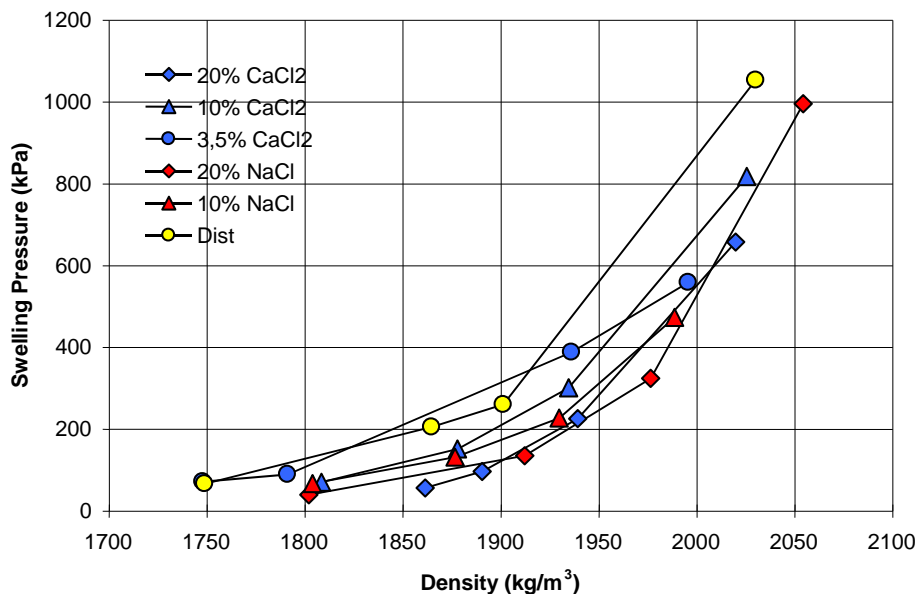
Figure 9: Swelling pressure of Friedland clay as a function of the electrolyte content
(After Clay Technology AB).

### 3.3 What is most Effective, the Top or the Bottom Clay Liner?

The diagram in Figure 3 demonstrates that the density is a key parameter for the trans-missivity of clay liners and that it should be as high as possible but low enough to avoid expansion. The effective overburden pressure on a top liner can hardly exceed about 200 kPa, and the swelling pressure should therefore not be higher than that in order to prevent expansion of the clay. This means that the density of a top liner of Friedland clay saturated with low-electrolyte water must be kept below about 1900 kg/m$^3$. As exemplified by the Högbytorp case the bottom liner may have an effective overburden pressure of 600 kPa and the corresponding allowed swelling pressure may hence correspond to a density at water saturation of about 2000 kg/m$^3$ for this type of clay saturated and percolated by salt-rich waste water. The hydraulic conductivity of the top liner consisting of the same clay and percolated by ordinary rainwater will be about 3E-11 m/s, and that of the denser bottom liner percolated by a 3.5 % CaCl$_2$ salt solution, approximately the same. After complete water saturation the transmissivity will be determined by the thickness of the liners and by the hydraulic gradient operating across them. If the thickness is the same the low hydraulic gradient of the top liner will give a lower through-flow than the equally thick bottom liner that is exposed to a gradient that is 20 times higher. By reducing the thickness of the bottom liner to a few centimetres the transmissivity of both liners would be the same.

A final conclusion is that it is meaningless to construct a bottom liner that is tighter than the top liner and great effort should instead be put on constructing a very tight top liner. For the ideal case with no penetration of water through the upper clay layer, no contaminating ions from the waste mass will enter or pass through the bottom layer and further to the underground.

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