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KYT SURFACE

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RESEARCH REPORT

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KYT SURFACE
Performance of a Landfill-Type Near Surface Repository

Interim report 2020

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Summary

Near surface repositories are being considered in Finland for deposition of short-lived, very low-level waste (VLLW) from nuclear power plant operations and decommissioning. The first near surface repository planned to be built in Finland will be based on a landfill-type design similar to that applied in Sweden where the bedrock and climate conditions are quite comparable to those in Finland (TVO 2020). This report discusses the preliminary safety functions for the landfill-type VLLW repository and the differences with normal and hazardous waste landfills. In a repository for radioactive waste, the long-term safety relies upon containment and isolation gained passively through a multibarrier system, and control of the radiological inventory and waste forms together with support for the passive safety approach using active safety measures like institutional control, without placing undue reliance on these active approaches (IAEA 2011, 2014). However, in a landfill for normal or hazardous waste, active monitoring and maintenance is also required after closure (SYKE 2008), for example in order to maintain sufficient performance of the drainage or gas collection system. This raises the question of the need for monitoring and maintenance during the active institutional control period (as defined in IAEA 2017) of a VLLW near surface repository. One alternative is to aim for enhanced barrier performance for ensuring passive safety of the system which may mitigate overall monitoring needs.

The landfill design consists of three main units: 1) a cover layer, 2) waste fill and waste packages (waste forms and containers), and 3) a foundation layer, all featuring multilayer structures and different safety functions. The natural barrier below the repository has its own role in ensuring the safety of the multibarrier system and similar to normal and hazardous waste landfills, the design should always be tailored considering the local natural barrier conditions of the site (SYKE 2008).

According to numerical modelling of a typical landfill design, the drainage function provided by drainage systems in a landfill play a significant role in controlling the volume of water entering and leaving the space filled by the waste. Especially important for water control in a landfill is the performance of the geomembrane retaining the waters within a drainage layer. However, considering a repository lifetime of several hundreds of years, the performance of the drainage layer is expected to decrease due to internal clogging of this structural element and possible degradation of the synthetic geomembrane, the long-term performance characteristics of which are largely unknown. Therefore, in the very long-term, the performance of the mineral sealing layers becomes of key importance for the safety of the system. Based on the numerical modelling results, the hydraulic conductivity of the mineral sealing layer has a significant effect on the performance of the landfill repository and, therefore, a target of 1E-10 m/s is recommended for the mineral sealing layers rather than the 1E-9 m/s value used for normal and hazardous waste landfills. Mineral sealing layers are also important in limiting radionuclide releases into the groundwater (through sorption reactions) together with the waste packages and filling material placed around them. The recommended layer thickness for a mineral sealing layer is ≥1 m. In addition, site-specific conditions of the natural barrier material should be taken into account in the overall design of the foundation layer.

Since most of the precipitation will be handled by the drainage system (at least in the beginning of the evolution of the repository), care should also be taken that the leachate water that has had contact with the waste is directed to a separate system (e.g., well, sedimentation pool) with monitoring and the means to prevent further dispersion of radionuclides.

Considering the cover layer, the role of the topmost zone also needs to be considered in the passive repository system. If, for example, growth of a forest at the site is accepted after closure, the cover layer thickness should prevent the ingress of tree roots into the level of the upper drainage layer.

Further uncertainties include, for example, the generation of gas in a near surface repository, radionuclide transport in barrier materials and the effect of freezing and drying on barrier materials (e.g., in the event the foundation layer is installed much earlier than the waste and the cover structures). These uncertainties are presently being investigated in on-going tests in KYT SURFACE task 1 (radionuclide transport) and task 2 (biodegradation of the waste and steel corrosion), and will be discussed as further input to the repository design in 2021.

Confidentiality	Public

Espoo 17.2.2021

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Preface

This report was compiled in 2020 as part of the KYT2022 Programme (Finnish Research Programme on Nuclear Waste Management 2019-2022). The KYT 2022 programme focuses on nationally important research topics with the aim to maintain and enhance national know-how in nuclear waste management and to promote collaboration between authorities, the nuclear industry and scientists.

The work presented in this report belongs to the second phase of the KYT SURFACE project concerning near surface repositories in Finland. In the second phase, the work in the KYT SURFACE project was divided into three tasks: 1) Radionuclide Transport, 2) Biodegradation of Waste and Steel Corrosion and 3) Performance of Engineered Barriers. This report belongs to task 3, with the aim to focus on the performance of engineered barriers in a near surface repository, especially concerning the performance of mineral sealing materials. In addition, this report describes the basic geotechnical properties of the material used in all of the tasks in KYT SURFACE phase 2.

The project manager of KYT SURFACE and the responsible person of this report is Paula Keto (VTT). The other main authors of this report were Harri Kivikoski, Ville Rinta-Hiiro, Timothy Schatz and Heidar Gharbieh (VTT). The geotechnical analyses were performed at VTT KT3 laboratories, excluding the hydraulic conductivity tests, which were performed at Tampere University (TERRA, Geo, Road, Rail) by Nuutti Vuorimies. The overall review of this report was performed by Laura Wendling (VTT).

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Espoo, Finland, 17.2.2021

Paula Keto, Harri Kivikoski, Ville Rinta-Hiiro, Timothy Schatz and Heidar Gharbieh

Contents

1. Introduction

Near surface repositories for very low-level radioactive waste (VLLW) are an option in Finland for the final disposal of waste from nuclear power plant operations and decommissioning. This repository type can also be applied to the disposal of naturally occurring radioactive material (NORM) wastes, for example, from industry and mining operations.

In August 2020, TVO (Teollisuuden Voima Oyj) submitted an environmental impact assessment programme (EIA programme) to TEM (Ministry of Economic Affairs and Employment of Finland) concerning the first near surface repository to be built in Finland in Olkiluoto. The near surface repository design would be based on a landfill-type repository design common in Sweden (see Aronsson 2019 and Keto et al. 2020) with the plan to start operating in 2023-2024 (TVO 2020). As an alternative, the programme also discusses expanding the geological repository currently in use (VLJ-cave).

According to TVO (2020), the near surface repository in Olkiluoto is dimensioned for a waste volume of 10 000 m^3 and has dimensions of 75 x 105 m (waste package filled area ~53 x 85 m). Approximately 65% of the waste to be deposited (6500 m^3/ 2400 t) consists of compressible operational waste (e.g., disposable protective clothing, paper, cloths used for cleaning) and the remaining 35% (3500 m^3/3400 t) of non-compressible (e.g., metallic scrap) waste. Depending on the waste type, the waste is compressed into pallets and/or packed in metallic waste containers or 200 L drums. The waste will have an average activity concentration of 100 kBq/kg at maximum with a total activity limit of 1 TBq. The actual disposal will be carried out over several campaigns, each a few weeks in duration, every ~5 years. In between, the facility is sealed temporarily. The repository will operate until 2090 after which it will be permanently closed. Active monitoring will be performed for as long as necessary considering the evolution of the waste. After closure, the institutional control period will begin, and the state of Finland will be responsible for further monitoring and control.

Detailed regulations and guidelines for normal and hazardous waste landfills in Finland are described by the Finnish Environment institute (SYKE 2002, 2008). Similar to a repository for radioactive waste, normal and hazardous waste landfill designs rely on multiple barriers with the aim to limit dispersion of contaminants from the waste into the surrounding environment. The question concerning a near surface repository is whether the guidelines provided for, e.g., hazardous waste landfills are directly applicable to a repository for VLLW. The radiological hazards posed by VLLW decline with time. However, waste that is classified as hazardous in the EU either remains hazardous or it becomes less hazardous very slowly. It is also the case that long-term and post closure safety of a near surface repository for radioactive waste shall rely on *passive barriers and engineering* (IAEA 2006, 2014). In addition, a near surface repository shall provide containment and isolation for a few hundred years under changing conditions, for example the increased likelihood of heavy rainfalls due to climate change, growth of more or different types of vegetation at the site (resulting in possible ingress of tree roots). This added vegetation could lead to the need for, e.g., a thicker top layer in comparison to normal or hazardous waste landfills. In addition, the need to monitor leachates for radiation and radionuclides is another issue that may need special consideration considering near surface repositories.

This report will discuss the performance of engineered barriers in near surface repositories and especially the ability of mineral sealing materials to function effectively as a barrier in the long-term and mitigate/retard radionuclide transport into the environment. The results presented in this report can be applied to the design of a near surface repository and in building a safety case for the repository. In addition, the report includes basic geotechnical characterisation information concerning the materials used in the radionuclide transport study (task 1) and the study concerning biodegradation of the waste and steel corrosion (task 2).

1.1 Scope, structure and limitations of this document

The scope of this report is to:

- Discuss, describe and analyse the performance of a landfill-type near surface repository under thecurrent and projected future repository conditions in Finland,
- Discuss safety functions for engineered barriers in a landfill-type repository,
- Discuss the factors affecting the performance of mineral sealing materials,
- Contribute starting data to the safety case concerning infiltration of water through the engineered barriers,
- Provide recommendations for the design and identify remaining knowledge gaps, and
- Describe the materials used in KYT SURFACE tasks 1, 2 and 3 (basic geotechnical material properties).

The methods used for covering the scope of this report are a literature study, numerical modelling and geotechnical tests. The expected performance of a landfill-type near surface repository is discussed in Section 2. Current landfill structures used in Finland are described in Section 3. Section 4 focuses on mineral sealing materials and the factors affecting their performance. The numerical modelling of the performance of a near surface repository is described in section 5 and laboratory analyses of the studied materials in section 6.

The report is limited to a landfill-type near surface repositories for VLLW. In addition, only the geotechnical studies made with the test materials are reported; outcomes of the radionuclide transport and biodegradation and corrosion studies will be detailed separately.

2. Expected performance of a near surface repository

A near surface repository for radioactive waste shall isolate the waste from the environment until the radiation levels of the waste are decreased to a level where the waste no longer poses a threat to the environment or to people. A simple rule is that repository shall isolate the waste for a period of roughly 10 times the half-lives of the radionuclides deposited in it, e.g., in the case of a radionuclide with a half-life of 30 years, the isolation capacity shall remain intact for at least 300 years. In practice, activity concentrations are also taken into account when defining the service life of the repository.

The safety of a near surface repository is realised through a combination of various factors, e.g., waste conditioning, waste packaging, waste acceptance criteria (WAC), site characteristics and the engineered barriers within the structure of the repository. In Finland, the radiation limits for the repository are given in the Government Decree on ionising radiation 1034/2018, (*Valtioneuvoston asetus ionisoivasta säteilystä*), in YVL C.2 Radiation protection and exposure monitoring of nuclear facility workers 1.11.2019 (*Ydinlaitoksen työntekijöiden säteilysuojelu ja säteilyaltistuksen seuranta*) and concerning long-term safety of the repository in The Nuclear Energy Decree 161/1988 (*Ydinenergia-asetus*). This report focuses on the structures of the repository and discusses the performance targets and implementation of these barriers.

The main structures of a landfill-type near surface repository (see Figure 2-1) consist of engineered barriers including cover and foundation structures, waste packages, fill material placed around the waste packages and the natural barrier, i.e., the underlying soil and bedrock.

Examples of landfill-type near surface repositories located in Sweden are reported in Keto et al. (2020). The following preliminary performance safety functions have been identified for the engineered barriers (excluding waste packages)

- Cover structures:
    - Function as a radiation shield.
    - Limit infiltration of water (surface runoff, precipitation or floodwaters) into the repository.
    - Control and collect water infiltrated through the topmost cover layer to minimise formation of leachate waters.
    - Control and collect gases generated in the waste.
    - Minimise the effect of erosion and ground frost on the performance of the repository barriers.
    - Prevent intrusion of vegetation (for example tree roots may be able to penetrate deep into soil) to avoid breakage of synthetic barrier structures.
    - Prevent intrusion of animals into the repository.
    - Minimise uneven settlements in the structures.
- Fill material around the waste packages:
    - Fill voids between the waste package.
    - Provide drainage function to minimise corrosion of the waste packages.
    - Provide stable chemical conditions for the waste packages.
    - Provide sorption capacity to retard transport of radionuclides.
    - Minimise uneven settlements within the waste fill and in the overlying layers belonging to the cover structure.
- Foundation layer
    - Provide a mechanically stable foundation for the waste packages.
    - Control and collect leachates via a drainage system enabling monitoring of radiation levels.
    - Prevent infiltration of leachates into the groundwater.
    - Retard transport of radionuclides into the surrounding environment.
    - Resistance to freeze/thaw effects if there is risk of freezing before the overlying waste packages and barrier materials are installed.
- Drainage systems
    - Inclinations and ditches are needed at the surface level of the repository to direct surface run-off waters away from the repository area.

- Drainage system are needed at the cover layer to direct infiltrated waters away from the waste fill and waste packages.

- Drainage system shall collect leachates from the foundation layer. The leachates shall be directed to a pool/well for monitoring. The pool/well system shall be designed to handle such leachates.

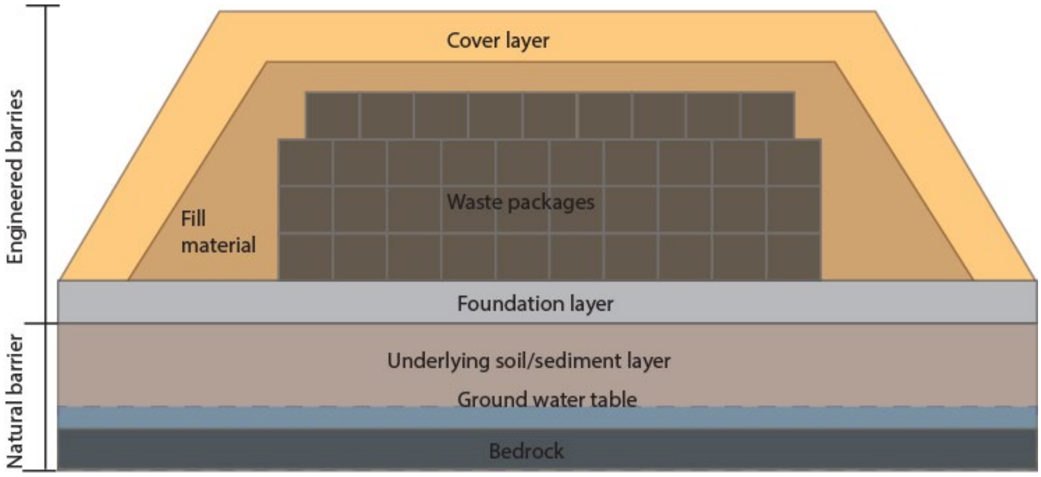

Figure 2-1. Main barriers in a landfill-type near surface repository.

3. Landfill structures in Finland

The structures of a hazardous waste landfill are presented in Table 3-1. An example of applying similar structures for a near surface repository are presented in Figure 3-1.

Table 3-1. Structural components in hazardous waste landfills in Finland based on SYKE (2002,2008) and Government decree 2.5.2013/331 on Landfills.

Cover layer			
Layer	**Function**	**Requirement / performance target**	**Design options**
Vegetation	Prevention of erosion of the top layer.		Grass, no trees
Top layer	Steers surface waters away (inclination, ditches, low permeability), shelters layers below from ground frost, erosion and plant or tree roots. Maximum inclination shall be limited to avoid slope failure	Low permeability (not defined, e.g., $1x10^{-8}$ m/s), thickness > 1 m, inclination of ≥5%, but small enough to avoid slip offs.	Low permeability natural material, e.g., glacial till or crushed rock (grain size distribution following the Fueller curve). Compacted at site, e.g., with a vibration compaction roller.
Drainage layer + filters	Drains infiltrating water away from the repository. Limits the amount of water infiltrating into the layers below. Reduce the hydrostatic pressure on the sealing layer.	Inclination ≥5%, high permeability, k-value $\geq 1x10^{-3}$ m/s, thickness ≥ 0.5 m	Drainage material: Coarse crushed rock or gravel. Filter layer: fine sand or filter textile to prevent clogging of the drainage layer.
Synthetic geomembrane + filter layers	Limits the amount of water infiltrating into the layers below and collects the drainage waters. Filter layers protect the geomembrane layer from contact with coarser materials.	Specific quality requirements for a bentonite mat and other geomembranes are presented in SYKE (2002, 2008).	E.g., HDPE membrane or bentonite mat. Filter layer of fine sand or filter membrane.
Mineral sealing layer	k-value should be the same as for the mineral sealing layer in the foundation layer.	k-value: $\leq 1x10^{-9}$ m/s, thickness: ≥ 0.5 m, see also section 4.1.	E.g., silt-rich till, clay or mixture of crushed rock and bentonite (bentonite content optimised based on the grain size distribution / empty void space of the aggregate). At installation, the standard procedure is to add 1-2% more bentonite than the required minimum for the mass. Compaction to 90-92% from the maximum Proctor dry density (with compaction roller or a plate). Material contains optimum water content at installation (from Proctor tests).

Gas collection system + filter layers	Collect gas generated in the landfill in a controlled manner	High permeability layer and piping collecting the gas into a system	Coarse crushed rock or gravel OR geosynthetic material, fine grained filter material or filter geotextile, piping system.
Fill material	Fill material used on top of the waste to limit uneven settlements.	Sufficient bearing capacity (dimensioned case by case)	Crushed rock, sand or gravel with relatively even grain size distribution. Compaction used for increasing bearing capacity. Inclination shall support the shape of the overlying structures (≥5%).
Foundation layer			
Layer	**Function**	**Specification**	**Design options**
Floor layer (named as filter material in hazardous waste landfills according to SYKE, 2002)	In hazardous waste landfills this layer has a filtering function maintaining the performance of the drainage layer. The waste is place on top of this layer.	Filtering function, not specified in more detail.	Sand or geotextile
Drainage layer + piping	Drainage layer and piping shall convey leachates to, e.g., a collection pond.	Inclination ≥3% towards the piping, high permeability, k-value ≥$1x10^{-3}$ m/s, thickness ≥ 0.5 m	Drainage material: Coarse crushed rock or gravel. Filter layer: fine sand or filter membrane. The piping shall withstand the chemical and mechanical loading from the waste and overlying structures.
Synthetic membrane	Used to aid collection of leachates.	Specific quality requirements for a bentonite mat and other geomembranes are presented in SYKE (2002, 2008).	E.g., HDPE membrane or bentonite mat. Filter layer of fine sand or filter membrane.
Mineral sealing layer	Used for limiting dispersion of leachates into the environment/groundwater. Required when the natural barrier does not fulfil the requirements set in Government Decree 4.9.1997/861 (section 3), see below.	k-value: ≤$1x10^{-9}$ m/s and thickness: / ≥ 1 m. See also section 4.1	E.g., mixture of crushed rock and bentonite (bentonite content optimised based on the grain size distribution / empty void space of the aggregate. At installation, the standard procedure is to add 1-2% more bentonite than the required minimum for the mass. Compaction to ~90% from the maximum Proctor dry density (with compaction roller or a plate). Material contains optimum water content at

			installation (from Proctor tests).
Natural barrier			
Layer	**Function**	**Specification**	**Design options**
Subsoil /sediments	Limit dispersion of contaminants to the environment, bear the weight of the waste and overlying structures.	k-value ≤$1x10^{-9}$ m/s and thickness ≥ 5 m	Natural sediments. If the sediments on site have poor bearing capacity, replacement by sediments with better bearing capacity.

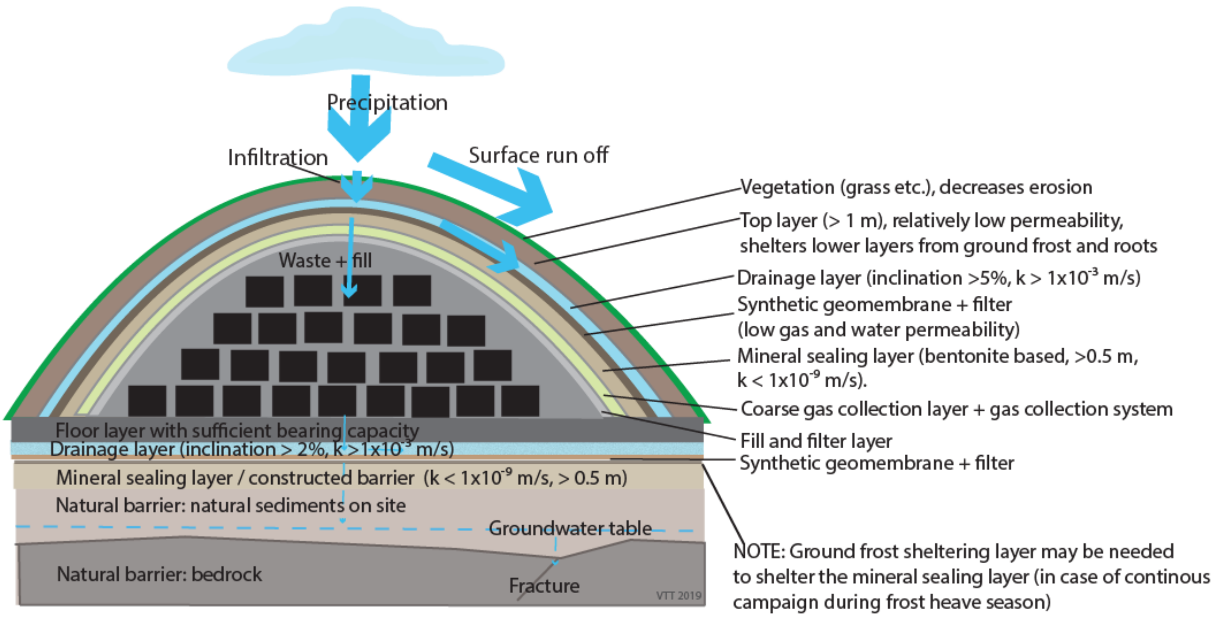

Figure 3-1. Example of a possible landfill-type near surface repository based on Finnish guidelines for hazardous waste landfills (SYKE, 2002, 2008). Figure reproduced from Keto et al. (2020).

3.1 Example landfill case from Ämmässuo, Espoo

As an example case, a Finnish landfill located in Ämmässuo, Espoo, which was described in detail in the journal of Finnish Geotecnical Society, Geofoor, by Samposalo (2008), will be briefly summarised below. An extension of the Ämmässuo landfill was planned in 2007 with the aim to reduce the effects of the landfill on the environment with enhanced landfill structures, gas collection systems and water control. The landfill was planned for a large amount of waste (15 million tonnes) with a maximum thickness of the waste fill of 70 m. The foundation structures of the landfill were planned to be permanent, since renewal or replacement of the foundation structures afterwards was considered to be impracticable. The foundation structure of the landfill is shown in Figure 3-2. The structure is otherwise planned according to Finnish guidelines for normal landfills (therefore, the thickness of the mineral sealing layer is only 0.5 m), but there is an extra sealing layer consisting of asphalt with overlying extra drainage layer for detecting any leakages through the mineral sealing layer.

The landfill was built on an area where the bedrock is revealed. In order to even out the rock surface, the bedrock was excavated and crushed rock was placed on top. The crushed rock layer was constructed with inclinations needed for the drainage systems within the landfill foundation.

On top of the crushed rock there is a sealing structure consisting of a 50-mm layer of load bearing asphalt (ABK120, 130 kg/m^2) on top of which there are two layers of low-permeability rubber-bitumen rich asphalt (KBVA, ~2x70 kg/m^2).

The mineral sealing layer (which is resistant to freeze/thaw effects) consists of a mixture of crushed rock and bentonite. This layer has a hydraulic conductivity of 6×10^{-10} m/s and is 0.5 m thick. The overlying synthetic barrier consists of a HDPE membrane with a minimum thickness of 2.5 mm. The HDPE geomembrane is protected by a geotextile (1200-3000 g/m^2), since the overlying drainage material consists of coarse crushed rock that could damage the membrane.

There is also a maintenance tunnel below the waste fill that is used for active maintenance of the drainage pipes (flushing of the drainage pipes to prevent clogging). The landfill extension area is isolated from the old landfill area by a vertical 200-250 mm-thick concrete wall and HDPE membrane.

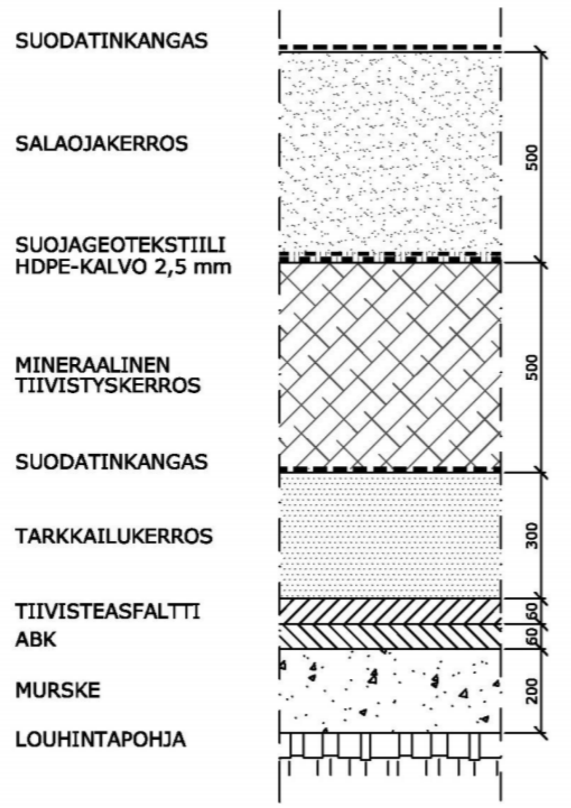

Figure 3-2. Foundation structures in the landfill at Ämmässuo (From bottom: excavated rock, crushed rock, additional asphalt sealing layer, additional drainage layer to detect leakages through the mineral sealing layer, geotextile filter, mineral sealing layer, HDPE geomembrane, geotextile protective cover, drainage layer and geotextile filter (reproduced from Samposalo 2008).

4. Performance of mineral sealing layers

4.1 Requirements for mineral sealing layers in landfills

Landfill cover layer structures are presented in Table 4-1 with respect to normal and hazardous waste disposal.

Table 4-1. Landfill cover layer structures (Government Decree on Landfills 331/2013, SYKE 2002, 2008).

Layer	Landfill for non-hazardous waste	Landfill for hazardous waste
Top soil cover ≥ 1 m	Required	Required
Drainage layer ≥ 0.5 m	Required	Required
Impermeable layer ≥ 0.5 m	Required	Required
Artificial sealing liner	Not required	Required
Gas drainage layer	Required	As necessary

Requirements for the mineral sealing layers of hazardous waste landfills are (SYKE 2002):

- Hydraulic conductivity ≤ 1×10^{-9} m/s.
- Thickness of ≥0.5 m in the cover layer and ≥1 m in the foundation layer (if the thickness of the subsoil is <5 m)
- Maximum allowed single deviation from the design level: ±30 mm.
- Maximum allowed unevenness over a distance of 5 m: ±20 mm.
- Inclinations in the planned directions.
- The upper surface must be free of granules, protrusions, etc. larger than 2 mm, which may cause point stresses to the geomembrane.
- Machine traces higher than 5 mm must be leveled.
- Shear strength ≥50 kN/m^2.

4.2 Effect of bentonite content

In landfill applications, the content of bentonite is usually optimised for the aggregate (crushed rock or sand) to be used in the mixture with the aim to efficiently reach the target k-value of $1x10^{-9}$ m/s. This optimization is done by defining the empty void space remaining in the aggregate assuming that the aggregate is compacted to a dry density state close (~90%) to its maximum grain size distribution, specific gravity and Proctor compaction test data are needed for the aggregate material. Assuming some swelling of the bentonite, the bentonite content may vary, e.g., 5-10%. Within this bentonite content the k-value typically remains below the target value for mineral sealing layers in landfills (<$1x10^{-9}$ m/s).

In this study, the effect of bentonite on the hydraulic properties of the mineral sealing layers have been studied with bentonite contents of 6, 8 and 10% (see Section 6 for laboratory test results).

Bourlanger-Martel et al. (2014, 2015) tested crushed rock (0–20 mm) and three crushed rock–bentonite mixtures. The average, as-received gravimetric water content of the crushed rock was 4.4%. Three different mixtures of bentonite and crushed rock were made in the laboratory by hand-mixing a commercially available PDSCo Grout bentonite powder and crushed rock to 5.0%, 6.5%, and 8.0% bentonite content by dry weight. The samples were compacted to 90% Proctor density. Permeability tests were conducted for approximately 100 h under low hydraulic gradients. Measured hydraulic conductivity values ranged from 3.5 × 10^{-9} m/s for the 5.0 weight-% (bentonite) to 4.8 × 10^{-10} m/s for the 8.0 weight-% (bentonite) (Bourlanger-Martel et al., 2015). (see Table 4-2).

Table 4-2. Main geotechnical properties of tested materials (Bourlanger - Martel et al., 2015). CRBM = crushed rock bentonite mixture and k sat (cm/s) represents the hydraulic conductivity of the material in cm/s corresponding to 3.5x10^{-9} m/s, 2.2x10^{-9} m/s and 4.8x10^{-10} m/s.

Parameter	Crushed rock	Bentonite	5.0% CRBM	6.5% CRBM	8.0% CRBM
Grain-size diameter (mm)^a					
d_{10}	0.38	0.05	0.20	0.18	0.16
d_{50}	7.05	0.27	6.527	6.368	6.203
d_{90}	17.20	0.50	16.98	16.92	16.86
d_{100}	20.00	1.00	20.00	20.00	20.00
C_U	24.00	6.02	42.73	47.67	52.73
G_s	3.04	2.59	3.02	3.01	3.00
k_{sat} (cm/s)	2.6×10^{-1b}	—	3.5×10^{-7}	2.2×10^{-7}	4.8×10^{-8}
ψ_a (kPa)	0.5^b	—	8	10–20	10–20
ψ_r (kPa)	7^b	—	15 000	15 000	15 000
θ_r (m^3/m^3)	0.02^b	—	0.02	0.02	0.02

Note: C_U, coefficient of uniformity (= d_{60}/d_{10}); θ_r, residual volumetric water content; —, not tested.

$^a d_x$, diameter corresponding to x w/w % passing on the cumulative grain-size distribution curve.

^{b}Data from Coulombe (2012).

Tables 4-3 and 4-4 show compilations of published hydraulic conductivity data. It can be concluded that mixtures containing 10% MX-80 have hydraulic conductivities in the range of 10^{-10} to 10^{-8} m/s depending on the dry density of the sample when percolated with distilled water (Pusch, 1998, Johannesson et al. 1999). If the hydraulic conductivity is measured using saline water (as may sometimes be the case with landfill leachates), the hydraulic conductivity increases. The effect depends on the salinity of the water and the composition of the saline water due to exchange of cations between the water and the bentonite (especially in case of exchange of Na^+ to Ca^{2+}) (Vieno 2000).

Table 2-3. Hydraulic conductivity of bentonite/ballast materials (Pusch, 1998).

Backfill type	Bentonite (MX-80) content	Dry density, kg/m^3	Density at saturation, kg/m^3	*K*, m/s Distilled water	*K*, m/s Salt water
SB (Forsm.)	10	1900	2200	3.4×10^{-10}	
SB (Forsm.)	10	1980	2250	1.2×10^{-10}	
SB (Forsm.)	10	2140	2350	1.1×10^{-10}	
SB (BMT)	10	1790	2130	10^{-9}	3×10^{-9} (2 % NaCl)
RB (Romele)	10	1870	2180	10^{-8}	
RB (Romele)	10	1970	2240	9×10^{-10}	
RB (Äspö)	10	2000	2260	2×10^{-11}	4×10^{-11} (Äspö)
RB (Romele)	20	1760	2110	10^{-11}	
RB (Romele)	20	1880	2180	10^{-11}	
RB (Äspö)	20	1730	2090	4×10^{-11}	
RB (Äspö)	20	1980	2250	2×10^{-11}	3×10^{-11} (Äspö)
SB (Forsm.)	30	1510	1950	1.1×10^{-11}	10^{-10} (1 % $CaCl_2$)
SB (BMT)	30	1750	2100	10^{-10}	10^{-9} (2 % NaCl)
RB (Äspö)	30	1870	2190	4×10^{-12}	
RB (Äspö)	30	1850	2100		6×10^{-11}

Table 2-4. Summary of hydraulic conductivity tests for soil-bentonite mixtures (Johannesson et al., 1999). Åspö reference water has salinity of 11 g/L (Vieno 2000).

				Final properties						
Test No.	Clay cont. (%)	Water	w_{ini} (%)	Proct (%)	w (%)	″d (t/m^3)	e	Sr (%)	K (m/s)	K with Back Pr. (m/s)
1	0	Dist.	5.6	96	8.6	2.21	0.24	97	1.40E-08	1.96E-08
2	0	Dist.	5.6	91	10.4	2.11	0.31	95	6.19E-08	1.33E-07
3	0	Dist.	5.6	101	5.7	2.33	0.19	90	1.66E-09	4.55E-09
4*	0	Dist.	5.6	94	8.3	2.18	0.26	88	8.50E-08	-
5*	0	Dist.	5.6	92	7.8	2.12	0.30	73	1.00E-07	-
6	10	Dist.	7.0	94	12.4	2.02	0.37	96	2.87E-10	3.40E-10
7	10	Äspö	7.0	94	12.1	2.04	0.36	96	5.12E-09	1.13E-08
8	10	Dist.	7.0	94	13.4	2.02	0.36	102	2.79E-10	5.62E-10
9	10	Äspö	7.0	94	12.4	2.04	0.35	99	2.67E-09	5.59E-09
10	10	Dist.	7.0	88	16.0	1.90	0.45	98	2.02E-10	1.34E-10
11	10	Äspö	7.0	90	14.1	1.95	0.42	95	4.26E-09	2.70E-08
12*	10	Äspö	7.0	98	10.7	2.11	0.30	97	1.77E-09	-
13	20	Dist.	8.0	93	15.5	1.91	0.45	97	4.62E-11	5.22E-11
14*	20	Äspö	8.0	94	15.2	1.93	0.43	98	4.14E-10	9.46E-10
15	20	Dist.	8.0	87	18.1	1.79	0.57	93	5.53E-11	6.25E-11
16*	20	Äspö	8.0	90	17.1	1.85	0.50	96	3.27E-09	5.51E-09
17*	20	Äspö	8.0	87	18.8	1.78	0.54	95	1.46E-09	2.17E-09
18	20	Äspö	8.0	79	23.1	1.62	0.69	91	5.36E-08	-
19	30	Äspö	13.0	91	19.7	1.77	0.56	98	4.71E-11	7.84E-11
20	30	Äspö	13.0	89	21.5	1.72	0.61	99	4.25E-10	4.49E-10
21*	30	Äspö	13.0	89	19.6	1.72	0.60	91	9.73E-11	2.01E-10
22	30	Äspö	13.0	88	21.5	1.71	0.61	96	6.32E-10	9.09E-10
23	30	Äspö	13.0	78	27.3	1.52	0.81	93	7.22E-09	-
24*	30	Äspö	4.6	96	15.9	1.86	0.47	95	6.00E-11	-
25*	30	Dist.	13.7	96	17.3	1.87	0.48	101	4.09E-12	-
26*	30	Dist.	13.7	95	17.1	1.85	0.48	99	1.10E-12	-
27	30	Äspö	6.5	89	20.8	1.73	0.59	97	2.86E-09	2.98E-09

Additionally, the quality of the bentonite, mainly smectite content, and composition of exchangeable cations (main cations being Na^+, Ca^{2+} or Mg^{2+}) within the bentonite have an effect on the hydraulic and swelling properties of bentonites (Vieno 2000). Gleason et al. (1997) compared the effects of changes in bentonite type on the hydraulic conductivity of compacted sand-bentonite mixtures. Two types of air-dry bentonite were selected in the study, specifically a sodium bentonite and a calcium bentonite. The mixtures consisted of different contents of sodium and calcium bentonite and three different types of sand. Samples contained bentonites at up to 20%. Hydraulic conductivity versus added bentonite for these sodium and calcium bentonite mixtures is presented in Figure 4-2.

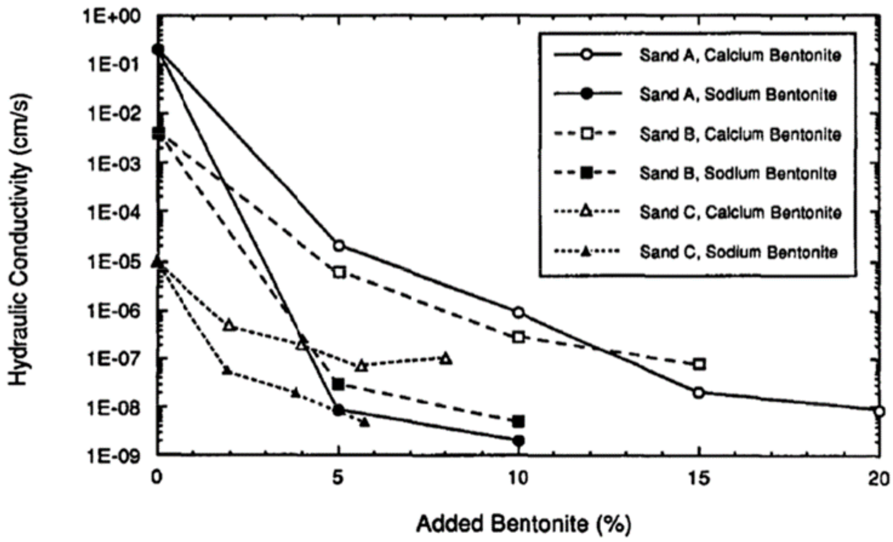

Figure 4-2. Hydraulic conductivity versus added bentonite for sodium and calcium bentonite/sand mixtures (Gleason et al., 1997).

The results of the hydraulic conductivity tests indicate that, in order to decrease the hydraulic conductivity to less than 1 x 10^{-7} cm/s, three times more calcium bentonite was needed compared with sodium bentonite. The effect of the main cation is evident in the beginning of the evolution of a landfill, but the effect may be reduced along the evolution of the repository due to cation exchange with the percolating rain or leachate water. This is one uncertainty identified for the long-term behaviour of a sealing layer.

When preparing a mixture at large-scale, e.g., in a concrete mixer with batch size of few tons, a very low bentonite content can in practice lead to an uneven bentonite distribution within the mixture, and this can result in a higher hydraulic conductivity than would be estimated for a uniform mixture. Therefore, the amount of bentonite added to a bentonite-crushed rock mixture is usually 1-2% more in field conditions than the defined optimum for the aggregate, in order to guarantee reaching similar hydraulic properties for the material as observed under a controlled laboratory setting.

In addition, to crushed rock or sand as the main component, bentonite can also be added to more heterogeneous materials to decrease hydraulic conductivities. Taha et al. (2015) performed tests on UKM soil (clayey sand of Malaysian origin) mixed with different bentonite contents (0%, 5%, 10% and 20%). The results showed that the addition of bentonite leads to significant decreases in hydraulic conductivity (Figure 4-3). The use of local sediments might be another option in preparing the sealing layer instead of using crushed-rock aggregates.

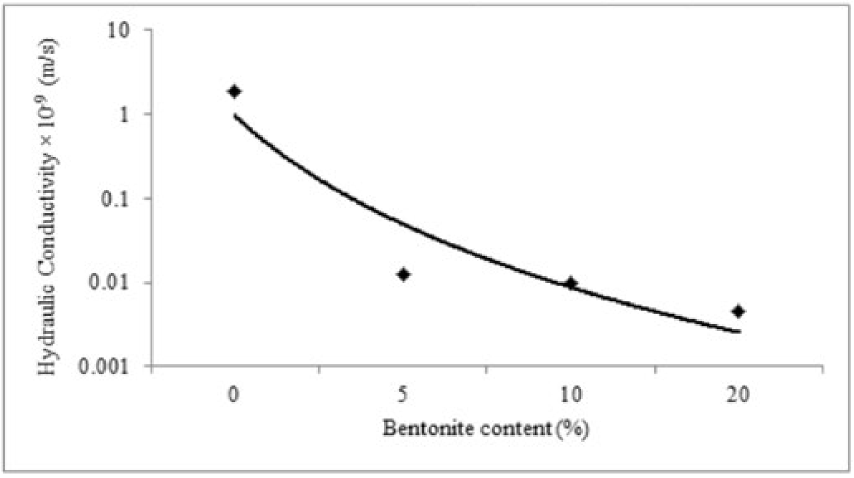

Figure 4-3. Hydraulic conductivity of UKM soil/bentonite mixtures as a function of bentonite content (Taha et al., 2015).

4.3 Effect of freezing & thawing

Bourlanger-Martel et al. (2015) measured saturated hydraulic conductivity changes of a 6.5% bentonite mixture after to freeze-thaw cycles. The results of the tests are presented in Figure 4-4. The saturated hydraulic conductivity values are normalised to the initial value (prior to any freeze-thaw cycle). Results show that the saturated hydraulic conductivities of a 6.5% rock-bentonite mixture increased by over one order of magnitude after only one freeze/thaw cycle but, more significantly, by over two orders of magnitude after three cycles. The freezing temperature was -13°C.

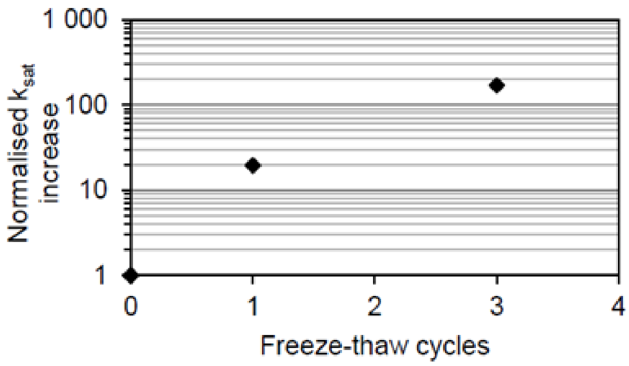

Figure 2-4. Increase in hydraulic conductivity due to cyclic freeze and thaw of a 6.5% bentonite mixture (Bourlanger-Martel et al., 2015).

Wong and Haug (1991) measured hydraulic conductivities of sand-bentonite mixtures before and after freeze-thaw tests. A comparison of the equilibrium hydraulic conductivities for the sand-bentonite specimens is presented in Fig. 4-5. The permeabilities decreased after freeze/thaw exposure with the greatest decreases occurring after the first freeze-thaw cycles. In general, the magnitude of the decrease in permeability of the sand-bentonite mixtures appears to be inversely related to bentonite content. The permeability of the 4.5% and 6% specimens decreased by almost one order of magnitude, whereas the permeability of the 13% specimen decreased by a factor of three. The permeability of the 25% specimen decreased gradually with each cycle.

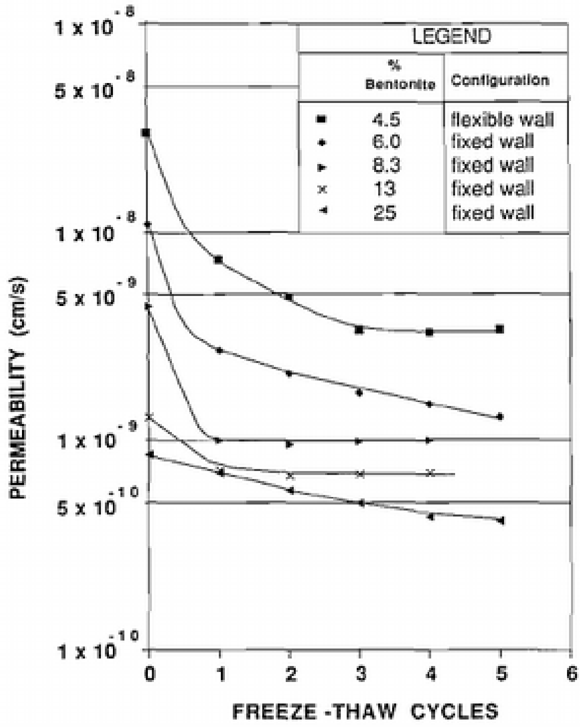

Figure 2-5. Comparison of permeabilities measured prior to and following each freeze-thaw cycle for sand-bentonite specimens (Wong and Haug, 1991).

The sand component in sand-bentonite liners forms a relatively incompressible physical structure capable of resisting freeze-thaw consolidation. However, although the sand controls compressibility, the bentonite controls permeability by restricting flow through the sand-bentonite matrix. The observed decreases in permeability due to freeze-thaw cycles during testing suggest that freezing and thawing either promotes hydration of the bentonite, lowering the permeability towards long-term test values or compresses the bentonite through thaw consolidation into the gaps between sand grains, increasing the density of the bentonite and lowering permeability to values associated with high-density sodium bentonite. This consolidation may occur during the growth of pure ice crystals in the centre of the voids during freezing (Wong and Haug, 1991).

Hydraulic conductivity tests of sand-bentonite mixtures with the bentonite content of 12% were performed by Kraus et al. (1997). After the initial hydraulic conductivity tests were complete, the permeated specimens were carefully removed from permeameters and sealed in plastic wrap to prevent desiccation. The specimens were then placed in a laboratory freezer (temperature -20 °C) and frozen three-dimensionally in a closed system. The specimens were left in the freezer for at least 24 h, at which point they were removed and allowed to thaw at room temperature (25 °C). This procedure was repeated until desired number of freeze-thaw cycles was attained.

Hydraulic conductivities of the sand-bentonite specimens frozen and thawed in the laboratory are presented in Fig. 2-6. No change in hydraulic conductivity occurred for the specimens permeated prior to freezing. These findings are inconsistent with those of Wong and Haug (1991) as freezing and thawing of sand-bentonite did not result in observations of significant decreases in hydraulic conductivity.

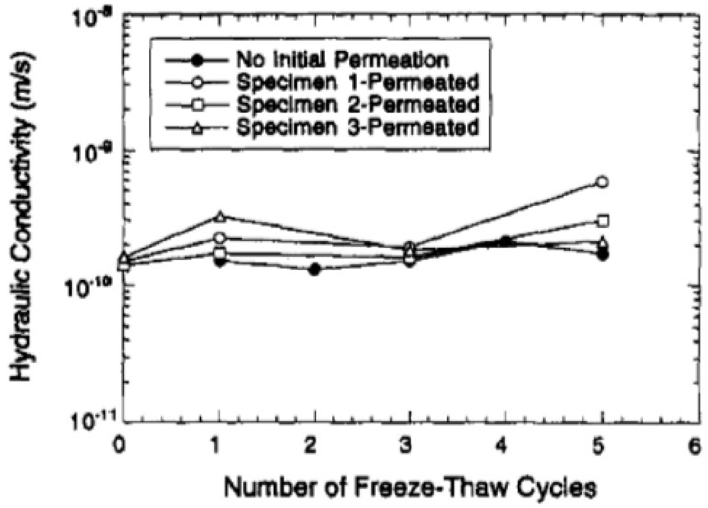

Figure 2-6. Hydraulic conductivity of compacted sand-bentonite specimens exposed to freeze-thaw (Kraus et al., 1997).

The effect of freezing is relevant for a landfill-type repository in case the foundation layer is prepared for a larger area and left without any cover materials sheltering the layer from freezing for one or several winters. In order to study the effect on freezing on the material performance, hydraulic conductivity tests should be performed with varying bentonite content (6%, 8% and 10%) after freezing and thawing cycles corresponding to the expected conditions in southern Finland.

4.4 Effect of drying

Similar to the effect of freezing, the effect of drying should be taken into account for foundation layer materials that remain exposed for long periods prior to installation of the waste, waste fill and cover layer.

Expansive soils experience a volume increase (swelling) upon wetting and a volume decrease (shrinkage) upon drying due to seasonal moisture fluctuations. Swelling behaviour is essential for maintaining low hydraulic conductivity and sealing of cracks in engineered clay barriers, but shrinkage and desiccation cracks developed during drying may act as preferential flow paths and influence the hydraulic conductivity and thereby impair the primary function of the barriers in geotechnical and geoenvironmental engineering applications such as landfills, embankments, etc.

Stewart (2001) reported on the shrinkage and desiccation cracking exhibited by bentonite-enhanced sand mixtures (BES) upon air-drying. Mixtures containing 10 and 20% bentonite by dry weight, compacted at moisture contents ranging from 8 to 32%, were investigated. All of the mixtures exhibited volumetric shrinkage upon air-drying, with the amount of shrinkage increasing with increasing initial moisture content. At any initial moisture content, mixtures containing 20% bentonite shrink more than those containing 10% bentonite, but the shrinkage is insensitive to the compactive effort. Compacted beds of BES containing 10 and 20% bentonite exhibit no visible desiccation cracking as the top surface is dried when compacted at moisture contents of 15 and 14%, respectively, and only minor cracking when compacted at initial moisture contents of 20 and 15%, respectively. For the range of mixtures tested, it appears that cracking only occurs when the volumetric shrinkage is more than about 4%.

Taha et al. (2015) performed tests on UKM soil (clayey sand of Malaysian origin) mixed with different bentonite contents (0%, 5%, 10% and 20%). It was found that both shrinkage and swelling strains increased with increasing bentonite content. Desiccation tests showed small, minor cracks for mixtures with 0% and 5% bentonite content and larger, more pronounced cracks in mixtures with 10% and 20% bentonite content (Figure 4-7). Samples were subjected to hydraulic conductivity testing after each of three wetting/drying cycles. The results indicate that the largest rise in soil hydraulic conductivity occurred after the first (20 and 10% bentonite) or second (5 and 0% bentonite) cycles (Figure 4-8). The drying process was conducted for a period of approximately 5 - 10 days depending on the sample type using an oven at a temperature of approximately 34 ± 2°C.

The effect of drying on hydraulic conductivity seems to be more significant for materials with higher bentonite content but it should be checked for bentonite-crushed rock mixtures with bentonite content varying from 6 to 10%.

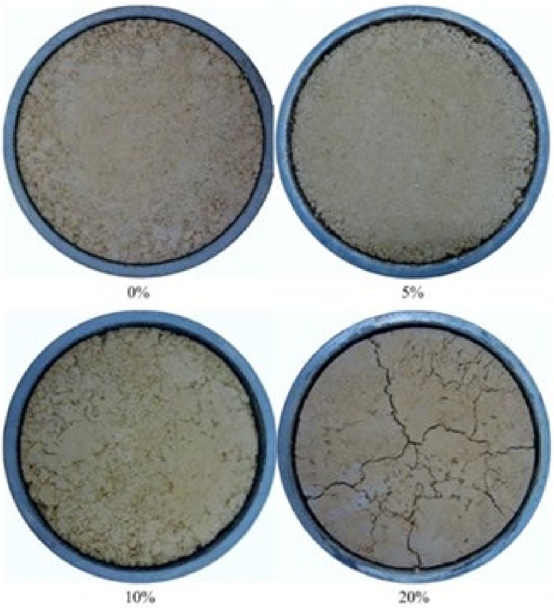

Figure 4-7. Appearance of UKM soil mixed with 0%, 5%, 10% and 20% bentonite after desiccation tests (Taha et al., 2015).

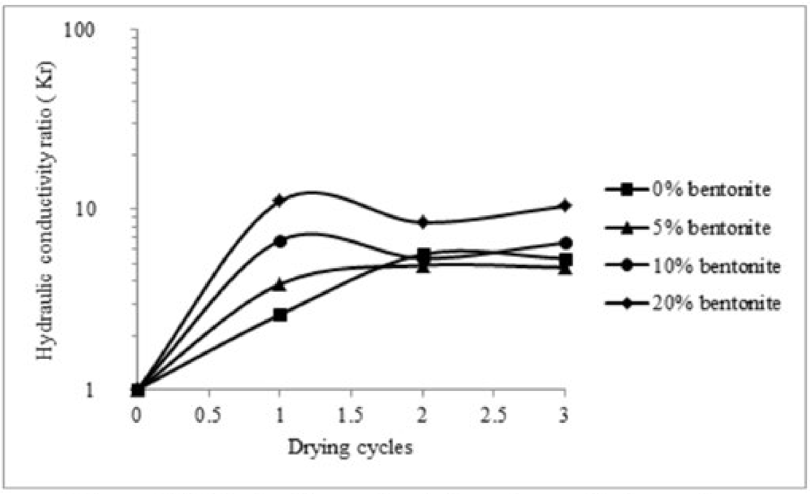

Figure 4-8. Hydraulic conductivity ratios vs. drying cycles for UKM soil mixed with 0%, 5%, 10% and 20% bentonite (Taha et al., 2015).

5. Numerical simulations for movement of water in the near surface repository

One of the most important functions of a near surface repository is to isolate the emplaced waste from the surrounding environment particularly by preventing leachate from leaving the repository. In an unwanted scenario, (rain or flood) water would infiltrate through the cover layer of the repository to the underlying waste. Interaction of this water with the emplaced waste may lead to contaminant extraction and transport. The resulting leachate could propagate through the foundation layers and then reach the groundwater or surrounding environment. To prevent this scenario from occurring, the structural layers of near surface repositories should be designed and constructed so that no water would infiltrate from the surface to the waste and through the foundation layer. This performance target is achieved by structural layers with very low hydraulic conductivity properties and, to support the performance target, also drainage layers to collect leachates for treatment and disposal (see Section 2). The structural layers should be designed so that the required properties are fulfilled with sufficient safety margins. The required dimensions, material quality and consistency of the layers should then be ensured during construction as well as proper installation to prevent mistakes and defects in the layers.

A variety of modelling applications are available to estimate the amount of water percolating through constructed layers of landfill type structures under different scenarios. One such application is the Hydrologic Evaluation of Landfill Performance (HELP) model, which was used in the calculations presented in this chapter.

HELP is a quasi-two-dimensional hydrological model which simulates movement of water across, into, through and out of landfills and other near-surface disposal systems. With the use of the HELP model, evaluations can be made to optimize landfill type structure designs that minimize leakage of water to the surrounding environment.

The HELP model is freely available (https://www.epa.gov/land-research/hydrologic-evaluation-landfill-performance-help-model). The latest version of the model was used in the calculations (HELP Model 4.0.1, 10/06/2020). HELP uses an Excel workbook with embedded macros to support the user interface. Technical documentation of the HELP model can be found in the user's guide of the HELP model version 4.0 (https://www.epa.gov/land-research/help-40-user-manual) and more detailed information including the solution methods is available in the user's guide of the HELP model version 3 (https://www.epa.gov/land-research/hydrologic-evaluation-landfill-performance-help-model).

With an extensive set of input data set by the user, the HELP model calculates daily, monthly, annual and average annual estimates of runoff, evapotranspiration, drainage, leachate collection, and liner leakage. The HELP model takes into account the following details: surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane and composite liners.

The most important input data include weather data as well as soil and design data. Weather data are classified into four groups: precipitation, temperature, evapotranspiration and solar radiation data. For the soil and design data, built-in layer parameters can be selected or alternatively the user can define the layer properties manually. The following layer categories are recognized in the HELP model: final cover soil (topmost layer), vertical percolation layer (soil), lateral drainage layer (soil), barrier soil liner, waste, geomembrane liner, and geosynthetic drainage net.

For the calculations presented in this chapter, the weather data were imported from the National Oceanic and Atmospheric Administration (NOAA) (https://www.ncdc.noaa.gov/cdo-web/search). The weather data (precipitation and temperature) consisted of 20 years of information (2000-2019) from three different weather stations: Helsinki Kaisaniemi (Primary station, Latitude 60.17 and Longitude 24.95), Helsinki Vantaa airport (Secondary station, Latitude 60.32 and Longitude 24.96) and Hyvinkää Hyvinkäänkylä (Tertiary station, Latitude 60.60 and Longitude 24.81).

Solar radiation data was imported from the National Renewable Energy Laboratory's National Solar Radiation Database (NSRDB) (https://nsrdb.nrel.gov/data-sets/archives.html). Specific data was not available for the Helsinki area, therefore, data from Port Alsworth, Alaska (60.20° N), which is located at the same latitude, was used.

Wind speed and relative humidity data were imported from the Finnish Meteorological Institute (FMI) (https://www.ilmatieteenlaitos.fi/avoin-data). Average wind speed was calculated over two years of wind speed data (2018-2019) from the Helsinki Kaisaniemi weather station. Average quarterly relative humidities were calculated using five years of data (2015-2019) from the Helsinki Kaisaniemi weather station.

In Table 5-1, the initial data used for the HELP model calculations are presented. It should be noted that these values are always case-specific but in this examination, the target was to use typical values that could be considered for a landfill type repository in the Southern part of Finland.

Table 5-1. Initial data.

Latitude	60.19
Years of simulation	20
Landfill area (ha)	1
Subject to runoff (%)	100
User specifies initial moisture?	No
Average wind speed (km/h)	13.3
Average first quarter relative humidity (%)	83.4
Average second quarter relative humidity (%)	68.9
Average third quarter relative humidity (%)	77.7
Average fourth quarter relative humidity (%)	85.8
Start of the growing season (d)	106
End of the growing season (d)	299
Maximum leaf area index	1
Evaporation zone depth (m)	50
Slope (%)	5
Slope length (m)	25
Vegetative cover	Poor grass
HELP model computed runoff curve number	75.5

In Table 5-2 and Table 5-3, input values for landfill layer properties are presented. The overall design is representative of a typical landfill with foundation structures under the waste and cover structures over it. Both the foundation and cover structures consist of several different layers having distinct functions (see Section 2). Drainage layers are constructed in both the foundation and cover structures to collect water infiltrating through the top soil layer in the cover and leachate from the waste in the foundation. Below the drainage layers, sealing layers are constructed and installed. The sealing layers can be composed of both geomembranes (or other corresponding solutions) and mineral sealing layers, both of which have low hydraulic conductivity and prevent fluid transport. Geomembranes are highly impermeable. However, the presence of seams or damage from installation may lead to points or regions with increased permeability. High quality manufacture and installation are both important to reach the designed target properties of the geomembranes and mineral sealing layers. The properties used as input in the HELP analyses should always be case-specific, considering real, measured values of the layer material properties. In the reference case used in the analyses, the hydraulic conductivity of the mineral sealing layers was 1E-9 m/s, which is the requirement set for the Finnish landfills. A gas collection layer was not included in the analyses as it would have a very small impact on the water infiltration. Its hydraulic conductivity properties can be considered to correspond to the properties of the drainage layers.

Table 5-2. Layers, layer thicknesses and layer materials used in the HELP model analyses.

	Layer	Layer number	Material description	Thickness (m)
Cover structures	Cover layer	1	Loamy sand*	1
	Drainage layer	2	Gravel	0.5
	Geomembrane	3	LDPE	0.002
	Mineral sealing layer	4	Bentonite/crushed rock	0.5
	Backfill around the waste	5	Flyash	4
Foundation structures	Drainage layer	6	Gravel	0.5
	Geomembrane	7	HDPE	0.002
	Mineral sealing layer	8	Gravel	1

** Loamy sand consist mainly (80%) of sand and has approximately 10% clay and 10% silt.*

Table 5-3. Layer properties, including geomembrane installation quality, used in the analyses.

Layer number	Porosity	Field capacity	Wilting point	Hydraulic conductivity (saturated) (m/s)	Drainage length (m)	Drainage slope (%)	Geomembrane pinhole density/ha	Geomembrane installation defects/ha	Geomembrane installation quality
1	0.437	0.105	0.047	1.70E-05	-	-	-	-	-
2	0.397	0.032	0.013	3.00E-03	25	5	-	-	-
3	-	-	-	4.00E-15	-	-	50	10	3/5
4	0.4	0.35	0.3	1.00E-09	-	-	-	-	-
5	0.5	0.4	0.3	1.00E-05	-	-	-	-	-
6	0.397	0.032	0.013	3.00E-03	25	5	-	-	-
7	-	-	-	2.00E-15	-	-	50	10	3/5
8	0.4	0.35	0.3	1.00E-09	-	-	-	-	-

The results of the calculation for the reference case (defined in Table 2 and Table 3) are shown in Table 5-4. In addition, the reference structure was tested using double the amount of precipitation (i.e., daily precipitation values were multiplied by 2) and the results are shown in Table 5-5. For the reference case, 6.7 % of the precipitation was accounted for as runoff and

49.9 % as evapotranspiration. The remaining infiltrating water was then effectively collected in the uppermost drainage layer with only <<1 % of the rainwater percolating/leaking through the mineral sealing layer of the cover structure. When double precipitation was used (Table 5), the proportion of runoff (13.4 %) increased, and the proportion of evapotranspiration (30.0 %) decreased. In total, in the typical precipitation case, 56.6 % was accounted for as runoff or evapotranspiration compared to 43.3 % in the double precipitation case. Thus, more water percolated to the drainage layer in the double precipitation case. However, similar to the typical precipitation case, <<1 % of water percolated or leaked through the mineral sealing layer.

Table 5-4. Output for the reference case relative to a 20-year time period. Change in water storage corresponds to a change in the volume of water (i.e., volumetric content) in all soil layers.

Average annual totals for years 1-20				
	mm	[std dev]	m^3	%
Precipitation	666.8	[122.5]	6668.4	100
Runoff	44.4	[38.5]	444.4	6.7
Evapotranspiration	332.7	[57.6]	3327.2	49.9
Cover structures				
Drainage collected from drainage layer	289.5	[83.1]	2895.3	43.4
Percolation/leakage through mineral sealing layer	0.004	[0.0009]	0.036	0.001
Average head on top of geomembrane	0.077	[0.02]	---	---
Foundation structures				
Drainage collected from drainage layer	0.004	[0.0009]	0.036	0.001
Percolation/leakage through mineral sealing layer	0.00006	[0]	0.0006	0.00001
Average head on top of geomembrane	0.000001	[0]	---	---
Water storage				
Change in water storage	0.14	[36.6]	1.42	0.02

Table 5-5. Output for the reference structure with double precipitation relative to a 20-year time period.

Average annual totals for years 1-20				
	mm	[std dev]	m^3	%
Precipitation	1333.7	[244.9]	13336.7	100
Runoff	178.5	[112.8]	1785.0	13.4
Evapotranspiration	399.6	[60.2]	3995.5	30.0
Cover structure				
Drainage collected from drainage layer	755.6	[218.8]	7555.7	56.65
Percolation/leakage through mineral sealing layer	0.008	[0.002]	0.084	0.001
Average head on top of geomembrane	0.200	[0.06]	---	---
Foundation structures				
Drainage collected from drainage layer	0.008	[0.002]	0.084	0.001
Percolation/leakage through mineral sealing layer	0.00006	[0]	0.0006	0.000005
Average head on top of geomembrane	0.000002	[0]	---	---
Water storage*				
Change in water storage	0.038	[75.8]	0.37	0.003

**Volumetric water content in the constructed layers*

In Table 5-6, results are shown from analyses where different repository designs were tested. The purpose was to explicitly demonstrate how the properties of the geomembranes and mineral sealing layers affect the functionality of the repository structure. Analyses were also performed without the geomembranes present, which can also correspond to the lowest possible quality of geomembrane installation. Additionally, effects of different saturated hydraulic conductivities and thicknesses of the mineral sealing layer were tested. These parameters are related to the quality of manufacture and installation of the mineral sealing material and the design of the mineral sealing layer. In all the analyses presented in Table 6, double precipitation was used.

The results show that when the geomembrane was removed from the cover (corresponding also to the lowest possible quality of installation), 2.3 % of the rainwater percolated/leaked through the mineral sealing layer and reached the waste layer. If there was no geomembrane in the cover and the drainage layer hydraulic conductivity decreased from 3E-3 m/s to 3E-7 m/s (corresponding to some blocking of the drainage), 5.9 % of the rainwater percolated/leached through the mineral sealing layer.

Almost no effect was found if the mineral sealing layer thickness was increased from 500 mm to 1000 mm, but if the mineral sealing layer had a saturated hydraulic conductivity of 1E-10 m/s instead of 1E-9 m/s the percentage of water percolating/leaking through the mineral sealing layer was 0.2 % which was remarkably lower than 2.3 % with the higher hydraulic conductivity. Clearly the hydraulic conductivity of the sealing layer has a significant effect on the long-term water control of the repository and therefore it can be recommended from a generic safety standpoint that the target hydraulic conductivity for mineral sealing layers in a near surface repository should be ~ 1E-10 m/s instead of 1E-9 m/s.

If no geomembrane was present in the cover and the saturated hydraulic conductivity of the mineral sealing layer was set to 1E-8 m/s, 15.6 % of water reached the waste layer. However, this water was effectively collected in the drainage layer of foundation with the reference layer properties, and only <<1 % percolated/leaked through the mineral sealing layer of the foundation. This scenario was then tested by increasing the thickness of the mineral sealing layer from 500 to 1000 mm. Again, almost no effect was found and 15.5 % of water percolated/leaked through the mineral sealing layer of the cover.

Finally, a scenario was tested where the geomembrane was absent from both the cover and the foundation. As a result, 2.3 % of water percolated/leaked through the mineral sealing layer in the cover and 2.0 % of the water percolated/leaked through the mineral sealing layer of the foundation. If the thickness of mineral sealing layer in the foundation was increased, almost no effect was found and 2.0 % of the water percolated/leaked through the mineral sealing layer.

Table 5-6. HELP model analyses with the basic structure and different scenarios that are defined in the topmost row. In all analyses, double precipitation was used. The resulting values are percent of initial precipitation.

	Basic structure with double precipitation	Cover: no geomembrane (corresponds also to the lowest quality of membrane installation)	Cover: no geomembrane and drainage layer hydraulic conductivity (k) decreased from $3*10^{-3}$ to $3*10^{-7}$ m/s	Cover: no geomembrane, mineral sealing layer thickness increased from 500 mm to 1000 mm	Cover: no geomembrane, mineral sealing layer k decreased from 10^{-9} to 10^{-10} m/s	Cover: no geomembrane, mineral sealing layer k increased from 10^{-9} to 10^{-8} m/s	Cover: no geomembrane, mineral sealing layer k increased from 10^{-9} to 10^{-8} m/s, and thickness increased from 500 mm to 1000 mm	No geomembrane in the cover and foundation	No geomembrane in the cover and foundation and in the foundation, mineral sealing layer thickness increased from 1000 mm to 2000 mm
Runoff	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Evapotranspiration	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Cover									
Drainage collected from drainage layer	56.7	54.4	50.7	54.4	56.4	41.1	41.1	54.4	54.4
Percolation/leakage through mineral sealing layer	0.001	2.32	5.9	2.30	0.24	15.6	15.5	2.31	2.31
Foundation									
Drainage collected from drainage layer	0.001	2.31	5.9	2.30	0.23	15.6	15.5	0.30	0.30
Percolation/leakage through mineral sealing layer	0.000005	0.00004	0.00009	0.00004	0.00001	0.001	0.001	2.01	2.01
Water storage									
Change in water storage	0.003	0.003	0.02	0.003	0.007	0.003	0.003	0.003	0.003

According to the HELP model analysis, the reference structure defined in this report was effective in preventing the rainwater percolating/leaking through the sealing layers of the landfill type repository structure. However, it was noticed that it is important that the drainage systems and sealing layers including the geomembranes (or other corresponding solutions) are properly manufactured and installed so that they would meet their target properties in a long-term perspective. Based on the analysis, increasing precipitation did not lead to increasing percolation/leakage through the sealing layers with the reference design, but rather more runoff was estimated. The amount of runoff and evapotranspiration can also be affected by the properties of the topmost soil layer as well as the surface conditions. The analyses also showed that geomembranes were effective in preventing fluid transport if their target properties are met. The thickness of the mineral sealing layer was not found to have a significant effect on the amount of percolating/leaking water, whereas saturated hydraulic conductivity played a major role, especially in scenarios where no geomembranes were present. It should be noted that thicker layers would be less susceptible to defects. It is also significant that the drainage is functioning properly. Blocking of the drainage could lead to greater amount of fluid transport through the cover and foundation, which was seen in the analysis. In summary, analysis with the HELP model provided an overview of the effects of different design options and material properties on the function of the landfill type of repository. This type of analysis could be useful in preliminary planning phases. The lifetime of the repository and its designed properties should be taken into account in each design case and functioning of the system should be monitored sufficiently.

6. Geotechnical laboratory tests performed in 2020

6.1 Materials

The materials studied in KYT SURFACE phase 2 are presented in Table 6-1. The geotechnical laboratory tests performed for these materials are discussed further in Sections 6.2 (Methods) and 6.3 (Results).

Table 6-1. Materials used in KYT SURFACE phase 2 tasks 1 (Column tests for radionuclide transport and behaviour), 2 (Biodegradation of Waste and Steel Corrosion) and 3 (Performance of barrier materials).

Material	**Product information given by the producer**	**Analysis performed in KYT SURFACE task 3 (Performance of engineered barriers, geotechnical tests performed in 2020)**	**Usage in KYT SURFACE tasks**
Rock flour (0-4 mm) = fine-grained crushed rock	Mineralogical composition: Mafic rock type, diabase. Plagioclase (47%), clinopyroxene (33%), olivine (17%), opac (2%), accessory minerals (<1%). Producer: Fescon/Maanrakennus	Water content Grain size distribution	Task 1: Column tests for radionuclide transport and behaviour at HY, studied as single component and mixed with bentonite (6 w-%) Task 2: Biodegradation of Waste and Steel

	Jouko Kärkkäinen Oy, Nakkilan murskaus.		Corrosion, studied as single material
Crushed rock (0-16 mm)	Mineralogical composition: Felsic rock type, granitoid typically consisting of quartz, feldspars, mica and accessory minerals. Producer: RUDUS	Water content Grain size distribution	Task 2: Biodegradation of Waste and Steel Corrosion
Crushed rock (0-2 mm)			Task 1: Column tests for radionuclide transport and behaviour at VTT, mixed with bentonite (6 w-%)
Bentonite	LUXGEL EG 28. Na-activated Ca-bentonite from Egypt. Powder: max 5% > 75 µm. Datasheet: Montmorillonite >75%, moisture content 10% (+/-2%), methylene-blue adsorption > 350 mg/g, swelling index 28 ml (2 g/100 ml/2 h), CEC 85 meq/100 g. Importer Lux Oy	Water content	Used in tasks 1 and 2, both at HY and VTT
Mixture of rock flour and bentonite (6%)	See above information on rock flour and bentonite	-	Used in task 1 at HY
Mixture of crushed rock (2 mm) and bentonite (6%)	See above information on crushed rock and bentonite	-	Used in task 1 at VTT
Mixture of crushed rock (16 mm) and bentonite (6%)	See above information on crushed rock and bentonite	Proctor compaction and hydraulic conductivity tests	Used in task 2
Mixture of crushed rock (16 mm) and bentonite (8%)		Proctor compaction and hydraulic conductivity tests	-
Mixture of crushed rock (16 mm) and bentonite (10%)		Proctor compaction and hydraulic conductivity tests	-

6.2 Methods

6.2.1 Water content

Geotechnical water content (w, %) is related to the quantity of water contained in a material and is defined as the mass of water (m_w, g) divided by the mass of dry solids (m_s, g) and the result is expressed as a percent following the instructions given in CEN ISO/TS 17892-1:2014. Geotechnical investigation and testing. Laboratory testing of soil. Part 1: Determination of water content.

6.2.2 The Modified Proctor Compaction Test

The Modified Proctor Compaction Test establishes the optimal water content at which a given soil type will become most dense under a controlled compactive force (SFS-EN 13286-2). In the Proctor test, moist soil is compacted into a mould in five layers of approximately equal mass with each layer being given 25 blows from a 4.9 kg rammer dropped from a height of 450mm above the soil. The blows must be distributed uniformly over the surface of each layer.

6.2.3 The Hydraulic Conductivity Test

The hydraulic conductivity of fine-grained soils is determined with the falling-head method (ASTM D5084 -16a, Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter). In the falling-head method, the soil sample is first saturated under a specific head condition. The water is then allowed to flow through the soil in a flexible wall permeability cell without adding any water, so the pressure head declines as water passes through the specimen. Before the hydraulic conductivity test, the specimen is compacted to 90% Proctor density with optimal water content determined by the Modified Proctor test.

6.3 Results

6.3.1 Water content

Water contents of the test materials are presented in Table 6-2.

Table 6-2. Water content of the KYT SURFACE phase 2 test materials.

Sample	**Water content (%)**	
Crushed rock	Sample	Average
	1,7	
	2,9	
	2,4	
	2,2	
	2,3	
	2,2	2,3
Bentonite EG28	Sample	Average
	11,5	
	11,4	
	11,7	
	11,4	
	11,5	
	11,4	
	11,3	
	11,1	
	11,3	11,4
Rock flour	Sample	Average
	0,6	
	0,6	
	0,6	0,6

6.3.2 Grain size distribution

The grain size distribution of the crushed rock and the rock flour was determined by the dry sieving method defined in SFS-EN 933-1 "*Kiviainesten geometristen ominaisuuksien testaus. Osa 1: Rakeisuuden määrittäminen, seulontamenetelmä*". The grain size distributions are given in Figures 6-1, 6-2 and 6-3.

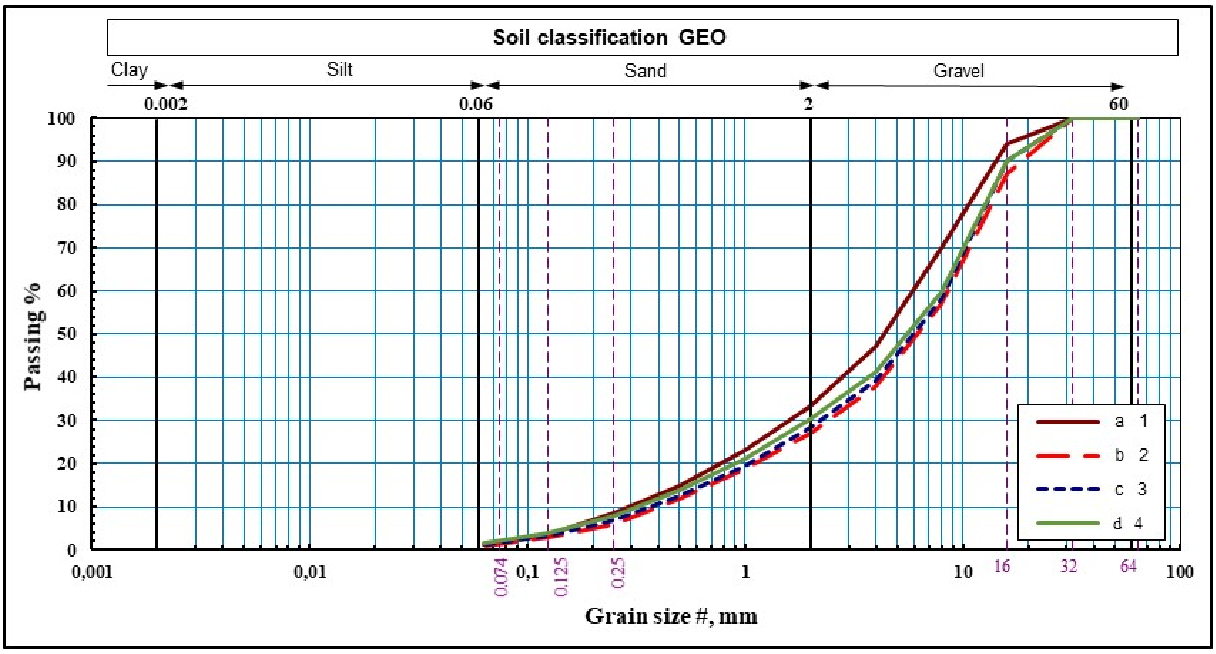

Figure 6-1. Grain size distribution of the crushed rock (0-16 mm). The proportion of fine particles (<0.063 mm) varied between 1.0 - 1.7% with the average being 1.3%.

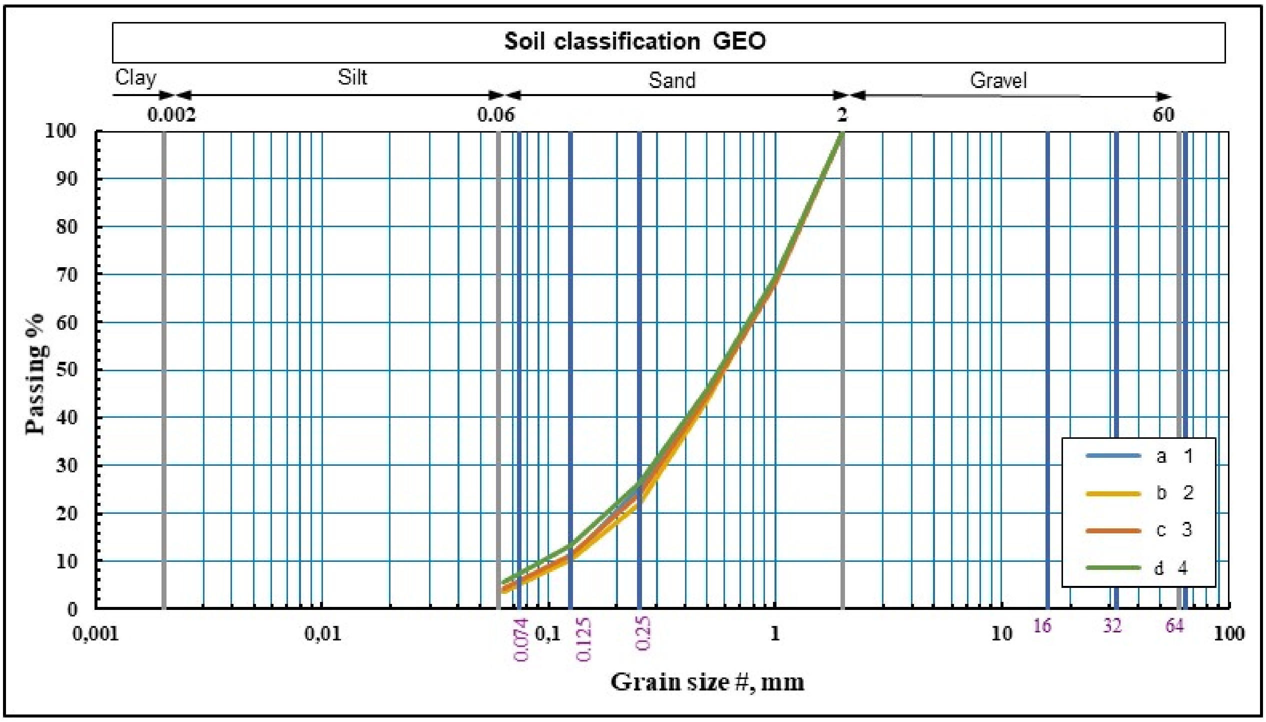

Figure 6-2. Grain size distribution of the crushed rock with maximum grain size limited to 2 mm. The proportion of fine particles (<0.063 mm) varied from 3.5 - 5.7% with the average being 4.3%.

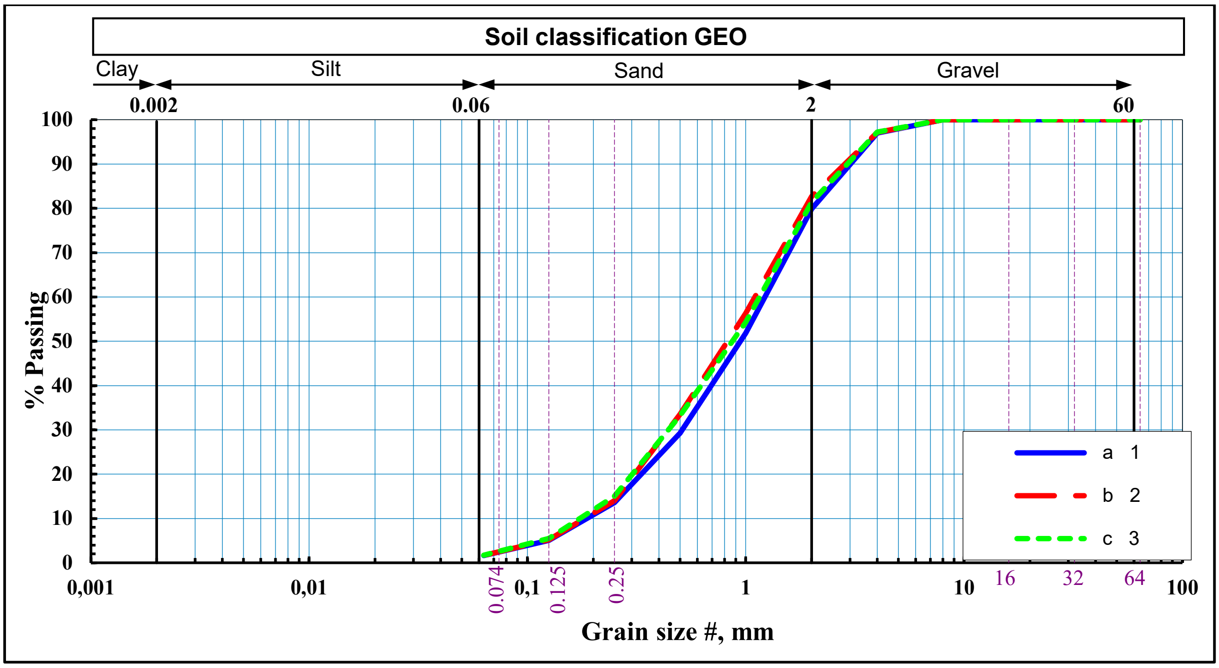

Figure 6-3. Grain size distribution of the rock flour (0-6 mm). The proportion of fine particles (<0.063 mm) varied from 1.6 - 1.7%.

6.3.3 Proctor compaction tests

Proctor Compaction Tests were performed for the crushed rock bentonite mixtures. The maximum dry density and optimal moisture content (SFS-EN 13286-2) were determined (Figures 6-4 to 6-8).

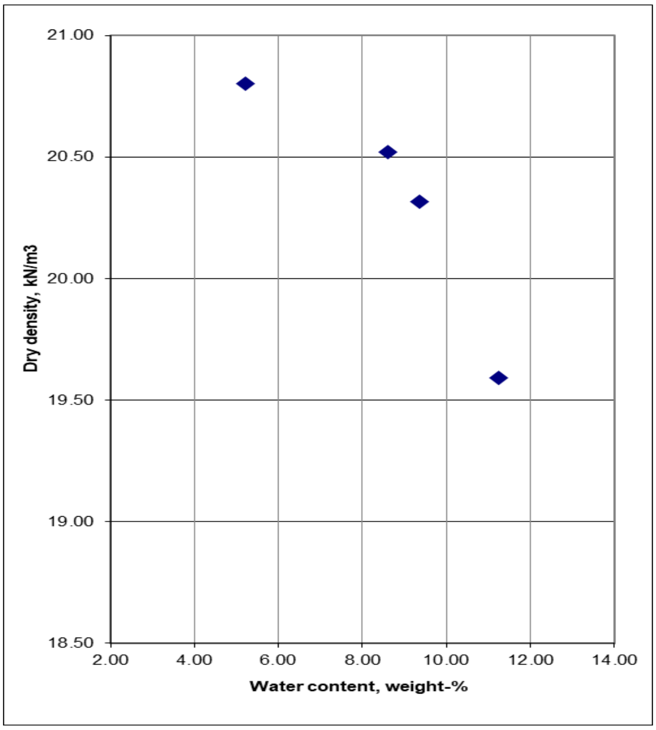

Figure 6-4. Water content vs. dry density of the crushed rock bentonite mixture with bentonite content of 6 weight-%.

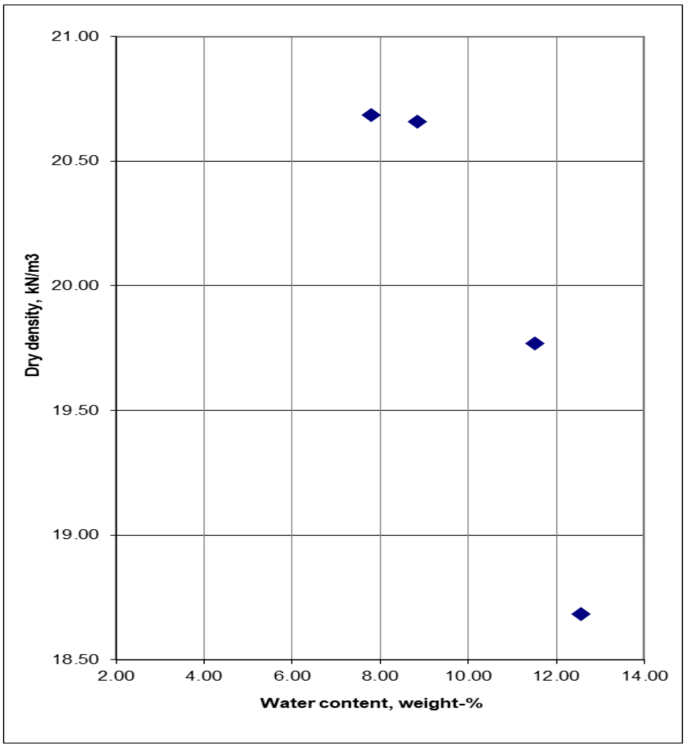

Figure 6-5. Water content vs. dry density of the crushed rock bentonite mixture with bentonite content of 8 weight-%.

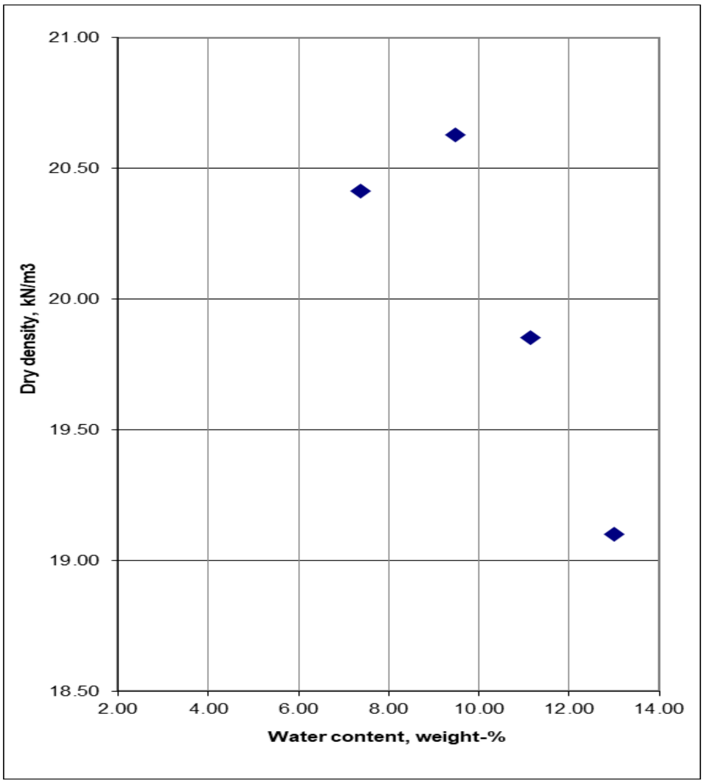

Figure 6-6. Water content vs. dry density of the crushed rock bentonite mixture with bentonite content of 10 weight-%.

The maximum dry densities are plotted as a function of bentonite content in Figure 6-7.

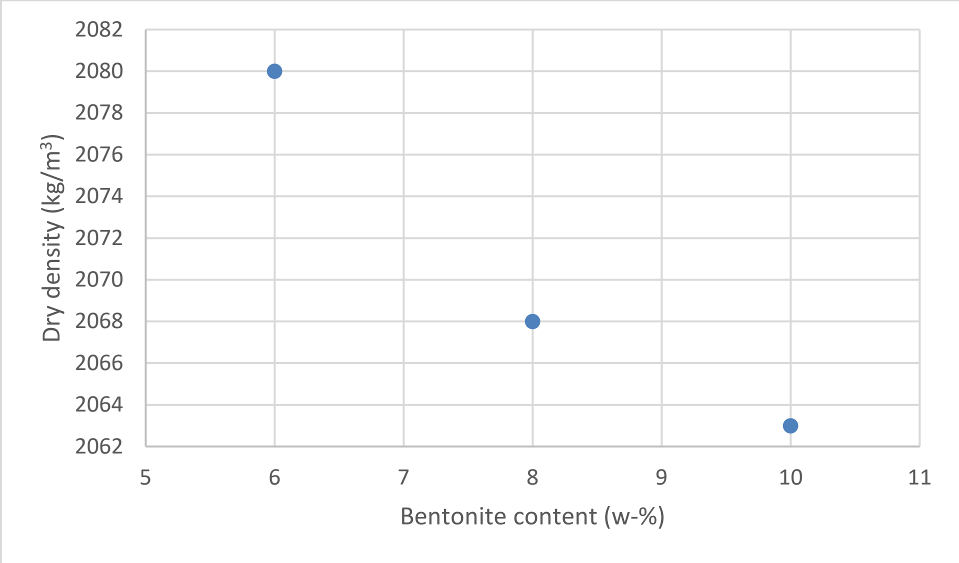

Figure 6-7. Maximum dry density as a function of bentonite content for the crushed rock/bentonite mixtures at optimal water content.

The maximum dry densities, 90% Proctor densities and optimal moisture contents of the crushed rock bentonite mixtures with different bentonite contents are presented in Table 6-3.

Table 6-3. Maximum dry densities, 90% Proctor densities and optimal moisture contents of the crushed rock bentonite mixtures with different bentonite contents.

Bentonite content, weight-%	Maximum dry density, kN/m^3	Optimal water content, %	90% Proctor density, kN/m^3
6.0	20.80	5.2	18.72
8.0	20.68	7.8	18.62
10.0	20.63	9.5	18.57

6.3.4 Hydraulic conductivity tests

The set of measured hydraulic conductivities and corresponding dry densities for the tested crushed rock bentonite mixtures (with bentonite contents of 6%, 8% and 10%) are presented in the Table 6-4 and in Appendix 1. The tests were performed with distilled water.

Table 6-4. Measured hydraulic conductivities and corresponding dry densities of the tested crushed rock bentonite mixtures (bentonite content of 6%, 8% and 10%).

Bentonite content of the mixture (%)	Dry density (kg/m^3)	Dry density, kN/m^3	Hydraulic conductivity (m/s)
6	1860	18.56	5.9×10^{-10}
8	1870	18.67	3.3×10^{-10}
10	1880	18.79	1.9×10^{-10}

7. Discussion, recommendations and remaining uncertainties

Near surface repositories, rather than underground facilities, are a potential new disposal option in Finland for very-low-level radioactive waste (VLLW). TVO is currently considering a landfill-type of design for a near surface repository for the first Finnish near surface repository. The design is based on that used in Sweden for similar geological and meteorological conditions. The design is also similar to those for hazardous waste landfills consisting of a cover layer, waste fill and foundation layer with different safety functions, aiming at minimising the amount of water infiltrating into the waste fill, controlling gases generated in the waste, minimising the amount of contaminated leachate water that will eventually reach the ground water and maintaining mechanical stability of the landfill. In a normal or hazardous waste landfill, the design requires some active monitoring and maintenance of the drainage systems before and after closure of the facility (SYKE 2008). Considering that underground repositories for radioactive waste typically rely on passive safety through multiple engineered barriers (IAEA 2006), the need for active monitoring (of collected leachates) and maintenance (of filter layer) after closure of a near surface repository shall be defined based on the characteristics and evolution of the waste (decay of radioactivity and amount of waste that is considered as hazardous). The need for an enhanced passive design of the repository (in comparison to a hazardous waste landfill design) is also something that should be discussed further.

The numerical simulations performed for this report confirm the importance of the drainage system for the performance of a landfill-type repository, as has been identified also for normal/hazardous waste landfills (SYKE 2008). Especially the role of geomembranes is important for controlling the amount of water reaching the waste and the amount of leachate water reaching the groundwater reservoir. In order to maintain the function of the drainage system as long as possible, the following should be considered:

- Careful installation of the geomembrane and adjacent filter layers to avoid breakage of the layer at installation and operation.
- Maintenance/flushing of the drainage pipes during the operational period and active post-closure period to prevent clogging. Clogging of the filter layers is also a factor to be taken into account.
- Separate drainage system for the potentially contaminated leachate waters and active monitoring during the operational period and active post-closure period (the need of which will be defined based on the evolution and characteristics of the waste).
- Preventing tree roots from reaching the geotextile in the cover layer. To be considered further is the thickness of the top layer and/or active measures during the active post closure period to remove vegetation/trees.
- Material selection and inclination of the top layer to enhance surface runoff.
- Maintenance of the cover structures if the monitoring shows the need to enhance the performance of the barriers.

The role of the mineral sealing layer in controlling the water flow in a repository is not critically important in the beginning of the repository lifetime. However, considering that the long-term performance of the geomembrane and the drainage layer can be expected to deteriorate, the role of the mineral sealing layers increases with respect to water control within the repository. In addition, the mineral sealing layer and the material placed around the waste containers are important for their potential to sorb certain radionuclides. In considering the design of the sealing layers, the following shall be considered:

- The thickness of the sealing layer (in the foundation layer) shall take the local site conditions into account including the natural barrier thickness and permeability. For hazardous waste landfills, the thickness of the mineral sealing layer (at the foundation) shall be at least 1 m in case the natural barrier thickness is < 5 m and it should have a hydraulic conductivity of k $\leq 1 \times 10^{-9}$ m/s. The same recommendation can also be given for a near surface repository. A thinner sealing layer thickness (in foundation layer) cannot be recommended since the thickness can also compensate for defects present at installation of the sealing layer.

- In case the natural barrier material has high permeability, a sealing layer (at the foundation layer) is needed in any case, as well as vertical cut-off walls to isolate the landfill area hydraulically from its environment.

- In areas with very thin overburden (in practice exposed rock surface), special structures, as in the Ämmässuo example case (see section 3.1), should be considered.

The hydraulic conductivity of the sealing layer is an important performance factor. For normal/hazardous waste landfills the limit is $<1 \times 10^{-9}$ m/s. However, to ensure long-term passive safety and water control of the repository when, potentially, the drainage layer and geomembrane no longer perform as designed, it is recommended that the hydraulic conductivity target for near surface repository sealing layer should be $\sim 1 \times 10^{-10}$ m/s rather than 1×10^{9} m/s. This conclusion is supported by the numerical modelling performed for this report showing that the hydraulic conductivity of the sealing layer has significant effect on the overall system performance. In practice, the target hydraulic conductivity can be attained by adjusting the amount of bentonite in the aggregate mixture so that the target hydraulic conductivity is reached at 90% Proctor dry density (achievable dry density in field conditions). In practice this may mean that the bentonite content varies from 6 to 10%, but the hydraulic conductivity should always be confirmed by measurement on a case-by-case basis. In addition, for ensuring a sufficiently homogeneous distribution of bentonite within the mixture in field conditions, 1-2% of extra bentonite (in w-%) is typically added on top of the optimum bentonite content.

- The bentonite material should have a high smectite content (e.g., >80%) and the dominant cations should be Na^{+} (natural or ion exchanged bentonite) for the best possible performance at the early stages of the repository lifetime. Whether the Na^{+} dominance changes in the long-term to Ca^{2+} and/or $Mg^{2+}$and to what extent under prevailing conditions is not yet known and remains to be studied further for safety assessment purposes.

- The effect of surface processes (freezing/thawing and wetting/drying) should be taken into account if the foundation layer remains uncovered for long time-periods. Ideally the aggregate selected for the mineral sealing layers should be relatively insusceptible to frost. The effect of these processes on hydraulic conductivity will be studied further in the next phase of the KYT SURFACE project.

Remaining uncertainties in the design and performance of a near surface repository include:

- Radionuclide migration in the fill material around the waste packages and sealing layer materials. Tests are currently ongoing at VTT and at Helsinki University and these issues will be discussed in the following phase of the KYT SURFACE project.

- Design/service life of the repository is specified based on the characteristics of the waste (case specific nuclides, activity concentrations, decay and proportion of hazardous waste). The current assumption is several hundreds of years, e.g. 300 years. A design/service life for the first Finnish repository remains to be defined.

- Functions during the post-closure period and division into active and passive monitoring periods. What would be monitored and how often.

- Active maintenance performed during the post-closure period.
- Generation of gas from the waste. Based on early results from KYT SURFACE task 2 (to be reported separately), some gas is generated when the operational waste is in contact with water. In addition, the numerical modelling shows that water will be able to infiltrate through the cover layer into the waste, so maintaining the waste packages in totally dry conditions is not a realistic option in a landfill design. Further test results on gas generation will be available in late 2021. The results may have implications on a) design of the waste packages (semi-impermeable metal packages with sealed lids) and/or b) need for a system/structures for controlling generated gas. If the gas generation is slow enough, no special systems may be needed provided the cover materials (especially the geomembrane) are not entirely gas impermeable. If the gas generation is high, gas venting systems may be needed.
- Waste acceptance criteria (WAC) and waste packages are not yet defined in detail and may have effect on the design. For example, filling of the empty voids in the waste packages may be needed to be able to provide sufficient stability of the landfill (collapse of the waste packages should be avoided).
- Drainage wells/sedimentation pools and the handling of possible radioactivity of the leachate water.
- Effect of wetting/drying and freezing/thawing on the hydraulic properties of the sealing materials.
- Stability should not be an issue if the instructions for landfills are followed (SYKE 2002, 2008). However, effect of the site conditions (soil properties and homogeneity) and loading from the waste packages shall be studied for the designed repository by modelling. Concrete slab placed underneath the waste is one possibility in the design providing bearing capacity and also drainage function for the system.
- Retrievability has not been discussed, but should be possible, at least when the packages remain intact.
- Site specific risk evaluation with respect to effects of climate change (erosion, flooding).
- More extensive reuse and recycling of metals instead of disposal. Some metals are already reused or recycled when the radiation level of the material is under clearance levels or after decontamination and when the process is viable from practical or economic point of view. Some components such as tanks, pumps, motors and valves can be potentially reused in industry largely as they are. If no economic use is available, then the items can remain or be sent for disposal as conventional industrial waste (e.g., in a municipal landfill site) appropriate to their physical, chemical or toxic characteristics. Additionally, components whose activity levels can be reduced to acceptable levels can be used for restricted nuclear use or defined non-nuclear applications (e.g., for smelting or for recycling under predetermined conditions).

8. List of Appendices

Appendix 1. Hydraulic conductivity results

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Teknologian tutkimuskeskus VTT Oy
Harri Kivikoski

Tilaus 19.10.2020
Murskebentoniitti, vedenläpäisevyyskokeet

Näytteet

Tilaaja toimitti murskeen (10 kg) ja bentoniitin (5 kg) ämpäreissä. Näytteet otettiin vastaan Tampereen yliopistolla 27.10.2020. Toimitettujen näytteiden edustavuus on tilaajan vastuulla. Taulukossa 1 on tilaajan koekappaleille ilmoittamat tavoiteltavat bentoniittipitoisuudet, kuivatilavuuspainot ja vesipitoisuus tiivistyksessä. Tampereen yliopistolla näytteille tehtiin kokeet työnumerolla 248/2020.

Taulukko 1. Koekappaleiden tavoitetiedot vedenläpäisevyyskokeissa

Bentoniitin osuus	*tiivistysvesipitoisuus* w_{opt}	γ_d
paino-%	%	kN/m³
6,0	5,2	18,72
8,0	7,8	18,62
10,0	9,5	18,57

Näytteiden esikäsittely

Bentoniitin ja murskeen vesipitoisuus määritettiin. Murske ja bentoniitti sekoitettiin keskenään niissä vallitsevissa vesipitoisuuksissa pyydettyjen kuivapainojen suhteissa. Kun murske ja bentoniitti oli sekoitettu keskenään, lisättiin ja sekoitettiin ionivaihdettu vesi, jotta saavutettaisiin Proctor-kokeella määritetty optimivesipitoisuus. Materiaalin vesipitoisuuden annettiin tasaantua suljetussa astiassa yön yli ennen koekappaleiden tekemistä

Testausmenetelmät

Vedenläpäisevyyskokeet tehtiin joustavaseinämäisessä sellissä vakiopainemenetelmällä standardin 17892-11:2019 mukaan.

Tulokset

Liitteessä 1 on esitetty koekappaleiden vedenläpäisevyyskuvaajat ja taulukossa 2 on esitetty määritetyt vedenläpäisevyyskertoimet 20 °C lämpötilassa. Vedenläpäisevyyskerroin määritettiin neljän viimeisen mittaustuloksen keskiarvona. Koekappaleet tehtiin ICT-kiertotiivistyslaitteistolla. Koekappaleen korkeutena käytettiin korkeutta konsolidoituneena ja halkaisijana koekappaleen alku-

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halkaisijaa. Kokeen loputtua, koekappaleen jännityksiä pienennettäessä (sellipaine, etu- ja takapaine) koekappale saattoi imeä itseensä lisää vettä ja laajentua ennen koekappaleen dimensioiden mittaamista kokeen jälkeen. Kokeessa käytettiin ionivaihdettua vettä. Koekappaleen keskimääräinen tehokas jännitys oli 50 kPa sellipaineen ollessa 200 kPa. Mittausten aikana keskimääräinen lämpötila oli 22,0 °C. Kyllästysasteen laskemisessa käytettiin oletuskiintotiheyttä ja B-arvoa ei mitattu.

Taulukko 2. Määritetty vedenläpäisevyyskerroin, k, koekappaleen kuivatilavuuspaino, γ_d ja hydraulinen gradientti, i, joissa vedenläpäisevyyskerroin määritettiin.

Koekappale (bentoniitti %)	γ_d kN/m^3	k, (20°C) m/s	i
O248_V1 (6%)	18,56	$5{,}9 \cdot 10^{-10}$	30,4
O248_V2 (8 %)	18,67	$3{,}3 \cdot 10^{-10}$	30,4
O248_V3 (10 %)	18,79	$1{,}9 \cdot 10^{-10}$	30,5

Kokeet tehtiin 12.11. – 9.12.2020. Alustavia koetuloksia lähetettiin 30.11.2020. Tulokset pätevät ainoastaan testatuille näytteille. Testausselostuksen saa kopioida ainoastaan kokonaisuudessaan. Mahdollisesti jäljelle jääneitä näytteitä säilytetään kolme kuukautta testausselostuksen päiväyksestä.

Projektipäällikkö, DI — Nuutti Vuorimies

Erikoislaboratoriomestari — Niko Levo

JAKELU — Tilaaja
Tampereen yliopisto

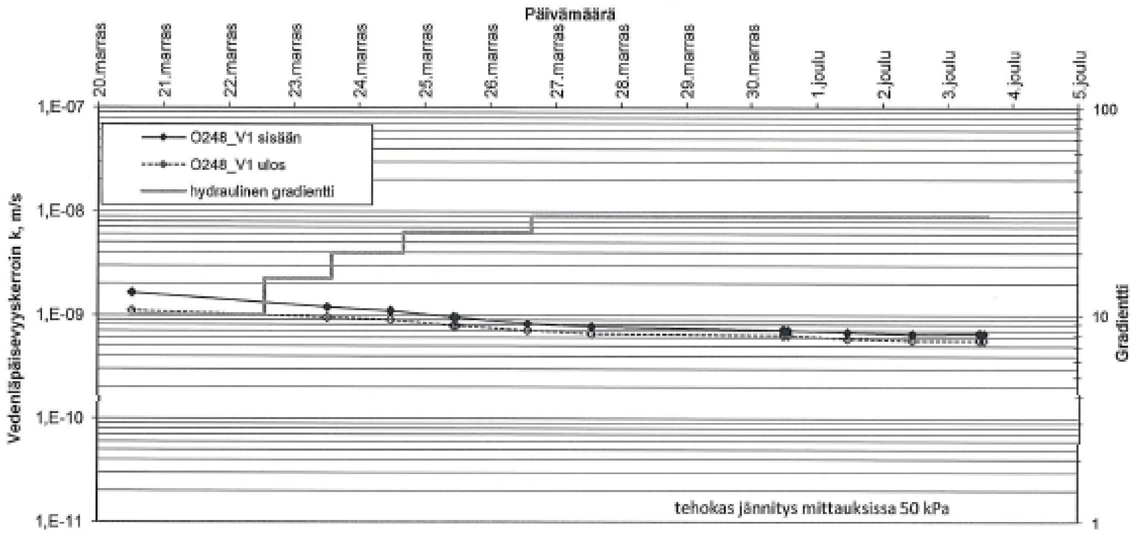
LIITTEET: — Liite 1. Vedenläpäisevyyskoetulokset (3 sivua)

VEDENLÄPÄISEVYYDEN MÄÄRITYS PEHMEÄSEINÄMÄISELLÄ MENETELMÄLLÄ KOLMIAKSIAALIKOESELLISSÄ

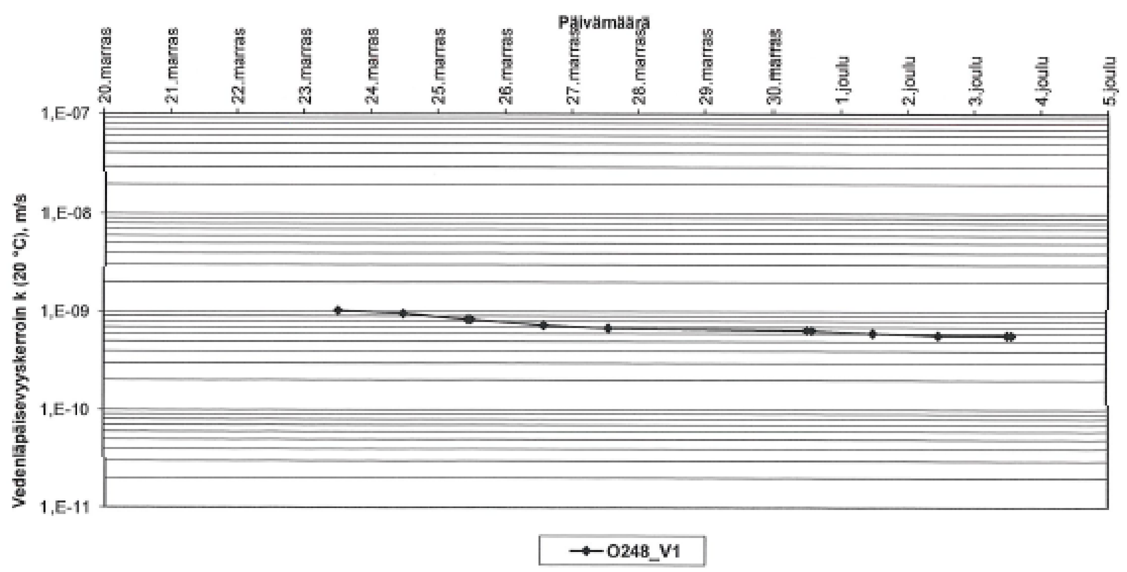
Tampereen yliopisto **Tutkimuskeskus Terra** **PL 600 33014 Tampereen yliopisto**	**ASIAKAS** Teknologian tutkimuskeskus VTT Oy **KOHDE** Moreenibentoniitit **TYÖNUMERO** 248/2020	HUOM!

TIEDOT ENNEN KOETTA			TIEDOT KOKEEN JÄLKEEN (lask ρ_s=2.65 g/cm^3)		
Näytteen korkeus	100,0	mm	Näytteen korkeus konsolidoitunee	100,0	mm
Näytteen halkaisija	100,0	mm	Näytteen halkaisija (mitattu)	100,0	mm
Näytteen pinta-ala	78,5	cm^2	Näytteen pinta-ala	78,5	cm^2
Tilavuus	785	cm^3	Tilavuus	785	cm^3
Paino ennen koetta	1576,4	g	Näytteen paino kokeen jälkeen	1684,6	g
			Näytteen kuivapaino	1486,1	g
Vesipitoisuus ennen koetta	6,1	%	Vesipitoisuus kokeen jälkeen	13,4	%
Näytteen märkäirtotiheys	2007	kg/m^3	Näytteen märkäirtotiheys	2145	kg/m^3
Märkätilavuuspaino	19,7	kN/m^3	Märkätilavuuspaino	21,0	kN/m^3
Näytteen kuivairtotiheys	1892	kg/m^3	Näytteen kuivairtotiheys	1892	kg/m^3
Kuivatilavuuspaino	18,56	kN/m^3	Kuivatilavuuspaino	18,56	kN/m^3
Kokoonpuristuma	0,0	mm	Näytteen kyllästysaste	88	%
Korkeus konsolidoituneena	100,0	mm			

Näytteen tunnus	O248_V1	
Piste:	6 % bentoniitti	
Syvyys:	-	
Valmistuspvm:	17.11.2020	
VEDEN VIRTAUS: Q1= näytteeseen menevä tislattu vesi Q2=näytteestä tuleva vesi		
mediaani k (20 °C)	**5,8E-10**	m/s
keskim. k (20 °C)	**5,9E-10**	m/s
Mittaaja:	NL, ES	



Vedenläpäisevyys, hyväksytyt tulokset

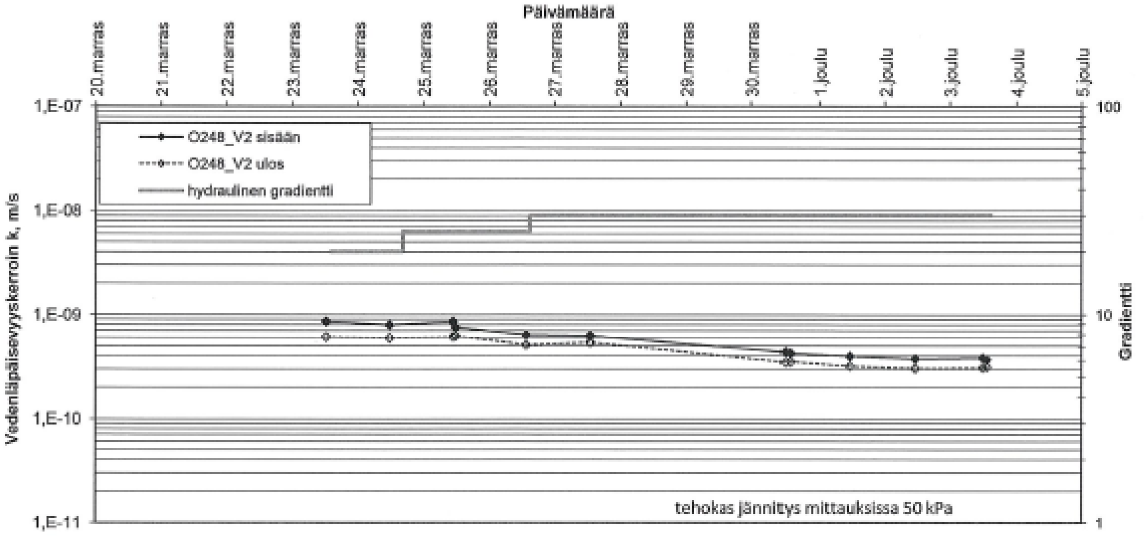


VEDENLÄPÄISEVYYDEN MÄÄRITYS PEHMEÄSEINÄMÄISELLÄ MENETELMÄLLÄ KOLMIAKSIAALIKOESELLISSÄ

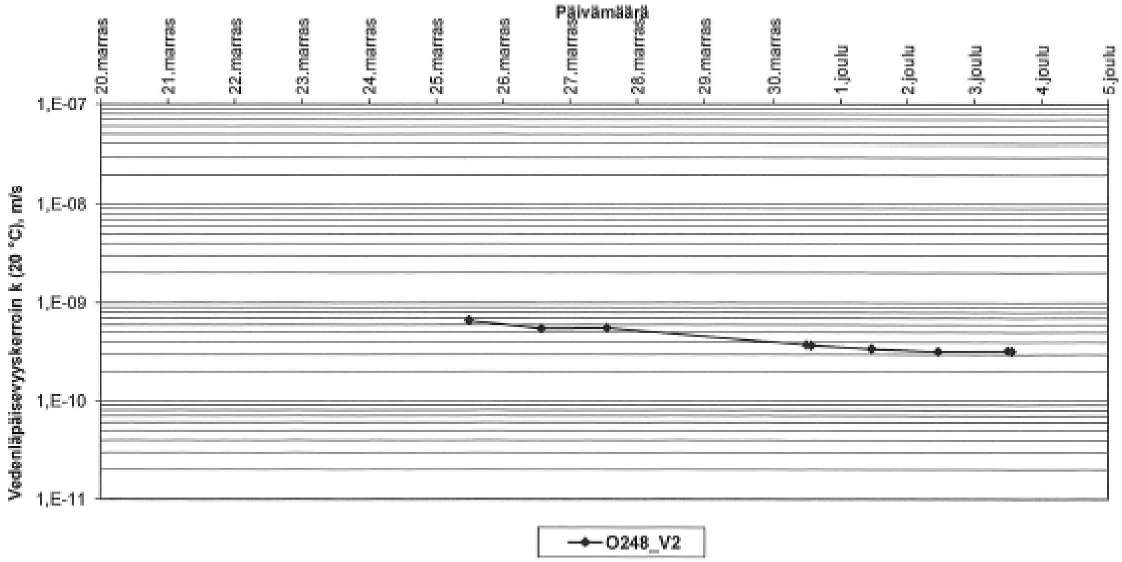
Tampereen yliopisto **Tutkimuskeskus Terra** **PL 600 33014 Tampereen yliopisto**	**ASIAKAS** Teknologian tutkimuskeskus VTT Oy **KOHDE** Moreenibentoniitit **TYÖNUMERO** 248/2020	HUOM!

TIEDOT ENNEN KOETTA			TIEDOT KOKEEN JÄLKEEN (lask ρ_s=2,65 g/cm³)		
Näytteen korkeus	99,9	mm	Näytteen korkeus konsolidoitunee	99,8	mm
Näytteen halkaisija	100,0	mm	Näytteen halkaisija (mitattu)	100,0	mm
Näytteen pinta-ala	78,5	cm²	Näytteen pinta-ala	78,5	cm²
Tilavuus	785	cm³	Tilavuus	784	cm³
Paino ennen koetta	1606,6	g	Näytteen paino kokeen jälkeen	1682,0	g
			Näytteen kuivapaino	1491,4	g
Vesipitoisuus ennen koetta	7,7	%	Vesipitoisuus kokeen jälkeen	12,8	%
Näytteen märkäirtotiheys	2048	kg/m³	Näytteen märkäirtotiheys	2146	kg/m³
Märkätilavuuspaino	20,1	kN/m³	Märkätilavuuspaino	21,1	kN/m³
Näytteen kuivairtotiheys	1901	kg/m³	Näytteen kuivairtotiheys	1903	kg/m³
Kuivatilavuuspaino	18,65	kN/m³	Kuivatilavuuspaino	18,67	kN/m³
Kokoonpuristuma	0,1	mm	Näytteen kyllästysaste	86	%
Korkeus konsolidoituneena	99,8	mm			

Näytteen tunnus	O248_V2	
Piste:	8 % bentoniitti	
Syvyys:	-	
Valmistuspvm:	17.11.2020	
VEDEN VIRTAUS: Q1= näytteeseen menevä tislattu vesi Q2=näytteestä tuleva vesi		
mediaani k (20 °C)	3,2E-10	m/s
keskim. k (20 °C)	3,3E-10	m/s
Mittaaja:	NL, ES	



Vedenläpäisevyys, hyväksytyt tulokset



VEDENLÄPÄISEVYYDEN MÄÄRITYS PEHMEÄSEINÄMÄISELLÄ MENETELMÄLLÄ KOLMIAKSIAALIKOESELLISSÄ

Tampereen yliopisto
Tutkimuskeskus Terra
PL 600 33014 Tampereen yliopisto

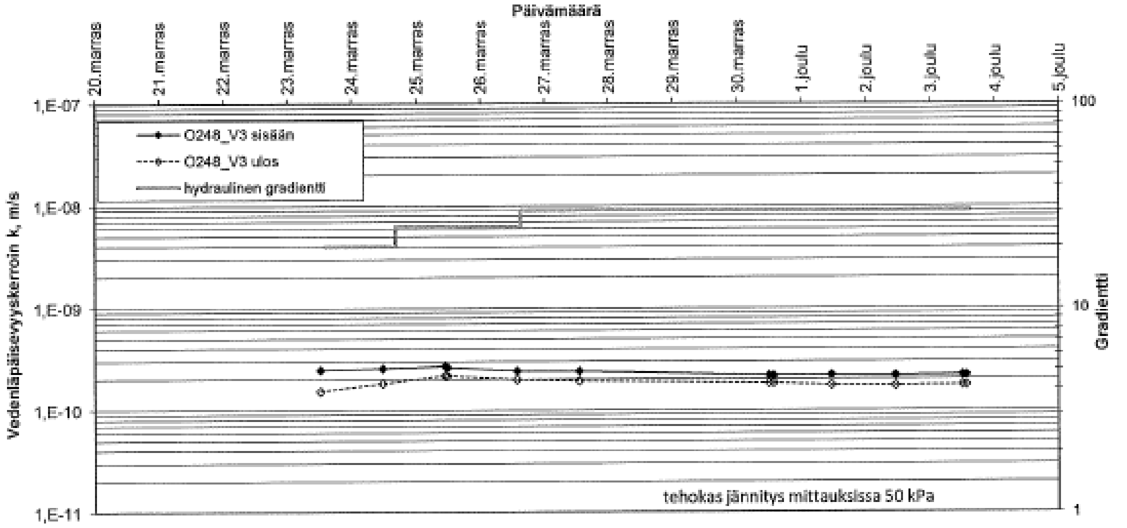
ASIAKAS	**Teknologian tutkimuskeskus VTT Oy**
KOHDE	**Moreenibentoniitit**
TYÖNUMERO	**248/2020**

HUOM!

TIEDOT ENNEN KOETTA			**TIEDOT KOKEEN JÄLKEEN** (lask ρ_s=2,65 g/cm³)		
Näytteen korkeus	99,8	mm	Näytteen korkeus konsolidoituneena	99,6	mm
Näytteen halkaisija	100,0	mm	Näytteen halkaisija (mitattu)	100,0	mm
Näytteen pinta-ala	78,5	cm²	Näytteen pinta-ala	78,5	cm²
Tilavuus	784	cm³	Tilavuus	782	cm³
Paino ennen koetta	1626,8	g	Näytteen paino kokeen jälkeen	1689,5	g
			Näytteen kuivapaino	1498,4	g
Vesipitoisuus ennen koetta	8,6	%	Vesipitoisuus kokeen jälkeen	12,8	%
Näytteen märkäirtotiheys	2075	kg/m³	Näytteen märkäirtotiheys	2160	kg/m³
Märkätilavuuspaino	20,4	kN/m³	Märkätilavuuspaino	21,2	kN/m³
Näytteen kuivairtotiheys	1912	kg/m³	Näytteen kuivairtotiheys	1916	kg/m³
Kuivatilavuuspaino	18,75	kN/m³	Kuivatilavuuspaino	18,79	kN/m³
Kokoonpuristuma	0,2	mm	Näytteen kyllästysaste	88	%
Korkeus konsolidoituneena	99,6	mm			

Näytteen tunnus		**O248_V3**
Piste:		10 % bentoniitti
Syvyys:		-
Valmistuspvm:		17.11.2020
mediaani k (20 °C)	**1,9E-10**	m/s
keskim. k (20 °C)	**1,9E-10**	m/s
Mittaaja:	NL, ES	

VEDEN VIRTAUS:
Q1= näytteeseen menevä tislattu vesi
Q2=näytteestä tuleva vesi



Vedenläpäisevyys, hyväksytyt tulokset