Ref. Ares(2018)5560112 - 30/10/2018

paperChain

# Implementation of circular case 5
D5.1 October 2018 (M17)

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This project has received funding from the European Union's Horizon 2020 research and innovation Programme under grant agreement N° 730305

| | |
|---|---|
| Deliverable No. | 5.1 |
| Dissemination level | Public |
| Work Package | 5 |
| Task | 5.5 |
| Lead beneficiary | LTU |
| Contributing beneficiary(ies) | LTU, BOLIDEN, PROCESSUM |
| Due date of deliverable | 31 October 2018 |
| Actual submission date | 31 October 2018 |

## Document history

| V | Date | Beneficiary | Author |
|---|---|---|---|
| 1 | 22/10/2018 | LTU, BOLIDEN, PROCESSUM | Susanne Nigéus, Josef Mácsik, Christian Maurice, Nils Eriksson, Pär Odén, Rodrigo Jr Embile, Marie Lindgren, Emma Rönnblom Pärsson, Gunnar Westin |
| **2** | 29/10/2018 | ACCIONA | Juan José Cepriá, Roberto Orejana |
| Final | 30/10/2018 | LTU, BOLIDEN, PROCESSUM | Susanne Nigéus, Josef Mácsik, Christian Maurice, Nils Eriksson, Pär Odén, Rodrigo Jr Embile, Marie Lindgren, Emma Rönnblom Pärsson, Gunnar Westin |

# Summary

This document D5.1 "Implementation of circular case 5" aims to provide necessary information to plan, design, and construct a sealing layer for mine waste deposits, using GLD from the PPI.

This guidance is based on results and experience from research projects and pilot experiments performed prior to the Paperchain project and a demonstration at Näsliden Mine, owned by Boliden Mineral AB. The R&D work was done by a consortium including Boliden Mineral AB, Processum, Luleå University of Technology, RagnSell AB, Ecoloop AB, Ramböll AB.

GLD are used to improve till, a soil available near the mine sites, to fulfil the technical requirements of a sealing layer material in the proposed solution, the GLD are mixed with till and compacted in a 50-cm thick layer. The present guidance describes the principle of mine remediation, the design of covers, and the quality control procedures necessary to ensure the quality of the final product. Further advices are provided regarding the construction of the cover and adequate machinery to mix and compact the materials.

This guidance gives necessary information for the PPI, waste managers and the mining industry to manage the remediation of mine waste deposits using GLD based sealing layers.

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## Keywords

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|---|---|---|---|---|
| *cover* | *GLD* | *sealing* | *mine waste* | *demo* |
| *quality* | *requirement* | *standard* | *environment* | *performance* |

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**Abbreviations and acronyms**

ARD – Acid Rock Drainage

$D_e$ – Diffusion coefficient

e – void ratio

GARD-guide – Global Acid Rock Drainage guide

GLD – Green Liquor Dregs

HC – Hydraulic conductivity (m/s)

n – Porosity

PSD – Particle size distribution

QA/QC - Quality Assurance / Quality Control.

$R_D$ – Compaction degree

$S_r$ – Water saturation (%)

SWCC – Soil water characteristic curve

TSC – Total solid content

V – Volume ($cm^3$)

w – Gravimetric water content (%)

$W_L$ – Yield point

$w_{nat}$ - Natural water content

$W_P$ – Plastic limit

WRC – Water retention capacity

wt. % – Weight percentage

$\psi$ – Matric suction ($mH_2O$)

$\psi_a$ – Air entry suction ($mH_2O$)

$\rho_d$ – Dry density ($g/cm^3$)

$\rho_s$ - Relative density of the grains ($g/cm^3$)

$\theta$ – Volumetric water content (%)

$\theta_r$ – Residual volumetric water content (%)

$\theta_s$ – Near saturated volumetric water content (%)

$\Theta$ - Effective saturation (%)

# 1 Introduction

## 1.1 Waste generation at the PPI

Most of the pulp and paper mills today use the sulphate production process. The process involves treating wood chips with sodium hydroxide and sodium sulphide to disrupt the chemical bond between cellulose and lignin thereby liberating the cellulose. The major advantage with this method is that the inorganic chemicals used in the process can be recycled and reused in the recovery boiler. However, large amounts of waste materials such as Green Liquor Dregs (GLD) are generated. Generally classified as non-hazardous, GLDs are a waste that is generated from the recycling of chemicals used in the production process (Figure 1). At the sulphate pulp mills, GLD is the largest waste fraction that usually ends up in landfills. The world's largest producers of sulphate mass are USA, Canada, China, Finland and Sweden (Skogsindustrierna 2006). In Sweden ~134 000 tons of GLD (dry matter content) are produced annually (Arm et al 2007). A recent survey made in an on-going project confirms these numbers for 2017.

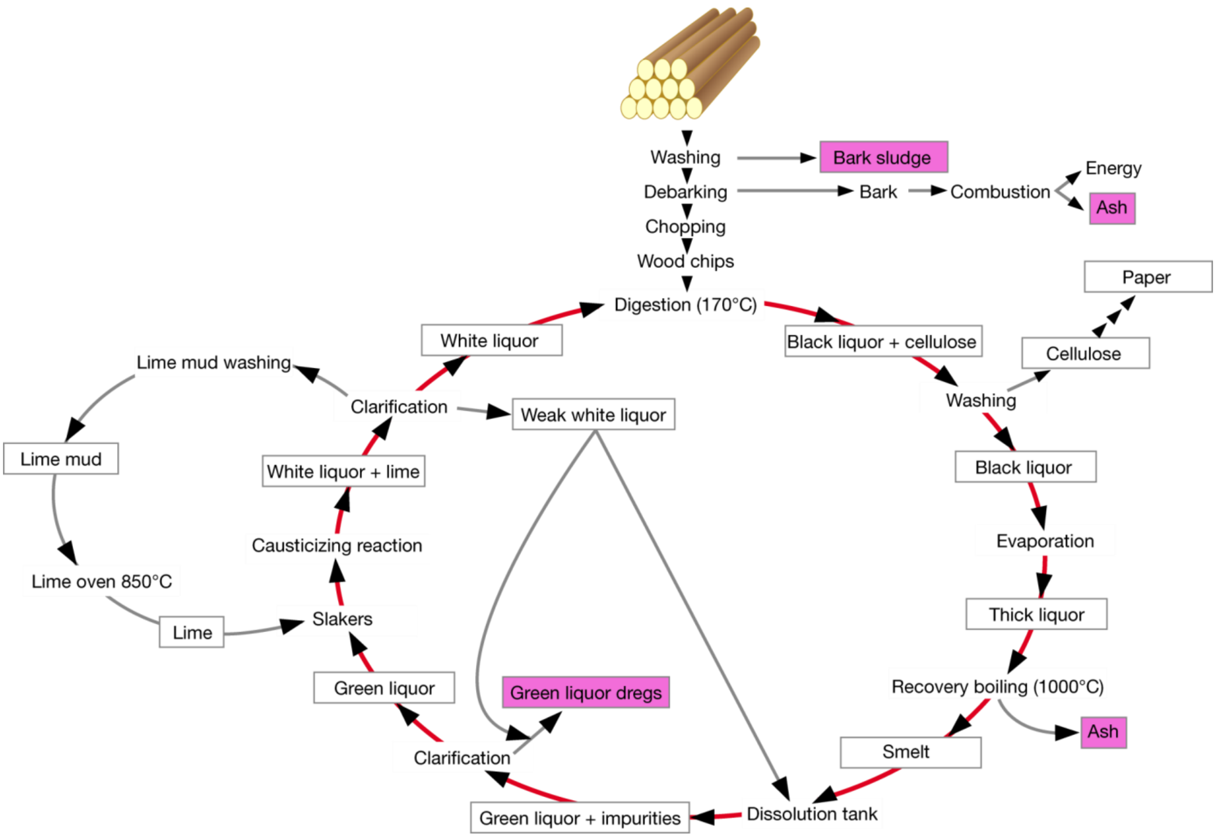


FIGURE 1. Retrieval of GLD from the sulfate process.

Utilization of GLD is currently limited. It has been used in several different sanitary landfill cover applications (Pousette and Mácsik 2000; Hargelius 2008). However, landfilling is a dominant method to dispose the material. Since the landfilling of GLD is costly, reusing the material would be a great gain for the pulp and paper mill industries. GLDs are classified as a non-hazardous chemical waste by the Swedish EPA (SFS 2001:1063). Pöykiö et al (2006) showed that GLD could also act as a neutralizing agent for acidic wastewater due to its naturally alkaline nature. GLDs have been previously used in applications as a stabilization agent for road construction (Toikka 1998). In recent years, studies have been performed on how to use lime waste to reduce metal leaching from mine tailings (Herbert et al 2007; Calace et al 2005; Sartz, 2010). Together with the fact that it is alkaline and have been shown to have a low hydraulic conductivity (Toikka 1998), and the capacity to remain humid, the possibility arises to use it for construction of sealing layers for sulfidic mine waste.

## 1.2 Mining waste management

Massive amounts of mine wastes are generated worldwide. Sweden alone generated 110-million-ton mine waste in 2017, accounting for 77 % of all waste produced during that year (Swedish EPA 2018). The global production of mine wastes was estimated at 15.000 – 20.000 million tons of solid waste each year, a sum greater than the waste produced from all other human activities taken together. Sulfide bearing mine wastes are generated at 10 of the 16 active mines in Sweden and may be found at hundreds of abandoned mines ranging from small to newly decommissioned sites that can be several hectares. These wastes need to be managed in an environmentally-, technically- and economically sustainable way.

About 70 % of the mine wastes in Sweden contain sulfide minerals (SGU and Swedish EPA 2017). If sulfidic mine waste is left in contact with oxygen and humidity, the sulfides oxidize and have the potential to produce acid rock drainage (ARD; Figure 2).


FIGURE 2. Descriptive figure of acid rock drainage (ARD).

ARD is a major long-term threat to the environment as it is associated with low pH and high concentrations of metals and metalloids (Akcil and Koldas 2006; Saria et al 2006). Weathering of minerals is a natural process, with increasing intensity of the processes in mining creating new surfaces. ARD is generated by the following reaction (Akcil and Koldas 2006):

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (1)$$

## 1.3 Objective

Previous research has shown that GLD has attractive properties that could be used in the remediation of mine waste deposit, specifically in the construction of sealing layers.

However, GLD cannot be used solely in a 50-cm thick layer because of geotechnical stability concerns i.e. there is a risk for landslide in the slope of the waste rock deposits. Therefore, R&D work has focused on mixing till and GLD in order to produce a material that can be used in slopes and has a low hydraulic conductivity, is able to withstand drying and remain humid with the purpose to reduce oxygen transport.

The objective of the project was to demonstrate that the GLD/till mixture can be produced, distributed, and compacted with conventional equipment, at a mine scale i.e. several hectares up to square kilometer.

## 1.4 Challenges

The main challenges identified in the research projects that have been conducted prior to Paperchain were associated with the heterogeneity of the GLD, such as variation in water content, making it difficult to handle during mixing with other materials and during compaction.

As research was performed at laboratory scale (kg) it was essential for the demonstration to show that mixing and compaction could be performed at industrial scale with widely available equipment.

The focus of the demonstration was therefore:

- Quality control of the incoming materials (GLD and till)
- Evaluation of the mixing (quality that could be achieved and the production rate)
- Compaction degree that can be achieved in slopes and flat areas.
- Evaluation of the function of the layer

# 2 Mine waste generation and remediation

## 2.1 Mining process and waste generation

Mining generates large amounts of waste as most of the rock excavated from the bedrock is waste and only a small portion of the ore ends as concentrate, the valuable fraction. Two types of mine waste are produced; waste rock and tailings (Figure 3). Waste rock is produced when excavating rock to access the ore and is used for back-fill of the mine, construction material or is placed on waste rock dumps in the vicinity of the mine. The ore extracted goes to concentration and enrichment plants. The residue after ore extraction is called tailings and is used for back-fill in the mine or pumped to a tailings management facility (Figure 3).

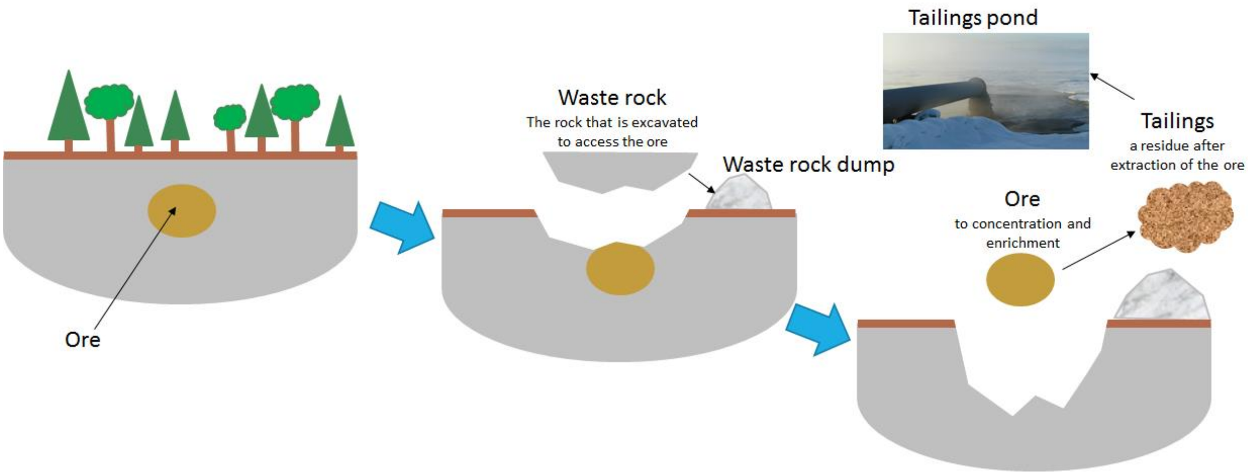


FIGURE 3. Waste generation in the mining process (reworked from SGU 2017).

## 2.2 Legal aspects

Waste Valorization is defined in the European Waste Directive (2008) and its national transpositions. The legal framework defines what waste is and how waste can become a resource. PAPERCHAIN follows these principles and takes into account for each circular case the applicable legal framework. The European general legal framework regarding the waste management and valorization is ruled by the following reference documents:

- European Waste Catalogue EWC (2014)
- Council Decision establishing criteria and procedures for the acceptance of waste at landfills (2002)
- UE Regulation concerning the establishment of a European Pollutant Release and Transfer Register (2006)
- UE REACH Regulation (2006)
- European Waste Directive (2008)
- CPR (2011). UE Regulation laying down harmonized conditions for the marketing of construction products (2011).
- Mine waste: Seveso Directive (1982) and the BREF (2009) in management of tailings and waste rock (currently under revision)

For waste valorization applications, specific European standards apply, especially regarding to the construction, such as aggregates quality determination standards for bituminous mixtures, safety controls, etc. In addition, local regulations must be taken into account for each Circular Case, as well as administrative permits (local government, council, etc.).

The mining sector is regulated by general (e.g. EQS for water) and specific (e.g., the Swedish Extractive Waste ordinance) national laws and each new mining operation must be approved under specific environmental regulations regarding emissions and pollutants release to surface and groundwater. However, certification regarding this Circular Case application is currently not available.

In Sweden GLD or other material to be used in mine waste remediation is regulated by the Mining Waste Directive (Mining Waste Directive 2006) and the Best available techniques Reference document (BREFs) together with several site specific functional requirements which can be expressed, e.g. in requirements regarding hydraulic conductivity, effective oxygen flux, leachability and strength.

These requirements are not fixed apart from what is considered BREFs, and are proposed by the operator to the Authorities, as part of the permitting process and fixed by the environmental court. The proposed solution should be sustainable, safe, result in an acceptable long-term load from the site to the environment and at the same time insure a long-term stability and durability preventing layer breakage and landslide etc.

There is a praxis on how to achieve this function requirement: the operator has to show to Authorities that the proposed solution (sealing system) fulfills BREF and the site-specific requirements set for the receiving environment. If proven, the approval from authorities is obtained and the construction of the sealing layer can start. All operating mines need to have an approved closure plan which is secured in the permitting process. In agreement with the Extractive Waste Directive, the Waste Management Plan and the Closure Plan should be up-dated at least on a five year basis.

The closure, including any covering of waste facilities, will be commissioned by the mining company according to the closure plan approved by authorities. If implemented closure measures are approved, the corresponding part of the closure guarantee may be released back to the mining company. The performance of the implemented closure measures need to be monitored and controlled at least for 30 years, or until the authorities are convinced the closure plan performs as designed.

# 3 Requirements on covers

## 3.1 Mine waste remediation

There are several ways to prevent ARD after mine closure (e.g. BREF document). The GARD guide (Global Acid Rock Drainage guide; Verburg et al 2009) categorizes different methods to prevent ARD after closure into two main categories; engineered barriers and water covers (Figure 4). Engineered barriers can be divided into liners and dry covers, where liners are typically designed to act as a barrier for contaminant flow from the waste into the receiving environment. Dry covers are typically designed to limit the ingress of water and oxygen into the waste.

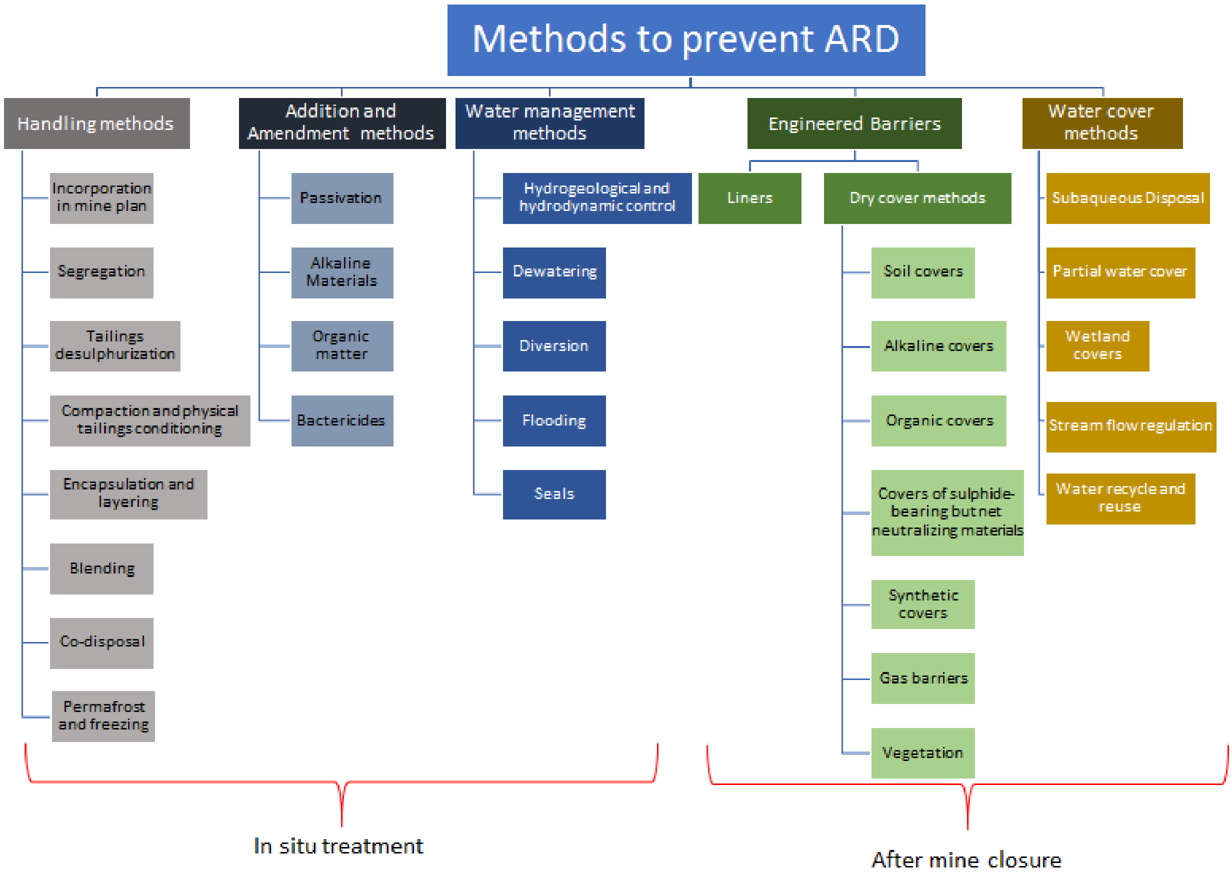


FIGURE 4. Different methods to prevent ARD from mine waste according to the GARD-guide (Verburg et al 2009).

According to the GARD guide the dry covers can be divided into soil covers, alkaline covers, organic covers, covers of sulfide bearing but net neutralizing materials, synthetic covers, gas barriers and vegetation covers (Verburg et al 2007).

## 3.2 Soil covers and sealing layers

A typical soil cover in Sweden consists of a sealing layer made of a compacted fine-grained material with a low HC and high WRC. On top of the sealing layer, an uncompacted protection layer is placed, usually made of till. The function of the protection layer is to protect the sealing layer from penetration of roots and frost. Above the protection layer, a nutrient-rich vegetation layer is usually placed for easier reestablishment of vegetation (Figure 5).

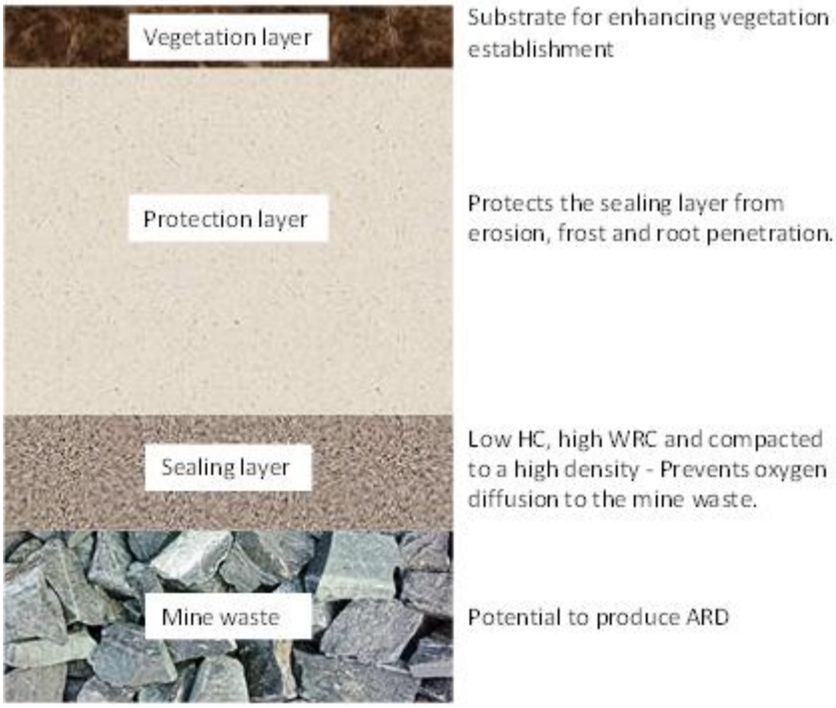


FIGURE 5. A describing figure of a typical soil "qualified" cover system in Sweden.

### 3.2.1 Leveling of the surface

Mine waste rock is commonly deposited in piles, with slopes at the angle of repose of the material Waste rock deposits therefore consist of a flat plateau and slopes being more or less steep.

The slopes built during deposition of mine wastes are often too steep (<1:2) and need to be flattened (at most 1:3-4) to be able to build a stable cover layer. For clay and fine-grained till, the effective angle of friction may be set to 30° (SGI 2007). The slopes of the flatter parts must be set to at least 1:10 and shaped to divert precipitation without damaging the cover.

Waste rock is normally a relatively coarse-grained material. The largest boulders might be up to a cubic meter, which results in large porosity of the pile. To prevent material from the sealing layer to flush into the pores, the surface of the waste-rock deposit must be levelled which sometimes imply using a more fine-grain material to fill the pores. Coincidentally, the surfaces are shaped and levelled to obtain adequate inclination of plateau and slopes of the pile.

Compaction of the terrace area (or levelling layer) surface is performed with a roller, equipped with a digital compaction meter (Figure 6). The dry density obtained normally exceeds 1.9 tons/m$^3$.

FIGURE 6. Compaction of the levelling layer (Näsliden year 2016).

The levelling layer may be constructed with a more fine-grained fraction of waste rock, crushed aggregate or till. Adjustment of slopes can be done with optical measurements and/or by machine control. The surface of the levelling layer needs to be smooth, without e.g. wheel-tracks. The surface of the levelling layer is scanned and used as reference for installation of subsequent layers.

### 3.2.2 Sealing layer

In an advanced "qualified" cover, the sealing layer is installed above the levelling layer. The sealing layer functions as an oxygen barrier which reduces the transport of oxygen to underlying sulfidic waste. The sealing layer, with a thickness of approximately 30-50 cm is made up of one or two compacted layers. Application in one single layer is sufficient if the compaction criterion is fulfilled and verified.

For each remediation project, a lowest acceptable compaction degree should be set in advance for each material mixture used. During the construction of the sealing layer, the compaction degree is controlled for quality assurance.

The main function of the sealing layer is to limit oxygen diffusion through the cover. Oxygen has two main ways of transport in a porous medium, dissolved in the pore water or in gaseous form in the unsaturated porosity. Often, oxygen diffusion coefficient of the sealing layer material is not measured, and hydraulic conductivity (HC) is usually used as an indicator to evaluate the effectiveness of a sealing layer as it is easier to measure. The requirements for HC in a sealing layer is site-specific but is commonly set to ≤$10^{-8}$ m/s in Sweden. To reach a low HC the sealing layer should be compacted to a high density

(Höglund et al 2004). Studies by Leroueil et al (2002) and Watabe (2000) on glacial till shows that the HC is highly dependent on the degree of compaction, with significantly decreasing values with decreased void ratio during loading. Another feature related to compaction that affects the HC is the molding water content of the material (Benson and Trast 1995; Leroueil et al 2002), i.e. the water content after compaction. A study conducted by Benson and Trast (1995) on thirteen compacted clays shows that the lowest HC was reached at molding water content of 1-2 % wet of the line of optimums. The optimum water content is the molding water content at which the highest dry density can be achieved. The presence of fine-grained material is another important factor that influences the HC. An increasing amount of fines in the material decreases the HC (Benson et al 1994; Benson and Trast 1995; Leroueil et al 2002), as the micro-porosity of the material decreases. In a study on tills conducted by Leroueil et al (2002) the HC decreased several orders of magnitude as the clay-size fraction increased from 2 to 12 %. Also, a study on clay conducted by Benson et al (1994) showed a strong relationship between clay content and HC and a weak relationship between the contents of fines and HC.

For a material to be used as an oxygen barrier on top of mine waste, its water retention capacity (WRC) is another important feature that must be considered, as high WRC usually corresponds to a high water-saturation (Sr). The transport of gaseous oxygen through fine-grained materials are mainly by molecular diffusion (Yanful 1993). At a relatively low degree of saturation, most oxygen transport occurs through the partially air-filled pores (Aachib et al 2004), due to the 10 000 times higher diffusion coefficient (De) in the air than in water (Yanful 1993). In addition to a higher diffusion coefficient, the dissolved O2 concentrations in the air are around 20 000 times higher than in water (Höglund et al 2004; Verburg et al 2009). Effectively the oxygen flux rate is significantly reduced when the degree of saturation is greater than 85-90 % as the air-phase becomes discontinuous (Corey 1957). The oxygen is then transported through the water phase (Aubertin and Mbonimpa 2001; Aachib et al 2004) and in a layer that is kept close to saturation, the $D_e$ in the soil can then be comparable to the De in water. It is then small enough to reduce the oxygen flux to a level comparable to that of a water cover (Yanful 1993; Aachib et al 2004).

One way to illustrate the WRC is to use a soil-water characteristic curve (SWCC), which shows the correlation between matric suction (ψ) and water content (gravimetric [w] or volumetric [θ]) or degree of saturation ($S_r$; Figure 7:A). The typical SWCC consist of three stages: capillary saturation, desaturation and residual saturation (Figure 7:A; Sillers et al 2001). The matric suction required to remove water from the largest pores corresponds to the break in the SWCC, where the soil is nearly saturated ($\theta_s$; Figure 7:A). This break in the curve is generally referred to as the air-entry suction ($\psi_a$; Figure 7:A). The water content corresponding to the asymptote of the SWCC at low degrees of saturation is called the residual water content ($\theta_r$; Figure 7:A). The SWCC is hysteretic, which means that matric suction for desorption (drying) is higher than for sorption (wetting), for a given water content (Figure 7:B; Tinjum et al 1997). This so-called hysteretic effect is caused by size differences between the bulk-pores and the interface-pores that connects the main-pores, which changes the contact angle between water and air during wetting (Tinjum et al 1997). Due to experimentally practical reasons, only the desorption curve is used when measuring WRC in a laboratory (Tinjum et al 1997). The shape of the SWCC is related to the soil type. Soils with smaller pores and finer particles usually have a higher ψa (Figure 7:C; Fredlund and Rahardjo 1993; Tinjum et al 1997; Sillers et al 2001). Also, the slope of the curve in the desaturation zone tends to become flatter as the soil particles become finer (Figure 7:C; Sillers et al 2001). Aside from particle size distribution, the molding water content is also known to affect the SWCC of fine-grained soils. Higher $\psi_a$ and a steeper slope for suctions greater than the $\psi_a$ can be observed as the molding water content increases (Tinjum et al 1997; Vanapalli et al 1996; Vanapalli et al 1999). Vanapalli et al (1999) studied the SWCC in fine-grained soils and found that if they are compacted dry of optimum water content, steeper SWCC are generated compared to those compacted wet of optimum water content. At dry of optimum water content, the specimen is influenced by its macrostructure and acts like a coarse-grained soil due to aggregation. At compacted wet of optimum, the microstructure is more important, leading to a higher $\psi_a$ than in soil compacted dry of optimum (Vanapalli et al 1999). In addition to molding water content, the initial density has a significant impact on the SWCC due to a decrease in the volume of voids with increasing dry density, leading to faster saturation (Vanapalli et al 1999).

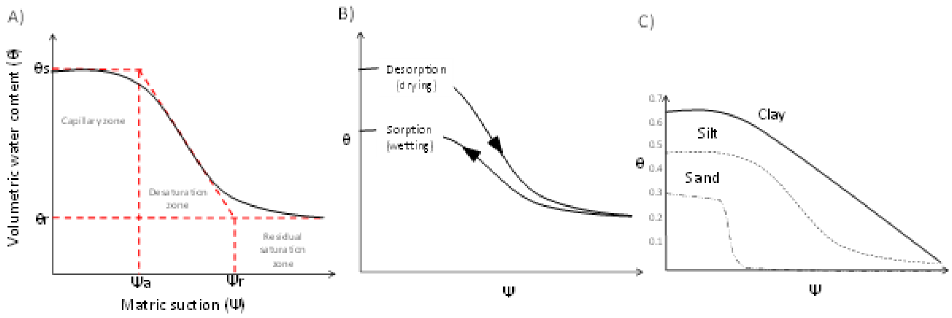


FIGURE 7. A) A typical SWCC, where ψa is the air-entry suction, ψr the water entry value, θs the nearly saturated water content and θr the residual water content (reworked from Tinjum et al 1997). B) A typical SWCC for desorption (drying) and sorption (wetting; reworked from Zhou et al 2012). C) A typical SWCC for clay, silt and sand (reworked from Sillers et al 2001).

### 3.2.3 Protective layer

The function of the protective layer is to protect the sealing layer against ground frost, dehydration, root penetration and as a water storage buffer. Traditionally, the layer consists of unsorted till (approximately of 1,5-2 m thickness due to normal depth of ground frost in northern Sweden). If the frost protection properties of the material can be enhanced, the thickness of the protective layer can be decreased resulting in reduced remediation costs.

By adding organic matter to the protective layer, it may also function as an oxygen-consuming layer. However, this effect is time-limited due to degradation of the organic matter.

### 3.2.4 Vegetation layer

The vegetation layer is used for quickly establishing vegetation that will function as an erosion protection. A suitable layer may be obtained by supplying organic matter into the top soil layer. One issue to consider before choosing material is which type of vegetation is desired in the long run. Tests are normally carried out concerning establishment of specific species, e.g. establishment of lichen on remediated areas. In the case of lichen, for example, no fertilizers should be added since that would make lichen outrivaled by various grass species.

Quick establishment of vegetation is important to decrease the risk for erosion. Hydro-seeding is an example of method for effective establishment of vegetation. Other methods commonly used is addition of sewage sludge to the vegetation layer. The risk for fertilizer leaking needs to be considered when constructing the vegetation establishment layer.

## 3.3 Improving till

A sealing layer in Sweden is usually made of a clayey till. The availability of a clayey till near a mine is however often limited. In such cases, till can either be improved or replaced to construct a suitable sealing layer. There is, therefore, a need for alternative solutions, e.g. bentonite amendment to till. However, bentonite production is costly both economically and environmentally due to resource consuming production methods.

Recycling of industrial residues as a sealing layer material is another option. Sweden produces 28 million tons of wastes, excluding mine waste, of which about 26 million tons is classified as a non-hazardous waste by the Swedish EPA and of that 6 million tons is residues from industrial production (Swedish EPA 2016). Most of these residues are deposited in landfills and only a small amount recycled. Using an industrial residue in a mine remediation program could be useful for both the mining industry and the industry providing the residue which in turn benefits the environment as less waste is deposited in landfills. The system serves as a circular economy as the industries aim towards reducing waste deposition. Some examples of industrial residues that have been previously used in mine waste covers are sewage sludge, fly ash, desulfurized tailings, coal combustion by-products (CCB) and steel slag (Hallberg et al 2005; Bäckström et al 2009; Dobchuk et al 2013; Lu et al 2013; Nason et al 2013; Park et al 2014; de Almeida et al 2015; Phanikumar and Shankar 2016).

# 4 Material characterization: GLD and Till

## 4.1 Green Liquor dregs - GLD

Previous studies have shown that a residue from pulp production, GLD, has properties suitable for a sealing layer i.e. it is fine-grained (d100 < 63μm), commonly has an HC in the range of $10^{-8}$ and $10^{-9}$ m/s and a higher water retention capacity (WRC) compared to materials with similar particle size, such as clayey/sandy silt (Mäkitalo et al 2014). A general trend in the pulp and paper industry to minimize landfill disposal is seen (Monte et al 2009) due to extensive costs (Eroglu et al 2006). This is a great driving force for the industries to find recycling options for their waste. In 2003 Sweden produced about 200 000 tons of GLD annually (SGI 2003), and production has slightly increased based on a survey made 2017 (unpublished data).

### 4.1.1 Properties of GLD

GLD is an alkaline, inorganic waste originating from the recycling process at sulfate pulp and paper mills. Pictures of GLD and an overview of the generating process can be seen in Figure 8. The main solid compounds of GLD consists of $CaCO_3$, $Mg(OH)_2$, C and metal sulfides, especially FeS (Sanchez and Tran 2005; Jia et al 2014). The liquid phase of the GLD consists of $Na_2CO_3$ and NaOH, which generates its characteristic high pH. GLD are regarded as an inert material (Mäkelä and Höynälä 2000) and has the same grain size distribution as silt (Mäkitalo et al 2014). Other characteristics of GLD are a high pH (10-11), relatively high porosity (73 - 82 %), a bulk density of 0.44-0.67 g/m$^3$, a compact density of 2.47 to 2.60 g/cm$^3$, a low HC ($10^{-8}$ and $10^{-9}$ m/s) and a high WRC (Mäkitalo et al 2014).

FIGURE 8. Pictures of GLD from four different paper mills, from top left to bottom right; Iggesund, Smurfit Kappa, Vallsvik and BillerudKorsnäs papermill in Sweden. The bottom two pictures are also from BillerudKorsnäs paper mill.

The natural water content of the sludge/dreg is in the range 80-160 % (total solids content, TSC, 38-55 %)[1]. GLD are difficult to dry, i.e. able to store water although dried in oven at temperature 105 °C. The compact density of GLD is in the range 2.5-2.8 tons/$m^3$. In some GLD, the water contents are close to the Yield point ($w_L$), i.e. the water content at which the material texture transforms from plastic into liquid. GLDs with water content close to the plastic yield are difficult to manage.

The hydraulic conductivity of GLD is generally low and decreases with increased compaction degree (Mäkitalo et al 2015a and b). The compaction degree increases with decreased water content due to the water content of GLD overshooting the optimal water content. Thus, it is of importance to control the water content (w) and the density of GLD to assess the adequacy of the material used as an additive in till. Compression test by CRS tests (Constant Rate of Strain) is recommended to examine the hydraulic conductivity of the material

Intensive mixing of GLD results in transformation from plastic to liquid consistency, which in turn affects the construction and compaction works. This risk is examined at the initial laboratory tests. The consistency limits of the GLD should be consider when deciding which mixing equipment to use, since sieve and sorting shovel (ALLU shovel), compulsory mixer or cultivator will affect the water content and hence the manageability of the Ti/GLD.

[1] Note that there are GLD with higher and lower water content. A preceding pilot study performed in Boden used GLD with water content in the range 73-115 % (43-56 % TSC).

TABLE 1. Properties of important Ti/GLD mixtures.

| Properties | Unit | Example | Method |
|---|---|---|---|
| Hydraulic conductivity, k<br>& compression properties | m/s | $5x10^{-8}$ – $1x10^{-8}$ | CRS, PERMEAMETER |
| *Compaction properties*<br>*Optimal dry density, $\rho_d$*<br>*Optimal water content, $w_{opt}$*<br>*Compaction degree, $R_D$* | <br>tons/m³<br>weight%<br>% | <br>1.25<br>20<br>> 95 | SS EN 13286-2:2004 |
| Bulk density | tons/m³ | 1.3 -1.5 | SIS-CEN ISO/TS 17892-1:2005 |
| Consistency limits$<br>*Plastic limit, $w_P$*<br>*Yield point, $w_L$* | % | - | SIS-CEN ISO/TS 17892-12:2007 |
| Shear strength$, $\tau_{fu}$<br>Uniaxial cone penetration test | kPa | - | ISO 22476-1:2012 |
| Grain density, $\rho_s$ | tons/m³ | 2.6 -2.75 | SS EN 1097-6 |
| Porosity och void ratio, n & e | % | - | |
| Leaching properties$<br>*L/S 0,1 – 10*<br>*Analysis of metal content in water* | <br>-<br>mg/l | - | SS-EN 12457-(1-4) |
| Water content, w | % | 80 -160 | SIS-CEN ISO/TS 17892-1:2005 |

$ *Properties assessed for the characterization of the material*

The properties presented in Table 1 are important parameters in assessing the adequacy of GLD used as an additive for till. Tests with different Ti/GLD mixtures should be carried out in order to decide the mixture recipe and target water content for the mixture components. Based on these laboratory results, the water content of the GLD is used as a quality criterion for the GLD. Preferably, the supplier of the GLD (the PPI or a waste manager) describes and takes responsibility for the basic properties of the dreg.

Sequential extraction has been performed on GLD and indicates relatively low bioavailability of metals in general (Nurmesniemi et al 2005). GLD has been used in a few sanitary landfill cover applications (Pousette and Mácsik 2000; Hargelius 2008) and the possibility to use GLD as a cover material for mine waste have been investigated in several pilot-scale studies (Chtaini et al 2001; Lu et al 2013; Ragnvaldsson et al 2014). The studies showed a reduced leachate formation by 40 % (Ragnvaldsson et al 2014), a reduction in leached metals (Chtaini et al 2001; Lu et al 2013; Ragnvaldsson et al 2014) and reduced oxygen diffusion to the mine wastes (Chtaini et al 2001). The long-term stability of the GLD has been studied by Mäkitalo et al (2016). The study concluded that aging of GLD mainly depends on the amount of water passing through the material, which is slowly changing its pH and chemical composition, primarily by leaching S and K. The GLD did not show any physical or mineralogical changes in the study that would affect its ability to prevent oxygen diffusion to the underlying mine waste. The WRC was observed to be >85 % under field conditions and a high degree of saturation was maintained together with low HC, independently of its age. The shear strength of the GLD increased over time, but not enough to ensure a long-term physical stability of the material alone in slopes. The main concern was expected to be the chemical stability of the GLD due to the high content of calcite, which might dissolve and profoundly change its properties. However, Mäkitalo et al (2016) saw from estimations of the density and HC of the GLD as well as their performance in the batch leaching experiments, no evidence that this will occur within the next thousands of years.

Considering its lack of long-term physical stability, due to a low shear strength, it is not reasonable to solely use GLD in the sealing layer in slopes. It is probably not feasible either, in most cases, from an economic point of view, due to the transportation costs such a solution would imply, because of relatively long distances to the mine sites (Alakangas et al 2014). Previous field studies on mixing GLD with till have shown promising results for the mixtures to be used as a sealing layer, with low HC, high WRC and increased compaction properties (Hargelius 2008; Jia et al 2013; Mäkitalo et al 2015a).

### 4.1.2 Variability of the GLD

A challenge when working with GLD is the heterogeneity in both physical and chemical properties between different paper mills, but also with time for the same paper mill. The material variation is visible, see pictures in Figure 8. To illustrate this variability, the results from the characterization of GLD from 15 Swedish papermills, generating 1 200 to 35 000 ton per year, are presented in Table 2. The TSC of the GLD differs between 33 and 75 %, clay content between 3 and 28 %, plastic limit ($W_P$) between 46 and 170 %, the yield point ($W_L$) between 60 and 330 % and the HC between $10^{-7}$ and $4x10^{-9}$ m/s (Table 2). These properties are factors controlling the compaction properties, HC, WRC and finally also the oxygen deterring function of a sealing layer.

A great chemical variation was observed between the GLD, up to approximately three orders of magnitude (Zn; Table 3). Other elements that differ significantly between the different GLD are Cd, Co, Cu and W (Table 3). The chemistry of the material controls the mineralogy which in turn affects the HC, WRC and oxygen diffusion.

The chemical and physical variation within GLD from the same papermill is also extensive, which is demonstrated in a study by Mäkitalo et al (2014). Such variability is challenging when GLD are to be used in a sealing layer as there is no guarantee that the properties of the GLD in the planning phase of a project remain constant when the GLD are delivered to the mine site.

TABLE 2. Physical characterization of GLD from 15 different paper mills. TSC = total soilds content, PSD = particle size distribution, $\rho_s$ = particle density, $W_P$ = plastic limit, $W_L$ = yield point and HC = hydraulic conductivity. GLD1 is from Smurfit Kappa paper mill and GLD2 from BillerudKorsnäs paper mill.

| | GLD produced (tons/year) | TSC (%) | PSD <63μm (%) | PSD <2μm (%) | $\rho_s$ (g/cm³) | wP (%) | wL (%) | HC (m/s) |
|---|---|---|---|---|---|---|---|---|
| GLD 1 | 10 000 | 43±4 (n=12) | 76±29 % (n=3) | 5.4±4.1 (n=3) | 2.49 | - | - | - |
| GLD 2 | 10 000 | 58±0,3 (n=3) | 100±0 (n=3) | 9,5±1,6 (n=3) | 2.63 | 161/170 | 185/232 | 4E-09 |
| Variation in GLD from 15 papermills | 1 200-35 000 | 30-80 % | - | 3-28 | - | 46-170 | 60-330 | 1E-07 – 4E-09 |

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TABELL 1. Chemical characterization of GLD1 from Smurfit Kappa paper mill, GLD2 from BillerudKorsnäs paper mill and a variation of GLD from 15 different paper mills. The concentrations represent an average of three different samples of the same GLD in mg/kg. The standard deviation of the three samples is presented as a ± value.

| Elements mg/kg | GLD1 | GLD2 | Variation in GLD from 15 different papermills |
|---|---|---|---|
| Ag | 1±0 | 0.7±0 | - |
| Al | 7 100±1 600 | 850±10 | - |
| As | 0.4±0.1 | 0.1±0 | <0.1-0.6 |
| Au | <0.01 | <0.01 | - |
| B | 11±1 | 4±1 | - |
| Ba | 270±50 | 78±1 | 135-772 |
| Be | 0.2±0.1 | 0.04±0 | <0.5-0.6 |
| Bi | 0.08±0.01 | 0.01±0 | - |
| Br | 2±1 | <2 | - |
| Ca | 73 000±6 000 | 200 000 | - |
| Cd | 3±1 | 1±0 | 0.09-14.8 |
| Ce | 3±1 | 0.8±0 | - |
| Co | 3±0 | 0.7±0 | 0.14-26.3 |
| Cr | 34±2 | 25±0 | 11.6-212 |
| Cu | 60±3 | 22±0 | 0.6-466 |
| Cs | 0.3±0.1 | 0.05±0 | - |
| Dy | 0.2±0.1 | 0.09±0 | - |
| Er | 0.1±0.02 | 0.06±0 | - |
| Eu | 0.05±0.01 | 0.02±0 | - |
| Fe | 2 700±500 | 580±10 | - |
| Ga | 2±1 | 0.08±0.01 | - |
| Gd | 0.2±0.1 | 0.08±0 | - |
| Ge | <0.1 | <0.1 | - |
| Hf | 0.13±0.06 | 0.03±0 | - |
| Hg | <0.01 | <0.01 | <0.04 |
| Ho | 0.04±0.01 | 0.02±0 | - |
| I | <0.1 | <0.1 | - |
| Ir | <0.01 | <0.01 | - |
| K | 8 500±1 700 | 1 270±60 | - |
| La | 2±1 | 0.7±0 | - |
| Li | 2±1 | 0.7±0 | - |
| Lu | 0.02±0.01 | <0.01 | - |
| Mg | 8 800±600 | 10 300±600 | - |
| Mn | 3 700±200 | 2 300±0 | - |
| Mo | 0.8±0.1 | 0.3±0 | 0.4-2.6 |

| Elements mg/kg | GLD1 | GLD2 | Variation in GLD from 15 different papermills |
|---|---|---|---|
| Na | 20 000±600 | 18 000±0 | - |
| Nb | 0.6±0.3 | 0.1±0 | <1-1.1 |
| Nd | 1 | 0.5±0 | - |
| Ni | 18±1 | 11±0 | 2.7-165 |
| Os | <0.01 | <0.01 | - |
| P | 1 200±173 | 980±10 | - |
| Pb | 7±1 | 1±0 | 2.2-188 |
| Pd | <0.02 | <0.02 | - |
| Pr | 0.3±0.1 | 0.1±0 | - |
| Pt | <0.01 | <0.01 | - |
| Rb | 31±6 | 6±0 | - |
| Re | <0.01 | <0.01 | - |
| Rh | <0.01 | <0.01 | - |
| Ru | <0.01 | <0.01 | - |
| S | 6 630±60 | 4 970±60 | 8 540-54 800 |
| Sb | 0.4±0.1 | 0.01±0 | - |
| Sc | 0.6±0.1 | 0.1±0 | <1-1.3 |
| Se | <0.5 | <0.5 | - |
| Si | 19 000±6 000 | 1 030±60 | - |
| Sm | 0.2±0.1 | 0.09±0.01 | - |
| Sn | 0.6±0.2 | 0.06±0.01 | 0.06-0.3 |
| Sr | 117±6 | 160±0 | 165-882 |
| Ta | 0.05±0.03 | <0.01 | - |
| Tb | 0.03±0.01 | 0.01±0 | - |
| Te | <0.01 | <0.01 | - |
| Th | 0.2±0.1 | 0.1±0 | - |
| Ti | 210±80 | 33±1 | - |
| Tl | 0.2±0 | 0.2±0 | - |
| Tm | 0.01±0.01 | <0.01 | - |
| V | 4±2 | 2±0 | <2-5.0 |
| W | 0.2±0 | 0.04±0 | <1-250 |
| Y | 1.3±0.6 | 1±0 | 0.7-3.2 |
| Zn | 720±50 | 230±0 | 1.8-4 560 |
| Zr | 6±3 | 1±0 | 1.8-12 |

## 4.2 Till

Till is a glacial sedimentary soil type containing particles of various sizes from boulders to clay (Figure 9). Till used in a sealing layer construction needs to be sieved. For the sealing layer, the fraction of particle size should be less than 20 mm. The content of fines in the material, i.e. particles <0.063 mm, have to exceed 30 % in the sieved fraction to fulfil the quality criterion.

FIGURE 9. Till contains all particle sizes from fine soil to boulder, depending on the original bedrock and the glacial transport distance.

The compaction degree, the hydraulic conductivity and the water retention capacity of the till, are key factors to consider whether the till is possible to use for the sealing layer or if modification is needed, e.g. with addition of bentonite of GLD. Clayey till with sufficient hydraulic conductivity (k < $10^{-8}$ m/s) does not need modification while till with hydraulic conductivity in the range $5x10^{-7}$ – $10^{-8}$ m/s may be modified with addition of GLD to increase the density and the capacity of water storage (Nigéus et al 2018).

If the till originates from an area with potentially high background levels of trace elements e.g. metals, a chemical characterization might be needed to control the chemical properties of the till, i.e. the content of metals, sulfur and its ability to oxidize.

Sieving/sorting generates large volumes of residual material consisting of gravel, cobble and boulders of particle sizes >20 mm. It is desirable and often necessary to use this material at the site, as filling material for landscaping purposes, in drainage layers or to reinforce the landfill base.

### 4.2.1 Properties of the till (<20 mm)

Properties such as PSD, compaction properties, water content, and hydraulic conductivity (k) are primary properties of the till which need to be examined. These properties are important information regarding the possibility (and need for modification of the till) to fulfil the functional criteria of the sealing layer. Moreover, the properties are important to estimate the amount of GLD needed to modify the original till to fulfil the functional requirements regarding hydraulic conductivity and water storage capacity.

- *Hydraulic conductivity* – one commonly used criterion is that the hydraulic conductivity of the sealing layer should be less than $10^{-8}$ m/s. The effective particle size (d10-10% of the material is of smaller particle size) gives an estimation of the expected hydraulic conductivity of the material and tills with an effective particle size <0.006 mm are necessary to obtain a hydraulic conductivity <$10^{-8}$ m/s.

- *Particle size distribution* – the particle size distribution of the sieved till affects the hydraulic conductivity of the sealing layer. Below, three various till materials (silty to sandy till) are presented, Figure 10. Two particle size distribution for GLD are also presented. The hydraulic conductivity of the till at optimal water content and compaction degree of 95 % is in the range of $10^{-6}$ m/s – $5x10^{-8}$ m/s, i.e. the criterion $10^{-8}$ m/s is not obtained. Amendment with GLD increases the fines content in the mixture.

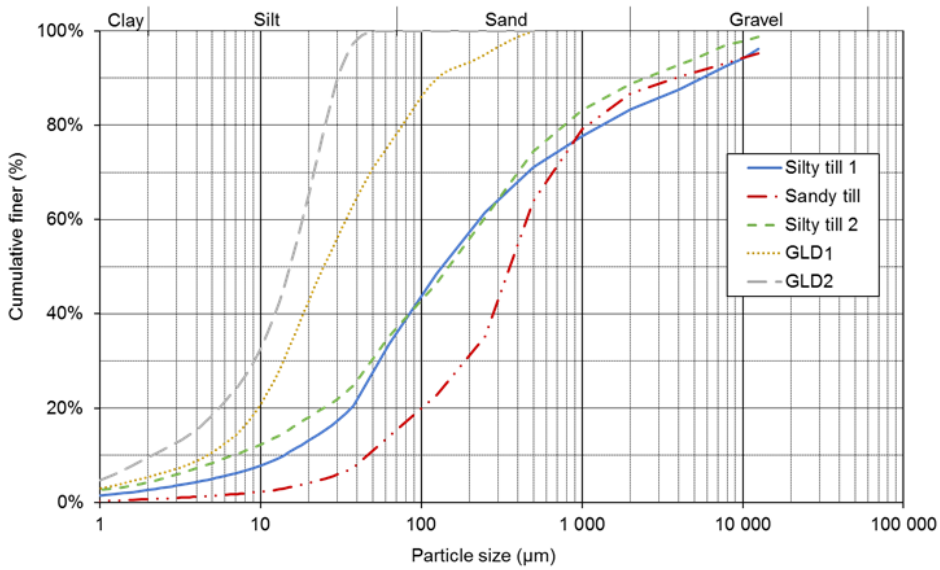



FIGURE 10. Examples of particle size distributions of various sieved tills (fraction< 20 mm) and GLD from two different paper mills (Smurfit Kappa- and BillerudKorsnäs paper mill).

- *Compacting properties* – the dry density of the Ti/GLD mixtures should be compared to the dry density of the pure till, used as reference value. The compaction degree affects the hydraulic conductivity of the till and for a material with low clay content, the compaction degree is crucial for the hydraulic conductivity criterion.
- *Summary* – The particle size distribution of the till, the grading, the compaction properties and hydraulic conductivity are important parameters used for assessing the adequacy of using the till for sealing layer (Table 4). To decide the need for adding GLD, the hydraulic conductivity of the till at compaction degree, D=90-95 % is examined. If the hydraulic conductivity is too high, the possibility to ameliorate the hydraulic conductivity of the till using GLD should be assessed. Coarse grained till with low content of fines (<20 %) is expected to be difficult to improve with an amendment.

TABLE 3. Typical values describing the till properties.

| Material | Properties | Unit | Example | Method |
|---|---|---|---|---|
| Till, Ti | Particle size distribution | - | 30 % < 0.06 mm (i 20 mm) | SS EN 933-1 |
| | Water content, w | % | 5 - 15 | SIS-CEN ISO/TS 17892-1:2005 |
| | Compaction properties<br>*Optimal dry density*<br>*Optimal water content*<br>*Compaction degree, $R_D$* | <br>ton/m³<br>weight %<br>% | <br>2.1<br>5-6<br>> 95 | SS EN 13286-2:2004 |
| | Hydraulic conductivity, k | m/s | $5x10^{-8} – 1x10^{-8}$ | SIS-CEN ISO/TS 17892-11:2005 |
| | Metal contents, Acid/Base$ | mg/kg | - | Verburg et al (2009) |
| | Bulk density$ $\rho_d$ | ton/m³ | 1.8 - 2 | SIS-CEN ISO/TS 17892-1:2005 |
| | Grain density$, $\rho_s$ | ton/m³ | 2.75 | SS EN 1097-6 |
| | Porosity och void ratio$, n & e | % | n: 0.3/0.45; e: 0.4/0.8 | SS 027117 |

$ *Properties assessed for the characterization of the material*

### 4.2.2 Variability of the till

The particle size distribution (PSD) and total solid content (TSC) vary also in till from the same site. Till was generated by erosion of the bedrock by the glaciers during the latest ice age. The PSD in a till depends on its generation process and on the kind of bedrock it originates from. In Sweden, tills below the highest coastline have been affected by the sea due to the uplift of the crust after the latest ice age. The waves have sorted out the finest material of the tills. The PSD in till from a quarry at Näsliden mine in Sweden was investigated and showed contents of fines (<0.063 mm) between 24 and 35 % (Figure 11) and TSC of 90-94 %. The wide range in these two factors have been shown to affect the final HC. Consequently, this variation makes estimation of field HC in a sealing layer where the till is to be used challenging.

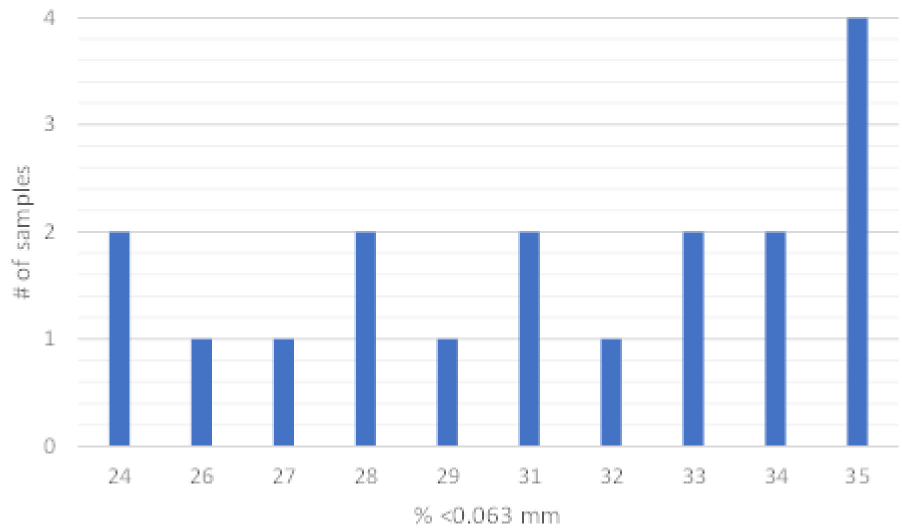



FIGURE 11. Variation in PSD (<0.063 mm) in till from the same till quarry.

# 5 Planning mine cover construction

## 5.1 Pre-study and recipes for mixtures of till and GLD

Several laboratory tests are strongly suggested to be performed in order to identify the optimal Ti/GLD mixture suitable for sealing layer purposes (Figure 12). Each till is unique and experience from previous studies has shown that GLD composition varies, especially with regard to water content. Initial tests to determine optimal GLD addition levels are therefore recommended to narrow the range of 5-7 % dry weight which is usually targeted.

For assessment of the hydraulic conductivity of the Ti/GLD mixture, the mixture is processed and compacted. The function of the GLD is to fill the void volume of the till. Depending on the grain size distribution of the till, various volumes of GLD are needed. Addition of 5-15 % of the GLD (fresh (wet) weight basis) is required to fill the void volume of till with a content of approximately 30 % fines. The exact amount of GLD required is project-specific and is usually decided during elaboration of the recipe. Addition of a higher amount of GLD than approximately 15 % (wt. %) leads to increased volume of the mixture. The content of fines and water of the till and the GLD together with the consistency limits of the GLD determines the choice of recipe as well as the interval for water content of the final mixture.

During the construction phase, the mixing ratio is expressed as % wet weight for the machine operator, to facilitate weighing of the correct amount of material. However, to compare the mixing ratios between different projects, it is desirable to use recipes which also present the % dry weight, to ensure that the same amount of GLD is added to the till. Hence, it is important that the water content of the materials is documented for each recipe used.

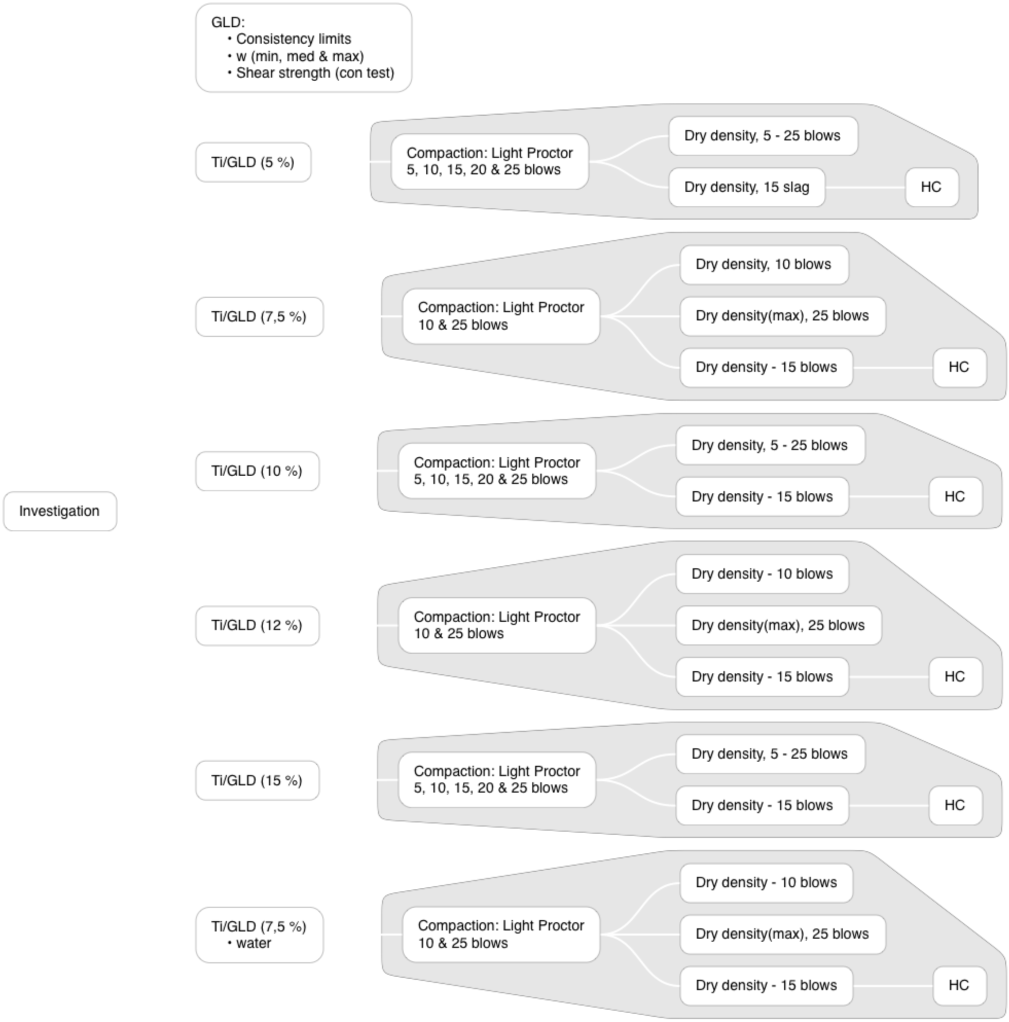



FIGURE 12. Example of scheme for elaboration of recipe of Ti/GLD mixture which meets the permeability requirements.

The targeted Ti/GLD mixture has low hydraulic conductivity at a defined compaction degree. The homogeneity of the mixture with regard to water content respectively compaction degree are used as criteria for quality control of mixture and the constructed sealing layer onsite (Table 5).

TABLE 4. Properties of the studied Ti/GLD mixtures.

| Material | Primary properties | Unit | Example | Method |
|---|---|---|---|---|
| Ti/GLD | Water content, w | % | 10 - 20 | SIS-CEN ISO/TS 17892-1:2005 |
| | Hydraulic conductivity, k | m/s | < $10^{-8}$ | CRS, PERMEAMETER |
| | Compaction properties | | | SS EN 13286-2:2004 |
| | *Dry density, $\rho_d$* | tons/m$^3$ | 1.80 | |
| | *Natural water content $w_{nat}$* | weight% | 11 -16 | |
| | *Compaction degree, $R_D$* | % | > 90 | |
| | Frost test – segregation potential$ | mm$^2$/Kh | - | TPPT-R07, Onninen (1999) |

$ *Properties assessed for the characterization of the material*

## 5.2 Planning and procurement

### 5.2.1 Pre-study and planning phase

The preparation phase is the first stage of the construction project, aimed at providing an overall description of the project regarding size, location, goals, alternative solutions, time- and cost frame and economy. Moreover, the preparation phase includes compiling actual information and available knowledge. The planning process should not become overly extensive and detailed since its primary purpose is to investigate possibilities and prerequisites for the project to take place.

A range of construction and ground works require permits in accordance with the Planning and Building Act. Crucial aspects are e.g. the location of the real estate and type and extent of the construction.

### 5.2.2 Contract forms

If the remediation is performed as a general construction contract (contract works), the following documentation should be established before procurement of the services. The mining company establishes a framework description of included part in the construction and the functional requirements for each part. These parts are:

- design and compaction of the levelling layer
- quality control of slope inclinations and the stability of the pile surface
- quality control of the materials

- specification of the requirements of the sealing layer, e.g. hydraulic conductivity below $10^{-8}$ m/s
- mixture of the sealing layer material
- distribution and compaction of the layers
- quality control of the mixtures and the compacted layers

The tender documents shall include the following documentation:

- Administrative requirements describing the project specific and procurement administrative conditions
- A technical description in accordance with General material and work description (AMA in Sweden) in which the requirements for compaction and the minimal requirements regarding the contractor's quality assurance are described
- A bill of quantities describing the material types and requirements and the quantities needed
- Occupational health and safety plan including security routines/requirements for the site
- Drawings describing present conditions, plan and sectional drawings (possibly details) showing the design of the final cover
- Other project specific documentation of interest, e.g. geotechnical surveys, material piles, existing wires and pipes etc.

Before the work begins, the construction documents are prepared to describe the construction of the final cover. In addition to the documentation established for the tender documents, machine control files for areas to be filled or excavated are prepared.

The contractor's self-inspection procedure should comprise the following documentation:

- Levelling layer – random sampling of the relative stability of the surface controlled by probing (per $m^2$ of the levelling layer)
- Sealing layer – random sampling of grain size distribution, water content, compaction degree (per $m^3$ of disposed material). Measurement of cover thickness. Automatic surface control of compaction degree performed with compaction roller.
- Drainage layer if necessary – random sampling of grain size distribution. Measurement of thickness of made ground.
- Protection layer - random sampling of grain size distribution. Measurement of cover thickness.
- Erosion protection – ocular inspection of the vegetation layer.

A technical description containing all design requirements is established. The construction documents present the planned construction including related construction drawings. The construction process is divided into three phases, a) investigation, b) product definition, and c) product presentation. Normally, these phases overlap.

a) The investigation phase comprises collection and processing of the information needed for the design. The investigation phase is summarized in a project investigation report forming a base for possible continued work
b) In the product determination phase the conditions and requirements are formulated in the program document, the Project Planning document, the Construction permit document, the Construction document and the Production document. The construction document and the production documents form the base for the product presentation.
c) In the product presentation phase, the operation and maintenance instructions are elaborated in order to continuously fulfil the requirements established in the program.

### 5.5.3 Material purchasing

Material purchasing is essential for the success of the remediation. From GLD generation to a completed sealing layer, the value chain is long and there are many key steps that have to be addressed properly:

- Generation of GLD and rejection of inadequate material
- Storage at the PPI or at external site
- Transportation
- Storage at the mine site prior to use

At each of the steps, there is a potential risk for the GLD to be adversely damaged. Quality control and measures to preserve the GLD are therefore necessary. Depending on the economic model adopted, this could be the responsibility of the PPI, the mining industry or an intermediary (a waste manager) contracted to perform this task. Depending on the economic model adopted, the role of the waste manager can include i) management of the GLD at the PPI, ii) transport, iii) storage, and iv) construction of the sealing layer. It is unlikely that the PPI and the mining industry would manage the remediation without involving a waste manager.

Quality control at the PPI to select material but also at the storage to ensure that the GLD has not been altered is necessary. As large amounts of GLD are necessary compared to the PPI ability to generate, long-term planning is necessary to ensure that needed amounts are available at the right time. The time table is also necessary to ensure that enough material is collected and to plan for storage and transport.

# 6 Construction and logistics

A pilot trial was performed prior to the full-scale cover demo at an old mine in Näsliden, Sweden (Figure 13) where 10 % GLD mixed with till were used to cover a ca 400 m² area.

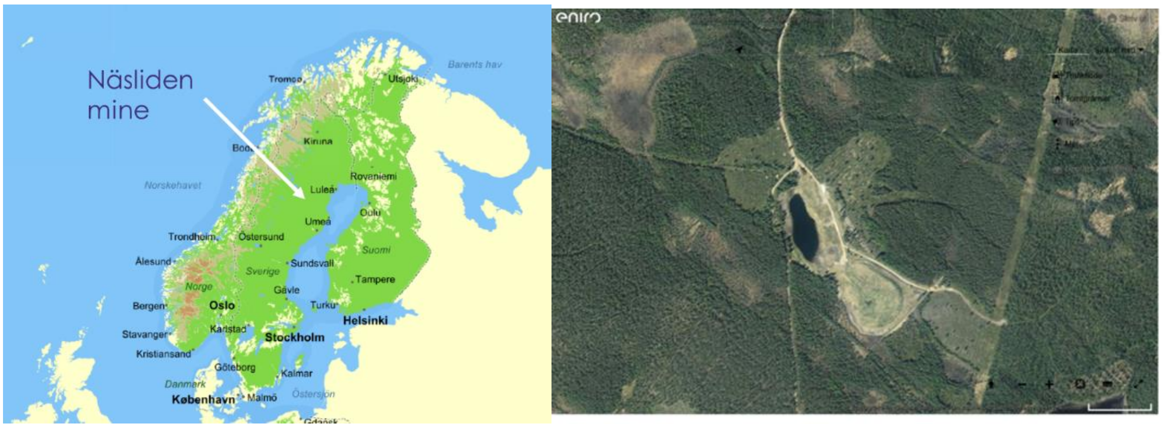



FIGURE 13. GLD based sealing layer pilot location, at Näsliden mine, Sweden.

The pilot and the demo were used to provide information regarding logistics, dimensioning, construction and quality control. Experience from the different steps of the projects is compiled in the following chapters.

## 6.1 Activity plan

The activity plan describes how the remediation process is carried out step by step. Each step is documented in a work preparation document. This preparation documentation is performed in seven steps, Q0-Q6 (Figure 14). Control of the compaction of the levelling layer, denoted Q0. Building the final cover is divided into the following activities:

- Control of the incoming materials, till, **Q1:1** and GLD, **Q2:1**
- Storage – till, **Q1:2** and GLD, **Q2:2**
- Dosage (Ti/GLD proportions based on the dry weight proportions of till/GLD, and the recipe is based on laboratory tests) **Q3**
- Mixture (Ti/GLD are mixed into a homogenous mixture) **Q4**
- Levelling/terracing **Q0**
- Distribution/compaction of the mixture as a sealing layer (control of layer thickness and dry density) **Q5**
- Distribution of protective layer and vegetation layer (control of layer thickness) **Q6**

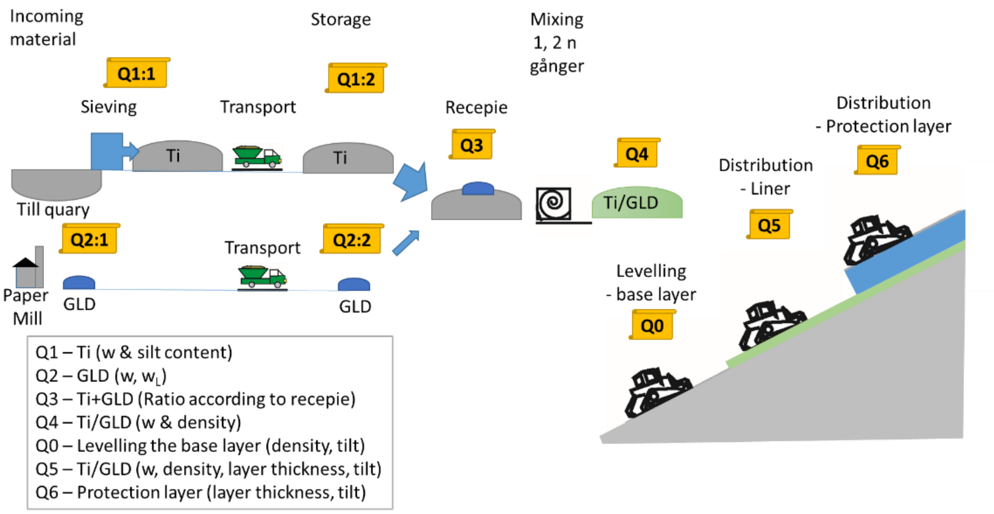



FIGURE 14. Conceptual model of the activities within the remediation process using Ti/GLD as sealing layer, where Q1-Q6 are quality control steps.

## 6.2 Routines for characterization and approval of incoming material, Q1:1 and Q2:1

### 6.2.1 Till – Q1:1

Grain size distribution and water content are investigated and documented. The control should be done before and after storage of the excavated till. The recipe is site specific, based on the results from the laboratory tests, and the till quality is assessed to fulfill the permeability criteria after addition of GLD. The site-specific recipe should be developed at an early stage based on the material available at the site and GLD that are available. The recipe should result in a span for GLD addition and instructions regarding optimum water content and density, as well as a tolerable span.

As component of a recipe, a till with a certain particle size distribution and water content is used. Under field conditions Ti/GLD ratio is prepared for mixing based on its wet weight. This ratio is based on the Ti/GLD- dry weight ratio. The chosen recipe must be adjusted when water contents of the till or the GLD varies in a batch. Thus, change of water content of the till and GLD must be controlled and followed-up. Variations in water content is compensated, e.g. if the till in field is wetter than the till in the laboratory test, the DS content is lower which results in a higher DS content of GLD (given that the water ratio of the GLD is constant). This may be compensated by reducing the added GLD to obtain the same TSC mixing ratio as in the recipe elaboration.

### 6.2.2 GLD- Q2:1

Green liquor dreg is controlled at the discharge by the pulp mills (factory/storage). Water content is one control parameter. In the event of disturbance in the pulp process, the generated GLD should be discarded. This is due to possible differences in the content and thereby the properties of the GLD, e.g. extreme variations of water content, presence of lime. The range of water content acceptable for the use of GLD is decided during the recipe process and is presented as criteria values.

## 6.3 Quality control/documentation, Q1:1/Q2:1

The particle size distribution, consistency limits and water content of the sieved till are controlled, tentatively one sample per 500 tons of till. The GLD is inspected visually before loaded on lorry. The PPI controls on a regular basis the water ratio of the GLD, taking one sample per 100 tons of GLD.

Documentation of the material should be requested by the receiver and the documentation is archived.

## 6.4 Transport

### 6.4.1 Till

The till is extracted onsite or transported from the nearest quarry. The material must consist of pure till without organic matter from the vegetation layer.

### 6.4.2 GLD

GLD is produced evenly all year around. While the amount of GLD needed per hectare is within the range of 500-1000 tons, the annual production of a normal-size mills is 2 000-20 000 tons, i.e. approximately 6-60 tons per day. Thus, the transport of GLD needs to be organized to provide enough material when the remediation starts.

Transport of GLD must be done without contamination of the material. Each load must consist of pure GLD without other materials to e.g. simplify the emptying of the truck. The consistency of GLD at water content > $w_p$ is plastic and the material might be difficult to unload due to the sticky consistency. At water ratios < $w_p$, the consistency of GLD is semi solid, which makes them generally more manageable. When sand or other materials are used on the flatbed to facilitate unloading, the properties of the Ti/GLD material will be altered, and thereby no additional material should be used.

## 6.5 Storage

To obtain an even production of Ti/GLD paste, large amounts of till and GLD must be stored onsite. It is important that storing does not affect material parameters. Below, different aspects are listed to consider when storing till and GLD.

The water content of the materials is a key factor influencing mixing conditions and thus, the permeability and geotechnical properties of the final product. Hence, correct water content of the materials in the production process is of importance, i.e. materials with water content within the range of the materials examined during the laboratory tests should be used. The recipes are based on dry weight but are expressed as wet weight ratio. This means that lower DS content of the till need to be compensated by increased amount of GLD as the proportion of dry GLD increases compared to the proportion of dry till. Regarding strength and compaction, it is of importance that the proportion of GLD, based on dry weight, is equivalent to the level as decided in the laboratory tests at the creation of the recipe. The variation in water content of the materials is thus a core parameter affecting the mixing proportions and the water content of the mixture. In turn, change in water content (w) may affect the quality of the mixture and thus the permeability and stability (slope stability) of the material

Storage of till and GLD must be carried out in such way that water content during storage is affected, i.e. minimizing water addition or drying of the materials. Before mixing, the water content of both materials is controlled. Water content is used as a control parameter in order to decide whether the Ti/GLD mixtures permeability is within the acceptable range for production of the sealing. These criteria are developed in the laboratory during elaboration of the recipe.

### 6.5.1 Till

The sieved till is classified as silty clay/clayey silt. The material is relatively permeable and is affected by precipitation and drought. Covered by tarpaulin, if possible, the till would be protected from both drying and precipitation. Precipitation may increase the till's water content and can affect the quality of the Ti/GLD mixture, which in turn might impair the hydraulic conductivity and decrease the slope stability. Till should be stored on a well-drained surface. Dry till is dust prone, which might cause working environment problems.

### 6.5.2 GLD

The surface which is affected by drought and precipitation should be minimized during storage of GLD. Figure 15 (a. Boden and b. Näsliden) shows examples of storage of GLD.

GLD must be stored on well-drained area and covered by tarpaulin. The ground surface is important, otherwise, GLD tends to mix with the underlying material which might result in a change of the mixtures properties. Occurrence of cobbles in the GLD might reduce production capacity, independently of the mixing technique used. Both forced mixer and shovel mixer are sensitive to fractions of cobble which might cause stoppages.


FIGURE 15. A) More than 2000 tons of GLD was stored from May 2013 to April 2014 (seen in the background). In the forefront Ti/GLD is being produced by forced mixer. B) Storage of GLD, covered by tarpaulin, during July-August of 2016, Näsliden. In the foreground, pre-mixing of Ti/GLD material is performed.

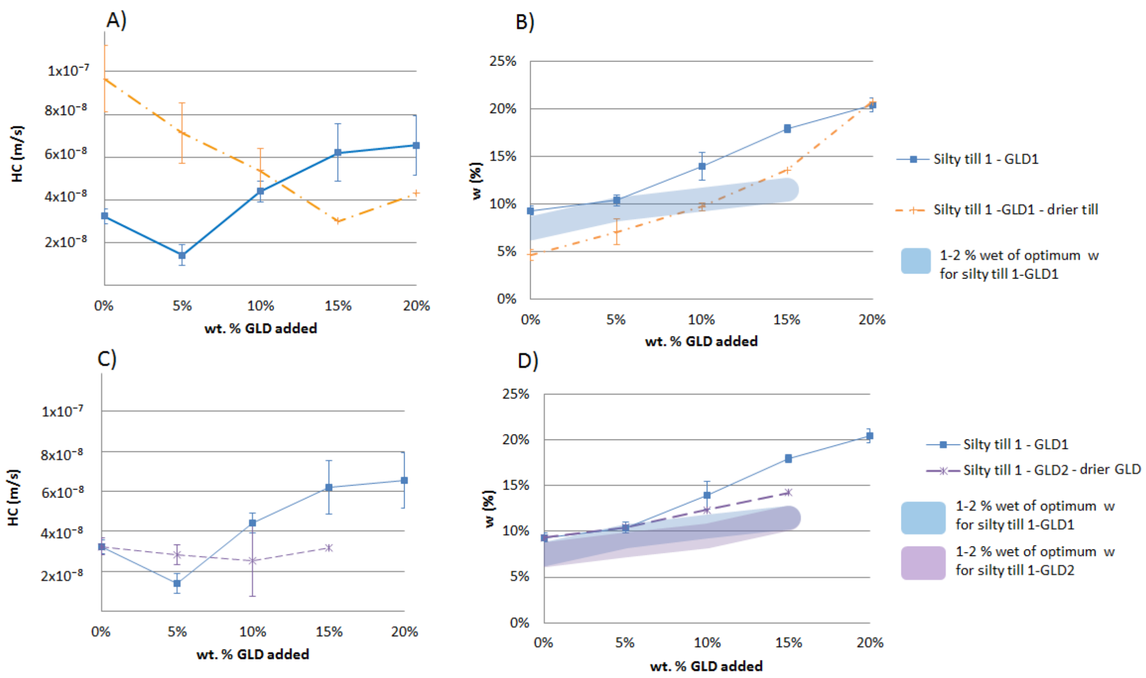
## 6.6 Production of Ti/GLD mixture

Production of Ti/GLD is performed using the mixing ratio defined in laboratory. The quality of the mixture depends on its water content and ratio of the components. For a mixture with 10 % (wet weight) GLD, the normal water content ranges are 5-15 % and 73-116 %, for till and GLD, respectively. Studies performed previously showed that a hydraulic conductivity of at least $10^{-8}$ m/s could be obtained with addition of 10-20 % GLD, based on wet weight and 5-11 % based on dry weight. Other quality requirements of the produced sealing layer, as well as other types of till and GLD might result in other mixing ratios. It is important to remember that all values are material specific, i.e. might change from case to case.

Quality control of the till is performed regarding water content and grain size distribution. GLD is quality-controlled regarding water content, consistency limits and grain size distribution. Water content is an important factor regulating compaction properties, hydraulic conductivity and compression properties of the mixture.

Optimal intervals of water content for till and GLD should be tested at the initial laboratory tests. It is important to use the value for the predicted water content during the full-scale project. Tolerance values for different water contents of the mixture (till and GLD, respectively) are tested regarding hydraulic conductivity of the compacted sealing layer, for a given Ti/GLD recipe.

Laboratory tests on different Ti/GLD show that the initial water content of the materials used in a Ti/GLD mixture as well as the final water content of the mixtures are controlling the hydraulic conductivity of the mixtures (Nigéus et al 2018). In a study conducted by Nigéus et al (2018) on Ti/GLD mixtures shows that the lowest HC in the mixtures was reached at 1-2 % wet of the optimum molding water content, which agrees with a study on clay conducted by Benson and Trast (1995). When using a drier till or GLD, more GLD could/should be added to the mixture to reach optimum HC, as the optimum water content is reached at a higher wt. % of GLD addition (Nigéus et al 2018; Figure 16).



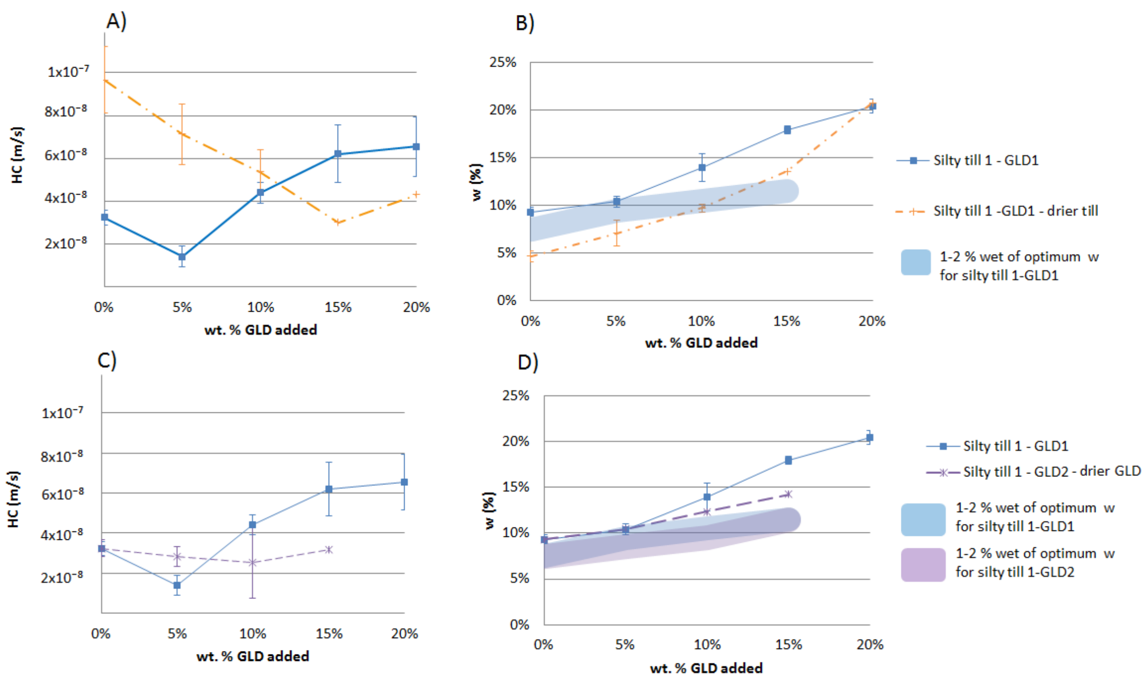




FIGURE 16. Hydraulic conductivity (HC) and molding water content (w) in different Ti/GLD mixtures.

Examples of mixing equipment are presented below. Each type of equipment is more or less fitted for different raw materials. Important factors when selecting equipment are the ability to produce a homogeneous mixture and to have sufficient mixing capacity. Pre-mixing using wheel loader is needed in order to obtain a homogeneous mixture quality using front shovel- and bucket mixer (Figure 17).


FIGURE 17. Pre-mixing by shovel. Pre-mixing is required before front shovel- and bucket mixing is performed. A) Pre-mixing Boden 2014, and B) pre-mixing and shovel mixing in Näsliden 2016.

### 6.6.1 Bucket mixer, ALLU type (Boden)

Till and GLD are weighted in a front shovel before mixing. The mixing is carried out with a bucket mixer (Figure 18). Bucket mixers have an average capacity of approximately 100-120 tons/h. A two-step mixing is estimated to be sufficient in order to obtain a homogenous mixture which corresponds to 40-120 tons/h. The mixing capacity depends on the ratio between GLD and till, but also on the water content of the materials. Weather might also affect the production rate. The pre-mixing is appropriate for batches of 70-100 tons. Mixing larger batches is complicated and may result in an additional mixing step with the bucket mixer. The final mixture should look homogeneous and manage to hold its shape during a squeeze test[2]. Alternatively, the mixture could be

[2] Squeeze test – Ti/GLD is squeezed like a snowball and holds its shape without crumbling

tested using MCV[3] (moisture condition value). The density/dry density of the mixture should not vary outside the range of tolerance limits elaborated for the application. A material specific MCV-template is needed for control of the homogeneity of the mixture.

**Pros:** Bucket mixers attached on front wheel loader or excavator provide good mixing quality and the method is reliable. When not needed for mixing, the wheel loader or excavator can be used for other works. The method works well for Ti/GLD with plastic consistencies.

**Cons:** Relatively low production rate. Pre-mixing of till and GLD is needed. The shovel is sensitive for small cobbles.

FIGURE 18. Bucket mixing by ALLU shovel (close up on the shovel).

### 6.6.2 Bucket mixer, ALLU type DH 4-23/X75 (Näsliden)

The mixing was performed with a sorting shovel (Figure 19). The average capacity of the sorting shovel DH 4-23/X75 is above 260 m$^3$/h. This corresponds to approximately 160 tons/h. The production capacity of ready to use Ti/GLD depends on the number of runs the Ti/GLD needs to be mixed. In Näsliden , a two-step mixing was used in order to obtain a sufficiently homogenous sealing layer material. The pre-mixing worked well for batches of 40 tons confirming the results of the field test at Boden.

**Pros:** The bucket mixer (DH 4-17-X75) provide good quality after two mixing rounds and the method is reliable. The mixing procedure can take place when enough material has been gathered and when not, the excavator is available for other works. The method

[3] The MCV method is used for elaborating a proportion of water ratio and compaction ability. Thus, the method generates a value of a soil type's sensitivity for changes in water ratio regarding compaction properties

works well for GLD of plastic consistencies. The production rate is high, above 100 tons/h. The second mixing is possible to perform directly on the dumper, Figure 19.

**Cons:** Pre-mixing of till and GLD is needed.

FIGURE 19. ALLU shovel. Round 2 of mixing by DH 4-17-X75. In the forefront, a batch of Ti/GLD after one round of mixing with bucket mixer is shown. Photo: Näsliden, Josef Mácsik.

### 6.6.3 Forced mixer (Boden)

The mixing capacity by forced mixer is 60-120 tons/h (Figure 20). Primarily, the equipment is used on campaign basis. Front wheel loader with shovel is needed for pre-mixing the till and GLD and for loading the pre-mixed Ti/GLD material into the forced mixer. The advantage of using a forced mixer is that the homogeneity of the mixture corresponds to 4-5 rounds of mixing using ALLU shovel. The mixing time is adjustable, and the maximal possible capacity is estimated to reach 120-150 tons/h. However, stoppages due to blockages by cobbles might decrease drastically the mixing capacity. Also, the forced mixer affects the consistency of the Ti/GLD mixture as water is pressed out of the GLD during mixing. Hopper feeder for GLD and till may be an alternative to pre-mixing.

**Pros:** Forced mixer provides good and even quality of the mixture. The method enables a more even production, than using a bucket mixer.

**Cons:** The reliability is risked if cobbles are present in the Ti/GLD mixture which could decrease the production rate drastically. Pre-mixing of till and GLD is needed. GLD with water content above its plasticity limit ($w > w_P$) might result in changing the mixtures behavior from plastic to liquid state.

FIGURE 20. Loading a forced mixer with pre-mixed Ti/GLD.

### 6.6.4 Rotary mixer (not tested within current project)

Rotary mixer is an alternative to mix materials. The mixing is performed after distribution of the material on the actual surface. The mixing depth of a rotary mixer is at most 0.3-0.5 m. A layer of till is distributed over the levelling layer, followed by a layer of green liquor dregs (Figure 21:A and 21:B). The thicknesses of the layers are decided based upon the recipe elaborated during the initial laboratory tests. Subsequently, the Ti/GLD material are mixed (Figure 21:C), followed by compaction of the material, Figure 21:D. The thickness of the compacted layer is estimated to be 2/3 of the original. The estimated capacity of the method is approximately 5 000 $m^2$ per day, based on one layer of Ti/GLD. The average capacity is estimated over 300 $m^2$/h for building two layers of Ti/GLD. The capacity expressed in ton/h is approximately 300 tons/h.

**Pros:** Substantial production capacity. Pre-mixing is not needed. Control of the mixing and compaction quality is possible to be performed at once. The rotary mixer grinds the till, which results in increased fine ratio (with lower permeability).

**Cons:** The technique was not tested within the project. The method is expected to be sensitive to precipitation. The compacted Ti/GLD layer must be covered immediately after compaction to avoid erosion and drying.


FIGURE 21. Examples of techniques of distribution, mixing and compaction from a road application, stabilizing of gravel road, Iggesund, where a) sieved till was distributed, followed by b) distributing green liquor dregs4, followed by c) mixing with a rotary mixer (milling depth 0,1 m) and finally d) the road after compaction.

Other general recommendations:

- Pre-tests are recommended in order to assess the method for distributing Ti/GLD and mixing under local conditions.
- The mixing time should be optimized in order to obtain a homogeneous mixture without separating water from the GLD, since this might lead to liquefaction of the GLD.
- Mixing and distribution should be performed during periods of relatively dry weather. Tolerance values for the water content for both till and GLD needs to be established as well as the dry density of the Ti/GLD mixture in order to ensure the function requirement.

## 6.7 Distribution and application of the material

The thickness of the distributed Ti/GLD must be at least 60 cm. The Ti/GLD layer is smoothed by a bulldozer (Figure 22). Subsequently, the layer is compacted by a compaction roller (Figure 22), at least three overpasses by vibrating compaction roller and three overpasses without vibrating roller. The thickness of the layer should be at least

[4] Mixing of green liquor dregs and fly ash used in a dirt road construction

50 cm after compaction. The method is suited for surfaces with an inclination less than 1:3, however it needs to be tested due to varying conditions from case to case.

In accordance with the control program, the surface is controlled regarding levels, compaction and water ratio. Slope inclinations might need adjustment to enable distribution of the sealing layer material. The number of overpasses by roller might need to be adjusted after control of the dry density and the bearing capacity is assessed to enable the working machines to distribute the protection layer. To serve as counteracting support during compaction, a support bank of Ti/GLD might be constructed around the area which is to be covered.

To reduce the risk for drought, erosion and loosening, the sealing layer must immediately be covered by a protective layer of at least 0.5 m thickness (Figure 22 and 23). The remaining part of the protective layer could be placed later. The weather conditions should be considered to limit crack formation and erosion. In the event of precipitation, placed but not compacted Ti/GLD paste can absorb water, which might result in a clayey consistency, which in turn might prevent subsequent compaction of the material.

FIGURE 22. Compaction of the sealing layer in one step (final thickness 0.5 m) and distribution of protective layer by bulldozer. Distribution of the sealing layer material was performed similarly by bulldozer (Näsliden year 2016).

FIGURE 23. Distribution of protective layer formed by 0 - 150 mm till (Boden year 2014).

## 6.8 Compaction

The Ti/GLD mixture is compressed by approximately 30 % by compaction. Compaction results in an increased dry density from approximately 1.5-1.6 tons/$m^3$ up to approximately 1.7-2 tons/$m^3$. Thus, it is important that the entire surface is compacted with the same number of overpasses. Otherwise, there is risk for variation in dry density and thus oxygen leakage through the cover.

The density of the compacted sealing layer is controlled by e.g. water volumeter (surface), isotope measurement (e.g. Troxler) or electrical impedance spectroscopy (e.g. SDG).

The density of the Ti/GLD-layer is governed by the load from compaction (roller) and vehicles (bulldozers). The protective layer might to some extent contribute to subsequent consolidation of less compacted Ti/GLD layer.

Experiences from tests in Näsliden show that a layer of 0.7 m thickness can be compacted and that it is possible to obtain a density > 1.8 ton/$m^3$ after 6 overpasses by vibrating roller (Figure 21). In this actual case, the density of the profile was controlled from the surface down to 0.5 m. The results show that the density criterion was obtained for the entire profile. The number of overpasses is decided during the preparation tests carried out initially for each project resulting in a compaction strategy.

## 6.9 Control and follow up

Quality control of GLD, till and the final mixture is necessary. The dry density of the distributed material is controlled. On site, the obtained density is controlled by e.g. Troxler. Hydraulic conductivity is evaluated from laboratory tests with corresponding dry density from laboratory tests. The thickness of the compacted sealing layer and the density are documented, e.g. by machine control files.

The experience and interest of the contractor are important factors to a successful project. Thus, it is of importance that people working with storage, production and construction are instructed and that self-checks are performed. During the training of the staff, it is important to explain the function of the final cover and the requirements of the included material. One part of the quality control is a detailed documentation of the performed work, e.g. by diary and photography. The documentation includes e.g. number of layers, performed distribution and compaction, and weather conditions. Field protocols are saved.

The documentation of till and GLD should be saved together with other documentation about storage, mixing, distribution, compaction and follow up.

The self-check includes control of the water content and grain size distribution of the till, the water content and consistency limits of GLD, and the water ratio and dry density of the final mixture after compaction. The requirements regarding density and water content should be followed up and documented.

Homogeneity is assessed using variations in the water content (w) and dry density ($\rho_d$) of the Ti/GLD. Large variations of w and $\rho_d$ indicate that the mixing is not homogeneous. These values should be compared to reference intervals, indicating if the sealing layer fulfils the permeability criteria. The Ti/GLD mixture must be free from visible lumps of GLD. By using bucket mixer, an homogeneous mixture can be obtained after the first round of mixing, provided that the materials are pre-mixed by shovel. A comparable homogeneity is obtained by forced mixer after pre-mixing of till and GLD.

Information about the water content of the GLD is compiled at the PPI providing the material. If the material is stored, it is important to control the water content before the Ti/GLD is mixed. Typical control level is 1 sample per 100 $m^3$ till respectively GLD. Control of the water content and bulk density of mixed Ti/GLD is performed based on the dry density of compacted sealing layer. Adequate control intensity is 1 sample per 900 $m^2$ placed material. More frequent control may be necessary during full scale field test and in the event of production failures.

# 7 Quality control and monitoring

Both components of sealing layer vary and need therefore to be controlled on a regular basis to ensure the quality of the sealing layer material. The quality control procedure comprises the following steps:

- A control of the GLD generated and provided is needed to make sure it has the right composition (mainly water content) to be used at the site.
- Assure that the material is stored in an appropriate way so as not to alter its quality (rain, snow and frost are example of risks). Proper control procedures must be implemented if it changes in the material quality occur over time during storage.
- Make sure that the till has the right quality (sieved and not to wet either), at the site and during production. Control that the right proportions are used, and the mixing is done properly.
- Control of the sealing layer compaction.
- Control of the protective layer thickness.
- Monitoring of how the sealing evolves with time. Alteration due to winter and desiccation are possible.

The pilot cover system is going to be monitored by instruments installed in the body of the construction. Example of the monitoring program installed in Boden is presented in Figure 24. The performance of the sealing layer and their ingredients include the control of soil parameters by both in-situ tests and laboratory analysis. For in-situ tests, a set of lysimeters and probes (Figure 25 and 26), was installed on top of- and below the sealing layer. The results are compared with a sealing layer constructed with a traditional bentonite amendment.

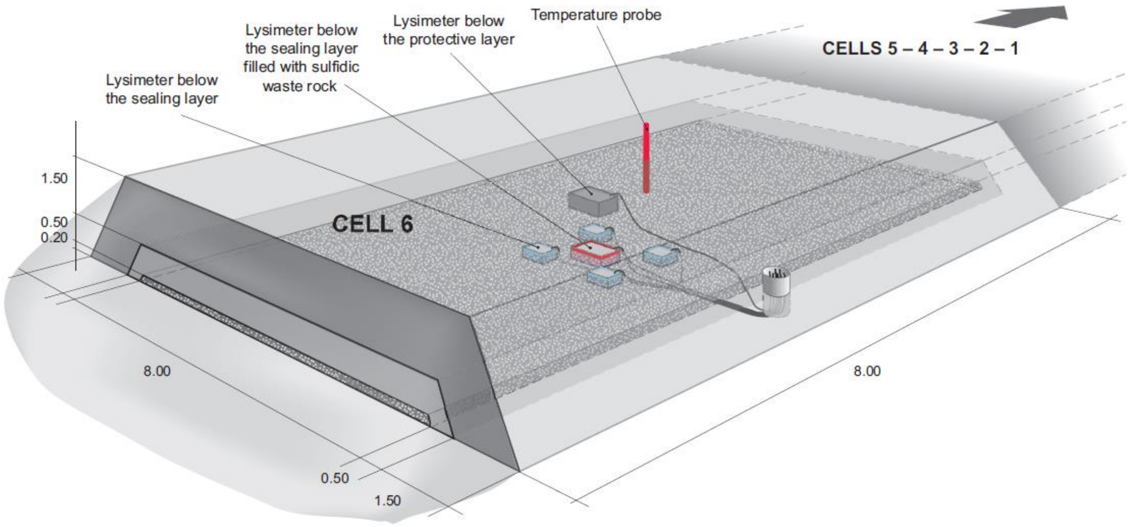



FIGURE 24. Sealing layer pilot technical performance monitoring.

FIGURE 25. Sealing layer monitoring. Lysimeters installation.

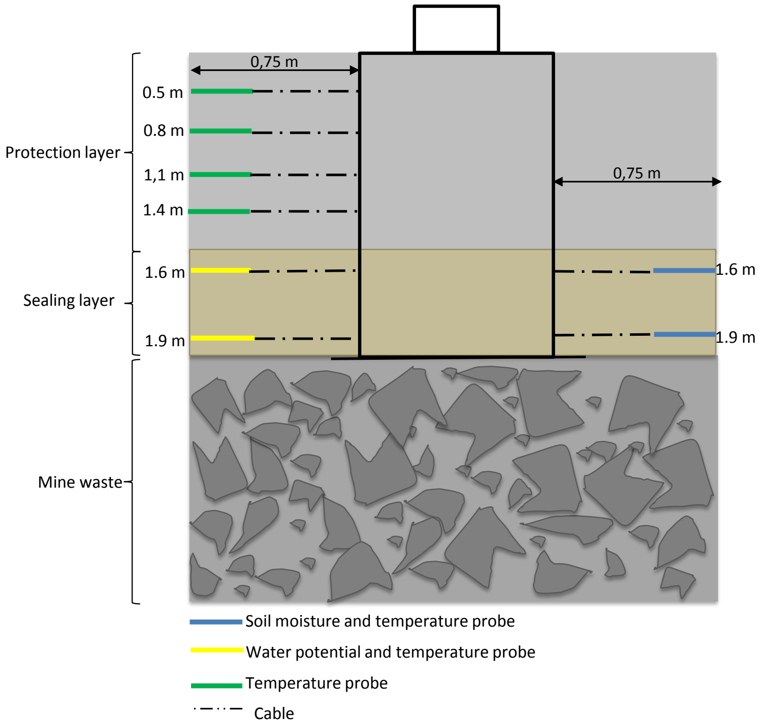



FIGURE 26. Soil cover monitoring at Näsliden mine, northern Sweden.

In relation to environmental performance, monitoring wells are used for water sampling, in-situ testing and laboratory analysis. The results obtained are compared with local applicable water quality standards and will be used to produce in a risk assessment to certify the absence of unacceptable risks for the application scenario.

# 8 Conclusive remarks

When closing mine waste facilities containing sulfide minerals one of the most common methods is to apply a cover system with different layers, such as a sealing layer and a protective layer of till. The primary function of the sealing layer is to minimize oxygen transport to the underlying mine waste. This is achieved if the water content in the sealing layer can be kept close to saturation, which sets high requirements on the materials to be used in the sealing layer as well as on the execution of its construction. The results from previous research projects and two pilot tests conducted in Boden 2014 have shown that GLD can be used to reduce the hydraulic conductivity and increase the water retention capacity of tills that is to be used in the construction of a sealing layer.

The pilot tests were used to study the feasibility of the proposed solution at industrial scale, i.e. mixing of the materials and construction of the cover. The results were used to assess the efficiency of the equipment and to evaluate the costs associated with the cover production and construction. The construction of a 0.5 meter thick sealing layer of GLD-amended till is economically viable compared to bentonite amendment when till with adequate properties for a sealing layer is not available at the site. However, laboratory and pilot tests do not provide sufficient information for full-scale production of sealing layer. A full-scale field study is therefore planned and the demonstration will propose an efficient method to produce and build GLD-based sealing layers.

Based on previous results, a guidance for characterization and definition of mixing recipes has been developed along with a method for mixing and compacting the sealing layers in field. This guidance was tested in field, at the closure of the Näsliden waste rock dump in Northern Sweden performed in 2017 by Boliden. Given its innovative character, no information was available on the robustness of the sealing layer at full scale, therefore, a large safety factor was used for the construction work regarding the mixing procedure, the compaction and the thickness, in order to be safe from environmental risks. As a consequence, the solution was oversized and has to be optimized before reaching the market.

A conclusion from the first demonstration is that a circular model based on GLD requires the involvement of the whole value chain, from the PPI, waste manager, contractor to the mining industry to ensure that appropriate GLD are gathered, stored, and sent to the decommissioned mine site and that the material quality is not deteriorated during transport or storage. The main objective of the coming field demonstration is to optimize the use of GLD in sealing layers. The demonstration site will be equipped to allow for a quantitative follow-up of the sealing layer made from GLD-amended till over time. This will involve monitoring of the oxygen transport through the sealing layer and the effect of the sealing layer on the underlying waste rock, which was not possible in the previous pilot tests. The monitoring will result in a definition of updated specifications for the guidance, including the optimisation of the layer thickness and the GLD amendment.

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