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KYT SURFACE

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KYT SURFACE
Complementary Considerations in Assessing performance of a Landfill-Type Near Surface Repository

Interim report 2021

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VTT

beyond the obvious

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Summary

Design basis and performance targets for a landfill type near surface repository have been examined as part of the KYT2022 SURFACE project, as well as the differences between a near surface repository and a landfill for hazardous waste landfill. The main difference comes from legislation and from ensuring passive safety for the repository after closure.

The effect of site conditions on the engineered barriers was studied from the perspective of low temperatures during winter in Finland. Numerical modelling shows that freezing of some or all of the engineered barriers in the cover layer can take place during a cold winter, especially in a situation when there is lack of sufficient snow coverage that would provide insulation. In normal and hazardous waste landfills, the frost shall not penetrate to the level of the mineral sealing layer. This leads to a recommendation of performing site and design specific numerical modelling on the frost penetration and, based on the results, considering cover top layer thicknesses that are more than the typical minimum 1 m used in normal and hazardous waste landfills. The potential impacts of post closure forestation also supports use of a thicker top layer to avoid puncture of synthetic liners by tree roots.

Limiting water inflow into the repository through the cover layer was identified as one of the key factors in ensuring long-term and passive safety for the near surface repository. This can be done by combining water tight synthetic liners with a mineral sealing layer. Limiting water flow to the repository decreases the quantity of formed leachates and can slow the generation of landfill gas.

The need for gas management systems depends on the rate at which gas is generated in the waste. In order to minimize gas generation from soft waste pallets containing organic waste, placing this waste into metallic packages was reviewed as an option. This would also enhance the mechanical stability of the repository.

Performance of the drainage systems at the foundation structure and collection and handling leachate waters was also assessed as part of this work. Some of the drainage is in any case needed for preventing accumulation of leachate water in the bottom of the repository. However, the effect of the drainage and leachate water collection system for post closure safety requires further considerations. If the cover layer works as expected and the waste is not in direct contact with the water, the generation of leachate water should be minimal.

Final recommendations concerning the design of the landfill type near surface repository will be summarised in 2022 including the analysis of results from KYT2022 SURFACE tasks 1 (radionuclide migration) and 3 (steel corrosion and microbial activity) on the repository design recommendations.

Confidentiality	Public

Espoo 14.2.2022

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Preface

This report was compiled in 2021 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 third phase of the KYT SURFACE project concerning near surface repositories in Finland.

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 Ville Rinta-Hiiro, Sami Naumer and Timothy Schatz (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).

The authors thank STUK (Arto Isolankila, Jarkko Kyllönen), TVO Oyj (Jere Tammela, Annukka Laitonen and Pasi Iivonen), Posiva Oy (Anne Kontula) and Fennovoima (Heikki Hinkkanen, Timo Siiskonen and Tuire Haavisto) and Fortum Oy (Pasi Kelokaski, Olli Nummi and Tapani Eurajoki) for comments and guidance during the planning and execution of the KYT SURFACE phase 2 project. We also thank Juuso Jokinen and Jyri Nummela from Fortum Oy for valuable discussions considering design and performance of hazardous waste landfills and presenting the current design of a hazardous waste landfill unit in Salo as an example.

The authors also thank the people working with KYT SURFACE phase 2 task 1 (Professor Gareth Law, Gianni Vettese HY and Melany Gouello, VTT) and task 2 (Minna Vikman, Pauliina Rajala). You are the best.

Espoo, Finland, 1.2.2022

Paula Keto, Ville Rinta-Hiiro, Sami Naumer and Timothy Schatz

Contents

List of abbreviations

Abbreviation	Explanation
AGM	Active gas management
GCS	Gas collection systems
HDPE	High-density polyethene
LFG	Landfill gas
VLLW	Very low-level radioactive waste
WAC	Waste acceptance criteria
NEA	Nuclear Energy Act
VLJ	Nuclear power plant waste (Voimalaitosjäte in Finnish)
MAJ	Low-level radioactive waste (Matala-aktiivinen jäte in Finnish)

1. Introduction

Very low-level radioactive waste (VLLW) is generated during the operation of nuclear power plants in Finland, both in Olkiluoto and Loviisa. VLLW consist of organic and metallic waste with <100 kBq/kg average concentration of radioactivity but more than the waste that can be released automatically from monitoring (<1 kBq/kg) or by case-by-case consideration (<10 kBq/kg) (Tammela, 2021). Additionally, in the future this type of waste will be generated as part of the decommissioning of a nuclear facility. Currently VLLW produced in Finnish nuclear power plants is disposed partly underground at a depth of ~100 m in intermediate depth geological repositories (Voimalaitosjäteluola and matala-aktiivinen jäte in Finnish (VLJ-cave, MAJ-silos)) and partly in a landfill located in Olkiluoto to be closed in near future (Tammela, 2021). Since the Nuclear Energy Act (990/1987) allows the disposal of VLLW in a near surface repository, using this option would save valuable underground space for waste with a higher level of radioactivity.

Near surface repositories have not yet been built in Finland and the basis for the design has been under discussion as part of the SURFACE project (Keto et al., 2019; Keto et al., 2020). In general, when VLLW is produced during the generation of nuclear energy it is regulated under the Nuclear Energy Act (NEA) (990/1987). The basic principles considered for any repository for nuclear waste are applied, including defence in depth and consecutive and mutually complementary barriers (STUK Y/4/2018, sections 13, 14 and 30), however considering a graded approach (STUK 2019). For short-lived VLLW placed in a near surface repository, the entry of the radioactive substances into the environment shall be prevented effectively for at least several hundreds of years (STUK Y/4/2018, section 32). Currently the service life estimated for the VLLW near surface repository is ~300 years based upon half-lives of the short-lived radionuclides contained by the VLWW (~30 years). During this time, the barriers placed in the repository shall be able to withstand the conditions prevailing near surface in Finland including precipitation, ground frost and phenomena linked to climate change including sea-level rise and flooding in coastal areas, increased precipitation, stormwater flooding, drying of structures and increased risks for forest and ground fires (Keto et. al 2019). Since the safety of the repository cannot rely on active monitoring or maintenance after closure and the ageing of barriers will will gradually change their performance with time, the design should be robust enough to provide sufficient isolation and containment for long periods of time. The long term-safety of the repository may not rely on institutional control as stated in the NEA. This may be in some contradiction with international guidelines (IAEA, 2011) stating that near-surface repositories could have institutional control after the closure up to hundreds of years. The form of the institutional control has not been defined, but could include, for example, land usage restrictions or monitoring to ensure that the barriers perform as expected.

Currently, TVO plans to build the first Finnish near surface repository at Olkiluoto and has evaluated the potential environmental impact of the facility (AFRY Finland Oy, 2020; TVO & Afry, 2021). The planned near surface repository at Olkiluoto will be used for disposal of operational VLLW, but the possibility of extending the repository at a later date for disposal of decommissioning waste has also been considered in the plans (TVO & Afry, 2021). The license application for construction of the facility has not yet been submitted (situation as of 10/2021). Operations are planned to start during 2023-2024 (AFRY Finland Oy, 2020; TVO & Afry, 2021). Fennovoima is also planning to build a near surface repository in Pyhäjoki (TEM, 2021) but those plans are less advanced.

This report is an interim report for the SURFACE project and the main purpose of this report is to discuss the required performance of the landfill-type of a near surface repository and give recommendations for the design. As part of this work, this report presents results on effect of freezing and thawing on engineered barriers, gas control systems available for handling possible gas emissions and strategies for handling of leachate waters monitoring and post-closure safety.

1.1 Scope, structure and limitations of this document

The scope of this report is to:

- Further discuss, describe and analyse the performance of a landfill-type near surface repository and discuss safety functions required for engineered barriers
- Study further the effect of freezing and thawing on performance of mineral sealing materials,
- Contribute starting data to the safety case concerning infiltration of water through the engineered barriers, and
- Provide recommendations for the design and identify remaining knowledge gaps.

The methods used for covering the scope of this report are a literature study, numerical modelling and geotechnical tests.

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 discussed in the next phase.

2. Expected performance of a near surface repository

The design of a landfill-type near surface repository resembles the design defined for hazardous waste landfills defined by the Finnish Environment Institute (SYKE 2002, 2008), see Figure 2-1 and Figure 2-2.

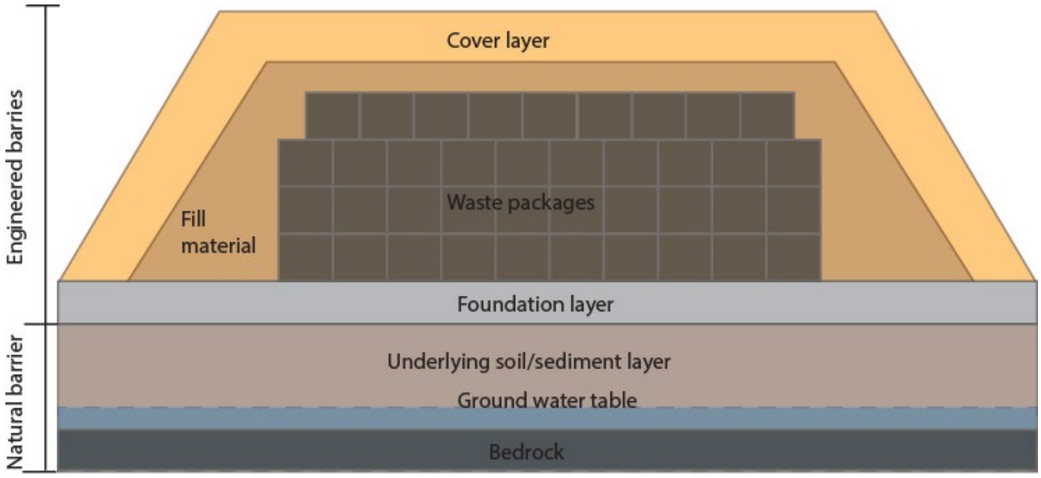


Figure 2-1. Main barriers in a landfill-type near surface repository. Figure from Keto et al. (2020).

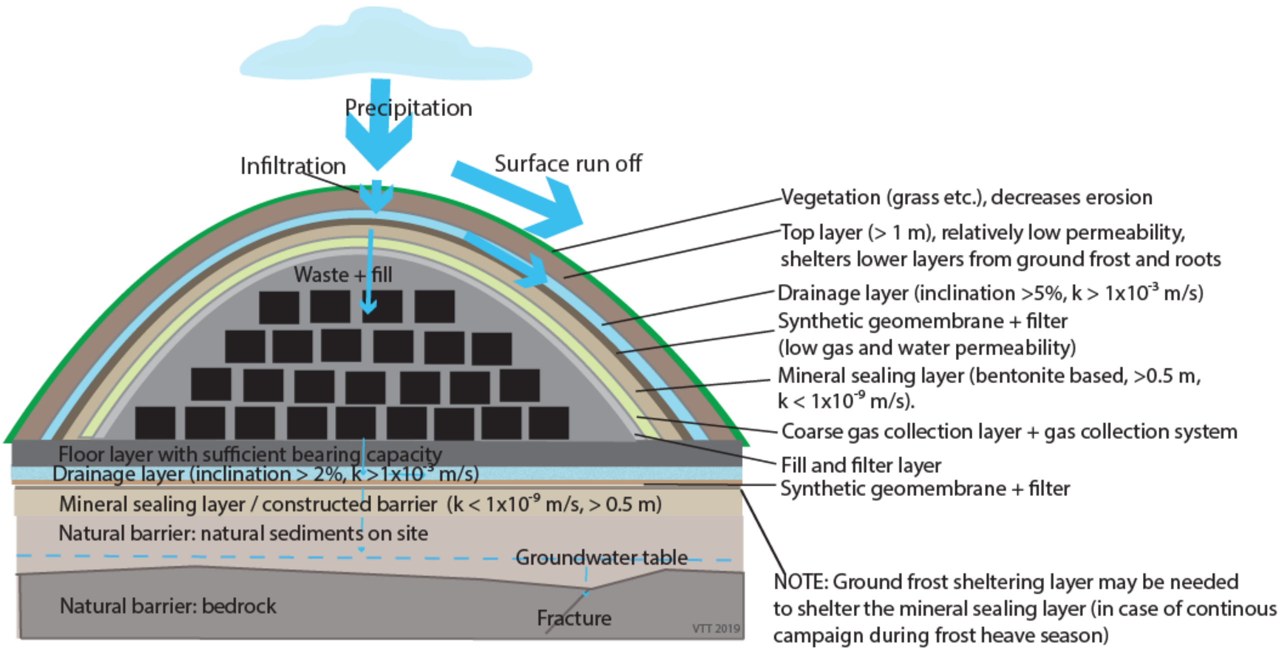


Figure 2-2. Example of a landfill type of a near surface repository based on Finnish guidelines for hazardous waste landfills (SYKE 2002, 2008). Figure from Keto et al. (2019).

The preliminary performance targets for the landfill type near surface repository were discussed in Keto et al. (2020) and are updated herein based upon expert opinions and stakeholder input provided during the SURFACE project seminar held in November 2021. The main differences identified between the design basis for a near surface repository and a hazardous waste landfills are related to:

- Legislation followed: Near surface repositories are regulated under the Nuclear Energy Act (Valtioneuvosto, 1987) and Radiation and Nuclear Safety Authority Regulation on the Safety of Disposal of Nuclear Waste (STUK, 2018a) In addition, the environmental impact of the repository is assessed as part of the licencing process. Hazardous waste landfills regulated by Waste Act (Valtioneuvosto, 2011), Waste Decree (Valtioneuvosto, 2012) and Government Decree on landfills (Valtioneuvosto, 2013).

- Waste acceptance criteria (WAC) is different: According to STUK (2018a), section 32 "[o]nly very low-level waste, the total activity of which does not exceed the limits laid down in section 6(1) of the Nuclear Energy Decree, can be placed in a facility constructed in the ground". The average activity concentration of the significant radionuclides shall not exceed value of 100 kBq per kg (Y/4/2018, section 1). The waste acceptance criteria for a hazardous waste landfill is defined in the Government Decree on landfills (Valtioneuvosto, 2013).

- Requirements on monitoring after closure: For a repository, the safety of the system cannot rely on active monitoring or maintenance. During the institutional control period, some monitoring and surveillance can be made, primarily for detecting possible degradation of the barriers and possibly to do some post-closure monitoring (e.g., monitoring periodically from groundwater pipes). The design of the repository should however be robust enough so that maintenance and repair activities remain minimal (IAEA, 2014b). For a hazardous waste landfill, monitoring of discharges to environment (groundwater, gas generation) shall take place for at least 30 years after closure (Environment Protection Act 527/2014, section 60). The operator of the landfill is responsible for funding these activities, e.g., through an upfront bank deposit (SYKE 2008).

- Human intrusion: Considering a repository, post-closure human intrusion has been identified as one of the risks related to near surface repositories, especially when the active institutional control period ceases (IAEA, 2014b). This risk can be controlled by, e.g., use of durable warning markers at the site and by measures linked to knowledge management, e.g., the preservation of records in archives (IAEA, 2014b). In a hazardous waste landfill the risks for human health are evaluated on a case by case basis depending on the type of waste deposited, discharges to the air and groundwater, and local conditions. If the risks for the human health is high, then problematic waste can be retrieved from the landfill. The risk can also be mitigated through land use planning (SYKE 2008).

- Service life: A near surface repository for radioactive waste shall isolate the waste from the environment until the radiation levels of the waste have decreased to a level where the waste no longer poses a threat to the environment or to people. A simple rule used is that the repository shall isolate the waste for a period of roughly 10 times the half-lives of the radionuclides deposited within 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. For hazardous waste landfills, the expected service life varies by case by case depending on the type of the waste deposited. Since post-closure monitoring is required for up to 30 years after closure, this can be considered as the last checkpoint when the performance of the hazardous waste landfill can be assessed.

- Mutually complementary barriers: "The long-term safety of disposal shall be based on long-term safety functions achieved through mutually complementary barriers so that the degradation of one or more long-term safety function or a foreseeable change in the bedrock or climate will not jeopardise the long-term safety" (STUK Y/4/2018, section 30). For a near surface repository, this is in practice provided by various factors such as: waste conditioning, waste packaging, applying WAC, site characteristics and the multiple engineered barriers placed in the repository. No similar definition exists for a hazardous waste landfill, but the structures implemented in practice provide similar type of functions.

How these differences in the design basis affect the actual design for a near surface repository is under discussion. Considering the requirement for passive safety after closure, the performance of the engineered barrier structures and especially the performance of the cover layer could be justified to be essential for ensuring long-term safety of the repository, as well as applying land-use restrictions after closure.

In the KYT SURFACE 2021 seminar, the following notions made were made during the discussions considering the performance of the near surface repository:

- The cover structure is sensitive for uneven settlements, e.g., due to compaction of the softer waste packages by the weight of the overlying structures. Uneven settlements can lead to formation of unwanted water pools on top of the landfill and to breakage of, e.g., thin synthetic liners used in the landfill. There are two possible measures to reduce this risk: 1) *place the softer waste also into metal containers* (as well as the metallic waste) and 2) *careful installation of the fill material* placed above the waste packages prior to installation of the cover layer structures. In addition, if settlements do take place, the cover layer should be repaired.

- Long-term performance of bentonite mat is not well known and sometimes at the time of installation the mat is prone to some breakage and the seams can leak water if not installed with sufficient overlapping. Considering the expected service life of the repository (~300 years*), it is recommended that a synthetic liner is combined with a mineral sealing layer* (e.g., mixture of crushed rock and 6-10 w-% of bentonite) with at least 0,5 m thickness and compacted in situ to dry density close to the Proctor maximum of the material. Successful compaction requires that the waste packages and the fill material placed around the waste fill provide sufficient mechanical support.

- *Thickness of the topmost layer* should be considered taking into account the future loadings from climate change and the vegetation growing at the site after closure. The requirement for the top layer thickness is in the normal/hazardous waste landfill design > 1 m. Whether this minimum thickness is enough considering, e.g., the depth of the roots of, e.g., pine trees or heavy storms should be considered.

- The *role of drainage layers* at the foundation layer collecting the water that has been in contact with the waste (leaching water) was discussed that in long term this might be route for radionuclide migration. On the other hand, if there is no route for draining water, water can start to accumulate into the repository increasing the risk of corrosion of the waste packages. In a landfill, the drainage function of the drainage pipes is typically maintained by flushing with water (Keto et al., 2020). If this not done, the pipes tend to clog with time. Some clogging of the drainage system will also take place after the closure of the repository.

- In the SURFACE 2021 seminar was discussed whether the target k-value (hydraulic conductivity) for the mineral sealing layers (at installation) should be $1x10^{-9}$ or $1x10^{-10}$ m/s. It was noted that considering that the waste is VLLW, the safety case may show that conductivity low as $1x10^{-10}$ m/s may not be needed. However, based on simulations made in Keto et al. (2020), the hydraulic conductivity of the sealing layer is a factor that effectively limits infiltration of water into the repository. In order to keep the waste as dry as possible, the hydraulic conductivity of the sealing layer of the cover layer should preferably be closer to $1x10^{-10}$ m/s than $1x10^{-9}$ m/s. Based on laboratory testing presented in section 6.2 herein, the target for the mineral sealing layer shall remain $1x10^{-9}$ m/s since it may be hard to compact the material on site to dense enough state to reach hydraulic conductivity of $<1x10^{-10}$ m/s. However, considering a combined structure consisting of a synthetic liner (bentonite mat or HDPE geomembrane) and the mineral sealing layer, the target of $1x10^{-10}$ m/s should be easy to reach. *It is recommended that hydraulic conductivity target of* $\leq 1x10^{-10}$ *m/s is given as the target for the combined synthetic liner and mineral sealing layer in the cover structure*, considering that some degradation will take place over time and to minimize the amount of water infiltrated through the waste.

How these notions are to be taken into account in the design should be discussed further. The recommendations given above are to be considered preliminary. However, they are based on experience from similar near surface repositories from Sweden and partly also from the experience gained in Finland on normal and hazardous waste landfills.

The preliminary safety functions suggested for the engineered barriers for a landfill type near surface repository were discussed in Keto et al. (2020) and presented in the KYT 2021 seminar including minor updates (marked with oblique text):

- Cover structures should:
  - Function as a radiation shield (*radiation levels at the ground surface should be the same as the natural background level*).
  - Limit infiltration of water (surface runoff, precipitation or floodwaters) into the repository. (*Recommendation: synthetic sealing layers combined with mineral sealing layer, k value target <1x10^{-10} m/s*)
  - 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 (*sufficient top layer thickness, grass*). As a design basis, ground frost should not be able to penetrate to the level of the mineral sealing layer. Similar requirement is in use for normal and hazardous waste landfills (Valtioneuvosto 1997).
  - 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.
  - *Prevent unintended human intrusion.*
  - Minimise uneven settlements in the structures.
- Fill material around the waste packages should:
  - Fill voids between the waste packages.
  - 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 should:
  - 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.
  - Be resistant 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 at least during the operational period of the facility. The pool/well system shall be designed to handle such leachates.

As stated already earlier in this chapter, the handling of leachate waters after closure of the repository possibly needs to be re-evaluated from the long-term safety point of view. Handling of leachate waters are discussed further in Chapter 5 (Handling of leachate waters).

3. Updates on the expected site conditions

In the report of Keto et al. (2020), the water movement in a landfill-like VLLW repository was assessed with numerical modelling. For the calculations, weather data was collected from relevant weather stations. In the analyses, double precipitation amounts were used to estimate the effect of future climate evolution. In this section, the effect of climate change on Olkiluoto area is assessed. This way, it can be ensured, that the precipitation we well as other model parameters used in the numerical modelling, are in line with future climate models.

Local effects of climate change for Finnish regions are addressed in the second part of a report by the Finnish Climate Panel (Gregow et al., 2021). They assessed the effects of three different scenarios, where 1) large, 2) moderate, and 3) no emission restrictions are met. The effects were addressed until the year 2080.

The report by the Finnish Climate Panel states that precipitation in Satakunta, the region, where Olkiluoto is located, is estimated to increase approximately 5%, if the large restrictions are met. The increase is reached by the year 2050 and it is estimated to stabilize thereafter. If moderate restrictions are met, the increase in precipitation is estimated to be 9% by the year 2080, and it would continue to increase afterwards. Finally, if no restrictions are met, precipitation is estimated to increase by 15% by 2080 and again keep increasing afterwards. In all three scenarios, most increase in precipitation would be observed from November to January.

Ruosteenoja et al. (2013) estimated maximum hourly precipitation rates of Finland based on a single RCA3-climate modelling run. RCA3 is a local climate model developed in Sweden. As only one climate model was used, its results should not be taken as an exact scenario. Nevertheless, it shows the magnitude of possible changes in the future. Ruosteenoja et al. (2013) estimated that the maximum change in hourly precipitation during the winter months (December to February) could increase by 42% by the year 2100. In the previous report (Keto et al., 2020), the precipitation used in the numerical modelling of the repository was estimated to double when compared to data from years 2000–2019. The estimated increase in precipitation in Gregow et al. (2021) and the estimated growth in maximum hourly precipitation by Ruosteenoja et al. (2013) are well below the estimates used in the numerical modelling.

Furthermore, Ruosteenoja et al. (2016) estimated that in a scenario with no emission restrictions, the solar radiation in the years 2040–2069 could increase approximately 5% during the summer months. The wind speed is estimated to remain more or less constant. Additionally, Gregow et al. (2021) estimated the number of days with sub-zero temperatures, snow cover depth and ground frost would all decrease notably by the year 2050. On average, the thickness of the snow cover has decreased 5 cm per decade between 1981 and 2020 while the number of subzero days has decreased by 6 days. Finally, Gregow et al. (2021) estimated, that urban runoff floods would increase, drainage basin floods would increase slightly or not be affected and sea floods would not be affected or decrease by the year 2050.

In Keto et al. (2020) annual solar radiation was estimated from a weather station in Alaska, USA, which had approximately the same latitude as Eurajoki. Data from the USA was used as no nearby solar radiation data were available for Eurajoki. Such an estimate does not consider local cloud coverage and other weather effects on solar radiation. Therefore, the increase of 5% in the solar radiation during summers discussed above does not significantly add any accuracy to the numerical modelling. If further accuracy is required, solar radiation data from an area near to Eurajoki could be used. Furthermore, as values for windspeed are not estimated to change drastically, the value from the previous year's report (Keto et al., 2020) should be valid even under updated weather conditions. However, if further numerical modeling is done, the effect on decrease of snow cover and subzero days could be considered.

Tuomenvirta et al. (2018) estimated how the sea level in once-in-hundred-year-floods caused by temporary sea level increase due to storms, air pressure changes and Baltic Sea level fluctuations will change between 2011 and 2100. They estimate that due to rise of ground level at the Baltic coast, the sea level in the events would decrease slightly before 2050. However, by 2100, the sea level in such events could increase by over 20%. Parjanne and Huokuna (2014) recommends that the minimum building height due to sea-related flooding occurring every 200 years should be 210 cm in the Rauma region. This estimate considers the estimated increase in sea level related flooding for the next 100 years. Olkiluoto area has set a minimum height of 350 cm from the sea level (TVO & Afry, 2021), which is well above the recommended minimum building height.

4. Gas Control

Landfill gas (LFG), comprised primarily of methane and carbon dioxide, is generated when organic matter is decomposed within a landfill. The rate at which the organic matter decomposes has an effect on gas production in a landfill. This production is influenced by the organic matter and moisture content of the waste (Goossens, 1996). Production of LFG can pose a risk to the landfill itself, as accumulating methane gas poses a risk of explosion (Rajaram et al., 2011). Furthermore, methane is a greenhouse gas. Therefore, collecting and removing LFG is desirable. In this section, the need for gas control in a landfill-type repository is assessed followed by a description of various gas collection systems.

4.1 Need for gas control in a landfill type near surface repository

Even though the planned repository for VLLW is not considered a landfill, it shares similarities in structure with landfills. Although the repository cover layers are designed to keep water out of the waste layer, some water could seep through it during the repository life. This infiltrating water could initiate the generation of gas in the repository. Depending on the rate at which gas is expected to be produced in the near surface repository, the production of LFG should be considered in the repository planning. Estimations of the gas generation rate in the worst case scenario were made as part of SURFACE project task 2 and will be discussed further in the final report of the project (to be published in 2023). Since the generation of the gas requires water, the ability of the cover layer to limit water infiltration to the waste is important for limiting the gas generation. Another measure to limit the gas generation could be to pack the soft, plastic covered organic waste pallets into metallic packages.

Regulations regarding nuclear waste management in Finland is presented in the Nuclear Energy Act (Valtioneuvosto, 1987), the Nuclear Energy Decree (Valtioneuvosto, 1988), the Radiation and Nuclear Safety Authority Regulation on the Safety of Disposal of Nuclear Waste (STUK, 2018a) and the Disposal of nuclear waste (STUK, 2018b). None of these state anything about gas produced in repositories. In normal or hazardous waste landfills, the gas generation is regulated by the Government Decree on Landfills 8 § (Valtioneuvosto, 2013).

Section 8 § (Valtioneuvosto, 2013) states, that LFG shall be collected and put to use if possible. If the collected gas cannot be utilized, it must be flared. Section 7, 42 § (Valtioneuvosto, 2013) states that the amount, the pressure and the consistency of the LFG has to be monitored monthly during the operational phase. The monitoring can be done semi-annually during the post-closure period. The periodicity of monitoring can be further increased if there is high confidence that a more temporally sparse monitoring schedule is sufficient. LFG properties to be monitored include methane, carbon dioxide and oxygen. Additional gases can be obligated for monitoring through an environmental impact assessment. The need for similar collection and monitoring systems in a near surface repository depends on the gas generation rate. The techniques used in normal/hazardous waste landfills for collecting, controlling and monitoring gas emissions are discussed further in the next subchapters. Such methods can also be applied to a landfill type near surface repository if needed.

4.2 Gas collections systems

Typically, gases produced in a landfill are handled with gas collection systems (GCS). Williumsen and Barlaz (2011) classify LFG management to active and passive systems. In active systems gas is extracted from the landfill by suction, whereas in passive system the gas pressure acts as a force, which vents the gas out of the system.

In active gas management (AGM) systems wells are drilled into the waste, where extraction pipes are installed. The wells can be either horizontal or vertical. The pipes are surrounded by permeable gravel, which allows the gas to travel from the waste to the pipes. The pipes are typically sealed with a bentonite or clay seal on areas where they penetrate the cover layer. The gas is extracted by applying suction to the wells, which causes the gas to travel in the pipes into a gas regulation station. Locating leaks in the collection system is easier if each extraction pipe is connected to a single gas regulation station. Another option is to extract the gas through the leachate collection system (Townsend et al., 2015). The extracted gas is collected from the regulation stations and can be either burned in torches or collected for industrial applications (Pipatti et al., 1996). A schematic of an AGM system with vertical pipes is presented in Figure 4-1.

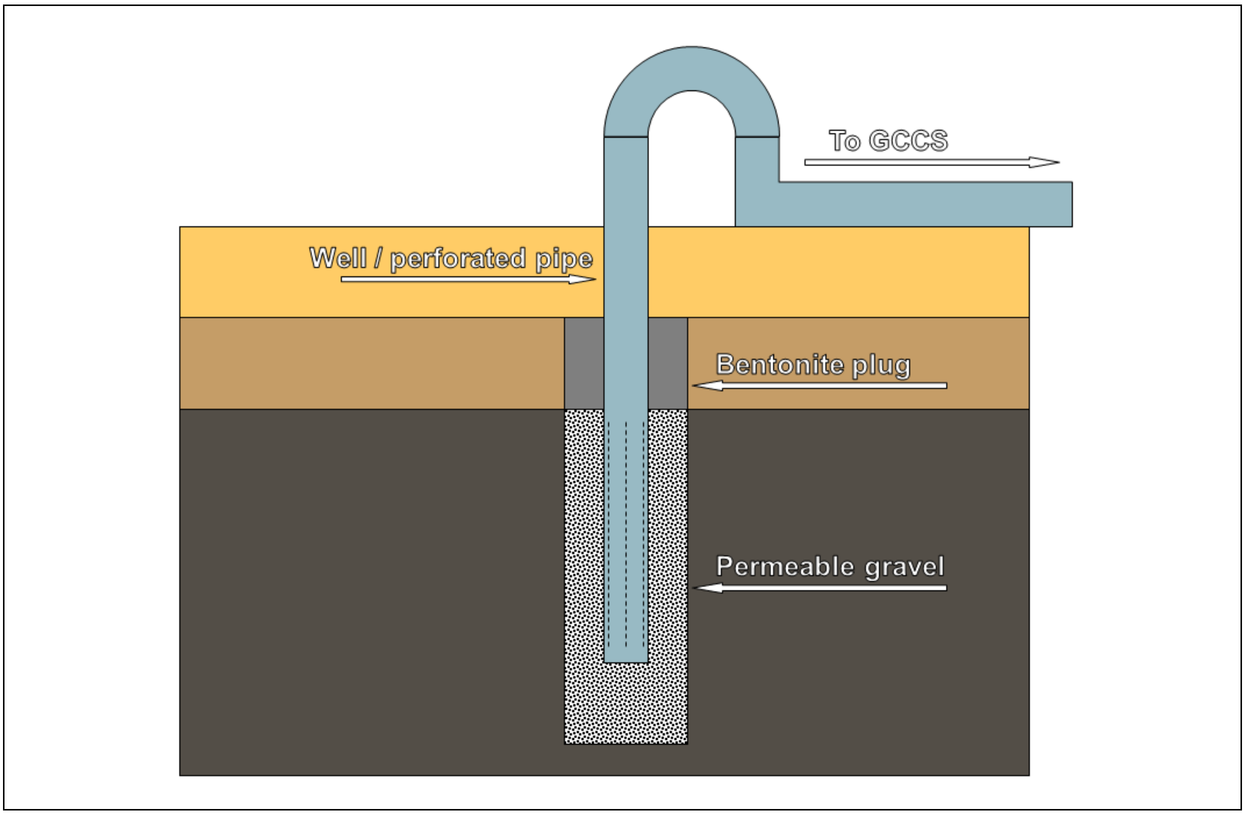


Figure 4-1: A schematic of an active gas management system.

According to Pipatti et al. (1996) vertical pipes are easier to install in AGM-systems, even after the closure of a landfill, and the number of pipes can be scaled up when the landfill is expanded. However, their suction efficiency is lower than for horizontal pipes and, thus, vertical pipes have to be placed closer together. Another issue with vertical pipes is water, which tends to block the drilled wells (Townsend et al., 2015). This is usually mitigated with pumps.

Horizontal pipes can be installed during the filling process of the landfill, and they operate with better efficiency relative to horizontal pipe systems. However, horizontal pipes are more easily damaged post-closure by the subsiding ground level. Horizontal wells also face the same problems with leachate water draining to the pipes. However, at some landfills, this effect has been used to also collect leachate. Horizontal wells closer to the surface are used to collect gas, whereas older systems closer to the landfill bottom, already saturated with water, are used for leachate collection (Townsend et al., 2015).

As there is already a need for a leachate collecting system in the foundation layer of the landfill-type near surface repository, collecting the LFG through the leachate system should be considered. Townsend et al. (2015) state that some gas will always migrate to the leachate collecting system. If the leachate and LFG collection systems can be combined in the repository design, it would decrease the number of piercings through the cover layer in the form of wells. This could presumably decrease unwanted water flow through the cover layer. However, such a drainage system would need active maintenance post-closure and would not act as a passive safety system. Next, some passive gas management systems are discussed more in depth.

In passive gas management systems, perforated pipes are again installed into permeable gravel. The gas pressure then forces the gas to enter the pipes, from where the gas is vented straight to the atmosphere without any extraction systems. An automatic solar ignitor can also be attached to automatically combust any exhaust gases. Their main objective is to prevent the buildup of pressure within the landfill (Rajaram et al. 2011). If a gas management system would be needed for a repository, it should nevertheless be passive at least after closure of the repository, as the safety of any repositories in Finland should not rely on active management and maintenance (Valtioneuvosto, 1987).

The need for GCS in a landfill-like VLLW repository should be assessed. As stated in Section 1, the waste contains organic waste and therefore gas would be produced from organic material degradation. However, the cover layer is also designed to limit water flow to the repository for as long as possible. This interplay poses issues for GCS design.

If water flow to the waste layer is very slow, it could take a very long time until any LFG is produced. The rate of gas production could also be low. Therefore, any GCS should be able to handle LFG possibly decades after landfill closure. It may also be the case that any GCS installed through the landfill structures could act as an additional route for water to enter the repository. Furthermore, a very dense cover layer could prevent natural leakage of LFG to the atmosphere and even with a low production rate the gas could then accumulate within the repository. This accumulation would then pose a risk of explosion, which could severely deteriorate the repository structures and performance. However, based on experience with similar types of repositories in Sweden, no evidence of problems due to gas generation have been detected (Aronsson, 2019). These observations may mean that the generation of gas is very limited and/or the gas can escape in a controlled manner through the low permeability liners used in the cover layer. A thorough assessment of LFG production and rate should be conducted to better understand long-term needs of the repository from this perspective. Any detailed plans for the use of a GCS should be made based on such an assessment. As a preliminary recommendation, the gas generation rate should preferably be limited as much as possible by restricting contact of the organic waste with infiltrating water to the level that no GCS would be needed. This would also limit greenhouse emissions (methane) from the repository. One option would be to include a GCS in one part of the repository for purposes of monitoring the need for such a system in the future.

5. Handling of leachate waters

Leachates are exfiltrating waters that contain dissolved soluble components from solids, such as landfill waste (Salem et al., 2008). Leachates are pollutants and can have negative effects on ground and surface waters. The primary reason for leachate transport from the landfill to the groundwater comes from the water level inside the landfill being higher than the groundwater level (CCME, 2006). Thus, to limit leachate transport to the surrounding groundwater, the water level in the landfill should be maintained below the groundwater level with a leachate collection system.

An aim of a cover layer of a VLLW-repository is to prevent water flow to the waste storage area. If the cover layer functions as intended, the waste storage area will stay dry, and little to no leachates are generated. However, if due to unexpected conditions the integrity of the cover layer is comprimised and water migrates to the waste area, leachates could be produced and thus a leachate collection system is required.

The report of Keto et al. (2020) presents the overall design requirements of the foundation layer and its drainage systems. The foundation layer includes, in addition to the drainage system, a synthetic membrane and a mineral sealing layer. In this section, a more detailed look of the foundation layer and leachate collection is made. The long-term plans for leachate handling are also discussed.

According to Syke (2002), the drainage layer collects and transports away leachates produced in the waste layer. The leachates can, for example, be transported to a wastewater treatment plant. A drainage layer consists of round, coarsely crushed rock. Pipes similar to those used in GCS are installed in the layer to collect and transport the leachates. A flushing system is also recommended to remove any accumulating waste in the leachate collection system. On top of the drainage layer, a filter layer can be installed to further decrease the migration of waste to the drainage layer.

Below the drainage layer, a synthetic membrane, for example a high-density polyethene (HDPE) membrane, is installed. The membrane catches any leachates that migrate through the leachate drainage layer. Finally, in between the synthetic membrane and the subsoil lies a mineral sealing layer. The layer consists of material with a very low hydraulic conductivity, for example a mix of bentonite and crushed rock. This layer slows down migration of any leachates that would pass through the synthetic membrane. Lee and Jones-Lee (1994) discuss the long-term effects of different types of wastes stored in landfills on the environment. They state that no matter how bottom layers are built in order to prevent leachate flow from a landfill, their quality will deteriorate over time. At some point, the quality has deteriorated sufficiently to allow the leachate to migrate to the underlying ground and groundwater. However, hazardous wastes at landfills usually remainharmful for the environment forever. In the case of a VLLW, it is assumed that the radioactivity of the waste will be on the environmental level after 300 years.

Rowe (2005) assesses the long-term performance of various landfill barrier systems. Their design adds another drainage layer below the mineral sealing layer when compared to Keto et al. (2020). Additionally, the double system includes geosynthetic clay liners between the synthetic membrane and the mineral sealing layer. The GCL consists of a layer of bentonite mat stitched together with needle-punching or chemical adhesives. A system consisting of two separated drainage layers can also increase the longevity of leachate collection, as any leachates migrating through the first layer could be captured by the second layer. Rowe (2005) estimates that the service life for HDPE geomembranes could be up to 160 years in the first liner and up to 600 years in the second liner if temperatures are maintained below 20°C. Considering this long service-life, this type of double-HDPE geomembrane foundation structure could also be an alternative for the near surface repository. However, in this case the discharges through the leachate collection system in the long term should be assessed for the safety of the system.

Finally, Rowe (2005) presents the most influential factors affecting the longevity of such leachate barriers. The most important factor is proper installation of the systems. In general, liners are prone to some imperfections in the installation of the liners and if uneven settlement takes place in the landfill. The leachate collecting pipes should also be regularly flushed to prevent blocking before closure of the repository. The blocking can also be mitigated by preventing placement of finely grained waste/waste fill material close to the liners or by using filter layers (see Figure 2-2). Another option that could be explored is to vacuum the pipes instead of flushing them. A vacuum procedure could be beneficial as, in an ideal case, no water would permeate to the waste layer, whereas flushing could introduce unwanted water to the layer.

Considering the role of an effective leachate water collection system in the foundation layer, it enables keeping the repository dry in addition to the sealing layers and water collection systems placed in the cover layer. If no such drainage system is placed in the foundation layer, it increases the risks for water accumulating within the repository. In that case, the water would stay in contact longer with the waste packages and also potentially with the waste. During the operative period, the leachate waters can be collected and treated, as necessary. After closure when active maintenance is no longer required from a repository, the drainage systems will eventually slowly deteriorate by clogging with minerals and the drainage function will decrease to some extent. Monitoring of the leachate waters is still possible after closure, but no active measures should be needed to treat the water. This enhances the need to minimize the water inflow to the repository through the cover layer. Further discussions on the role of this pathway as a radionuclide release route is needed in the next phase of the SURFACE project.

The role of HDPE geomembranes in a repository is to be assessed from the point of view of how they affect migration of the radionuclides from a repository. Considering a service life up to 160 years for a single HDPE layer (considering that the installation is made with care), an HDPE membrane in combination with a mineral sealing layer is a viable option for using bentonite mat in both sealing layers (the alternative for using bentonite mats is discussed in Keto et al. 2019, 2020). In the foundation layer, HDPE layers enhance collection of leachate waters through the drainage layer and limit migration of radionuclides through the foundation structure. Due to this effect, the role of the drainage systems as a route of escaping radionuclides requires further consideration. For this reason, double-HPDE layers in the foundation layer are not currently recommended for the repository. For the cover layer, this option could however be studied further, also taking into account the effect of such structure on gas generation and control (see section 4).

6. Monitoring

The general principle in the nuclear energy act is that long-term safety of nuclear waste repositories must not rely on active institutional control, such as monitoring or surveillance (Valtioneuvosto, 1987). However, it is stated, that monitoring can still be applied in repositories, for example for boosting the public acceptance of nuclear waste deposition. The safety standards of IAEA are, on the other hand, in contradiction with the Finnish law, as they state that institutional control on near-surface repositories should last for several tens to hundreds of years (IAEA, 2014a). As the need for a monitoring program for VLLW-repositories is still unclear, some possible measurements conducted both in VLLW repositories outside of Finland and in conventional landfills are presented in this section.

CCME (2006) state that the first step in a landfill monitoring program is defining the natural environmental base case. This baseline is used as a reference point for all following measurements. They also state, that monitoring should be conducted both during the operational period and after the closure of a landfill. The monitoring programs should monitor the physical movement of the landfill and the quality of leachate, leakage, groundwaters and surface waters, sediments, and air emissions. Furthermore, SYKE (2008) provide guidelines on monitoring and surveillance of conventional landfills in Finland that can be applied also for monitoring of a near surface repository, at least during the operational period.. In addition, background radiation of the site should be monitored before any operations with the VLLW take place at the site (Keto et al. 2019).

The physical movement of the landfill mainly occurs due to cover layer subsidence (CCME 2006). SYKE (2008) state that after the closure of a landfill, the cover layer will start to subside depending on the waste properties and the quality of the waste layer compacting. The duration of the subsidence is dependent upon how long the waste degrades and deforms. SYKE (2008) suggests that the final cover layers are only installed after most subsidence has already occurred. However, in the case of a VLLW repository, the corrosion and degradation of waste will be very slow. Subsidence/settlement is likely in the soft waste pallets, but this could be avoided by packing soft waste into metallic containers as well as the metallic waste. Additionally, all cover layers are designed to be installed as soon as possible to limit water flow to the waste layer. Thus, it could be expected that after the closure of the repository, the ground level will continue to gradually subside. The guidelines of SYKE (2008) suggest that monitoring of ground level subsidence should be continued after the closure of a landfill.

In addition to the ground level subsiding, the physical quality of the landfill area should be monitored. Such monitoring could include overall perimeter checks to ensure that the cover layer and other structures are operating as intended (CCME 2006). In addition, the growth of vegetation could be monitored to remove all saplings. The risk that trees and their roots pose on the integrity of the cover layer was discussed in chapter 2. Other aspects to monitor and check include the effect of erosion, the quality and integrity of ditches, and other monitoring systems (SYKE (2008).

Measuring of various waters both within and outside the landfill is a very important part of landfill monitoring. Firstly, waters within the waste layers should be monitored every half year for the height of the water, the temperature and the pH (SYKE (2008). In addition to the water within the waste layer, the leachate waters directed and collected in the leachate collection system should also be monitored. This can reveal vital information about how well the designed barriers of a landfill are operating (CCME 2006). The guidelines of SYKE (2008) suggest that both the quantity and electrical conductivity of the leachate waters should be monitored. CCME (2006) state that leachate waters should be monitored every quarter year (three months) during operation, while SYKE (2008) suggest that measurements would be carried out every half year (six months) after the landfill closure.

According to SYKE (2008), a minimum of three monitoring pipes should be installed for water monitoring in the waste layer. The pipes should be installed such that one pipe is upstream and the rest of the pipes are downstream of the measured area. Within the waste layer, this should accommodate the inclination of the waste layer and thus the internal flow of leachate waters. Usually, such monitoring pipes are perforated plastic pipes that can be surrounded with a filtering layer consisting of sand. Pipes that are used for gas monitoring should be perforated between 1 m from the surface down to the hard bottom of the landfill. The quality of the leachate waters can be monitored from the leachate collection system.

In addition to the landfill waters, LFG should be monitored in landfills. According to CCME (2006) the most important aspect to monitor is the formation of explosive gases. If such gases accumulate and explode, serious damage could be inflicted on the landfill structures, such as the cover layer. The properties to be measured include methane, carbon dioxide and oxygen levels (SYKE, 2008). The gases within the landfill can be monitored with similar pipes as the landfill waters. CCME (2006) also suggest that some LFG originating from decomposition of organic matter can be indirectly monitored from the temperature, oxygen and water content of the waste layer. The recommendations discussed above are for normal/hazardous waste landfills, but can be adapted for a near surface repository. In addition to these, radiation levels and nuclide concentrations should be monitored from the leachate water and groundwater samples, as well as from the air (Keto et al. 2019).

7. Effect of freezing conditions on sealing layers

7.1 Numerical modelling for thermal conditions

7.1.1 Introduction and methods for the thermal modelling

In the near surface repository system, freezing of the repository layers can lead to harmful consequences. Frost heave of the subsoil could damage, e.g., the mineral sealing layer or the drainage systems. Freezing of the mineral sealing layer can also cause irreversible failures, which lead to an increase in hydraulic conductivity of the mineral sealing layer. This is why the mineral sealing layers should be protected from freezing conditions. One way to prevent freezing of the mineral sealing layers is to schedule the construction operations outside winter periods. However, in the long-term, there is a potential for freezing of the mineral sealing layer in the cover layers, taking into account the period of hundreds of years during which the near surface repository should fulfil its targets. Thermal properties and thickness of the layers above the mineral sealing layer will affect its thermal conditions. Extremely cold winter periods are also possible in the long-term and can lead to greater frost depths than may typically be expected. Since the performance of the near surface repository should fulfil its targets for such a long period, the analyses for frost-susceptibility should include these extreme conditions.

In the thermal modelling performed for this project, the purpose was to study the frost-susceptibility of a generic near surface repository system. We tested how different thicknesses and thermal properties of layers in the near surface repository would affect the thermal conditions of the mineral sealing layers. Weather scenarios were also varied. The thermal modelling was performed using TEMP/W finite element software by GeoStudio.

For the weather data, freezing indices were calculated from the temperature data measured in the Helsinki area during 1967-2007. The data were uploaded from the open data source provided by the Finnish Meteorological Institute. Based on the data and with the use of statistical methods, freezing indices (h°C) were defined for an average winter period (F2), winter period occurring once in 5 years (F5), winter period occurring once in 20 years (F20), and winter period occurring once in 50 years (F50). For these different design winter periods, average monthly temperatures were defined (Figure 7-1) and for the summer periods, average summer periods were used. In the thermal analyses, the weather conditions were simulated such that all simulations began with an average winter (F2) followed by an average summer and lastly, either F2, F5, F20 or F50 winter.

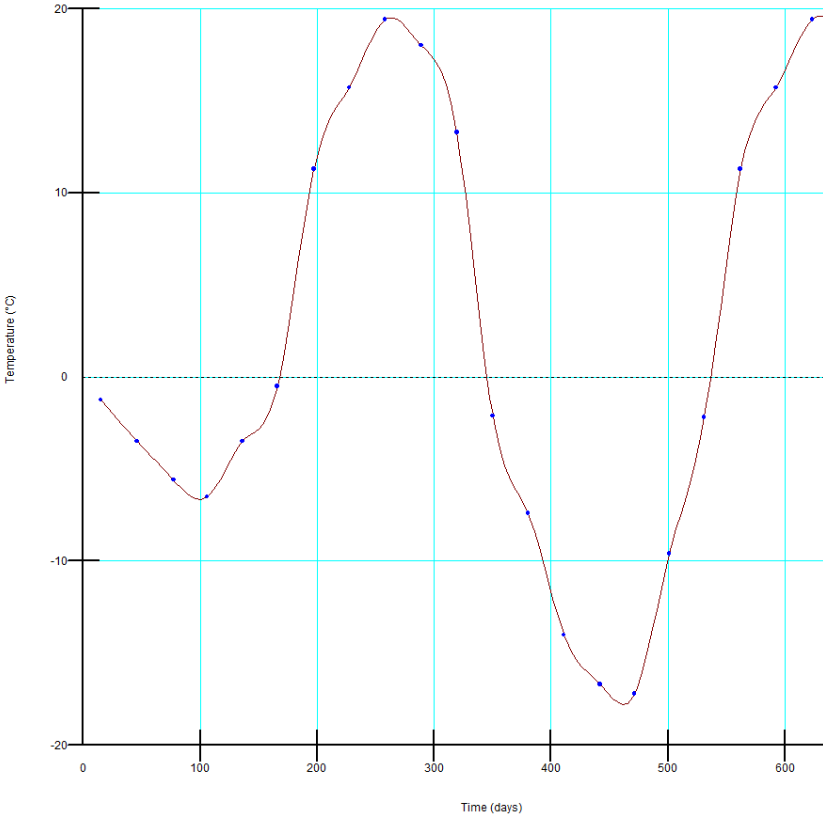


Figure 7-1. An example of temperature data for the simulations with TEMP/W. All simulations started with a F2 winter, followed by an average summer and by F2/F5/F20/F50 winter (F50 in this example).

Table 7-1 presents properties of different near surface repository layers used in the TEMP/W simulations. For the simulations, the following properties for the materials/layers were required: dry density, in situ volumetric water content, thermal conductivity (unfrozen and frozen) and volumetric heat capacity (unfrozen and frozen). In the simulations, a simplified thermal model was used, meaning that the thermal conductivities for the frozen and unfrozen states were fixed values and no unfrozen volumetric water content functions were defined. The values presented in Table 7-1 were defined based on target properties (dry density and water content) of the repository layers and knowledge from literature (thermal conductivity and heat capacity) (e.g., Farouki 1986). These values represent typical or average values for these types of materials/layers. The values should be defined separately for each individual design. Thermal properties differ between different soils and depend strongly on the density (porosity) and water content. Here, moraine was chosen to be used as a typical material in the top soil layer and in the ground.

Table 7-1. Layer properties used in the TEMP/W simulations.

Layer	Material	Dry density (kg/m^3)	Vol. water content (%)	Thermal conductivity, unfrozen (W/mK)	Thermal conductivity, frozen (W/mK)	Volumetric heat capacity, unfrozen ($kJ/m^3/K$)	Volumetric heat capacity, frozen ($kJ/m^3/K$)
Top soil layer	Moraine	1800	18	1.7	2.0	2110	1735
Drainage layer	Gravel	1800	5	1.4	0.9	1585	1470
Mineral sealing layer	Bentonite with crushed rock	2100	21	2.4	2.5	2460	2020
Backfill	Rock flour	1840	17	2.1	2.5	2080	1730
Ground	Moraine	1800	18	1.7	2.0	2110	1735

7.1.2 Results - freezing of the foundation layers

A scenario where the foundation layers (mineral sealing layer and drainage layer on top of the subsoil) would be constructed and freezing conditions would occur before any layers were constructed on top of the foundation layers, could lead to a risk of freezing of the mineral sealing layer. This scenario was tested in the TEMP/W simulations.

The results are shown in Figure 7-2, Figure 7-3, Table 7-2 and Table 7-3. Based on the results, freezing of the mineral sealing layer would occur with average winter temperatures (F2). During F20 and F50 winter periods, the mineral sealing layer was frozen through the entire layer. With the F50 winter, almost 1 m of the moraine subbase would freeze, causing possible frost heave.

If snow were taken into account, a 30 cm thick layer of snow would prevent the mineral sealing layer from freezing during F2 winter. During F50 winter, 90 cm of snow would be needed. Two types of insulating materials, expanded clay and polystyrene, were also tested in the simulations. It would require 20 cm of expanded clay or 5 cm of polystyrene to prevent the mineral sealing layer from freezing during F2 winter. During F50 winter, it would require 60 cm of expanded clay or 15 cm polystyrene on top of the foundation layers.

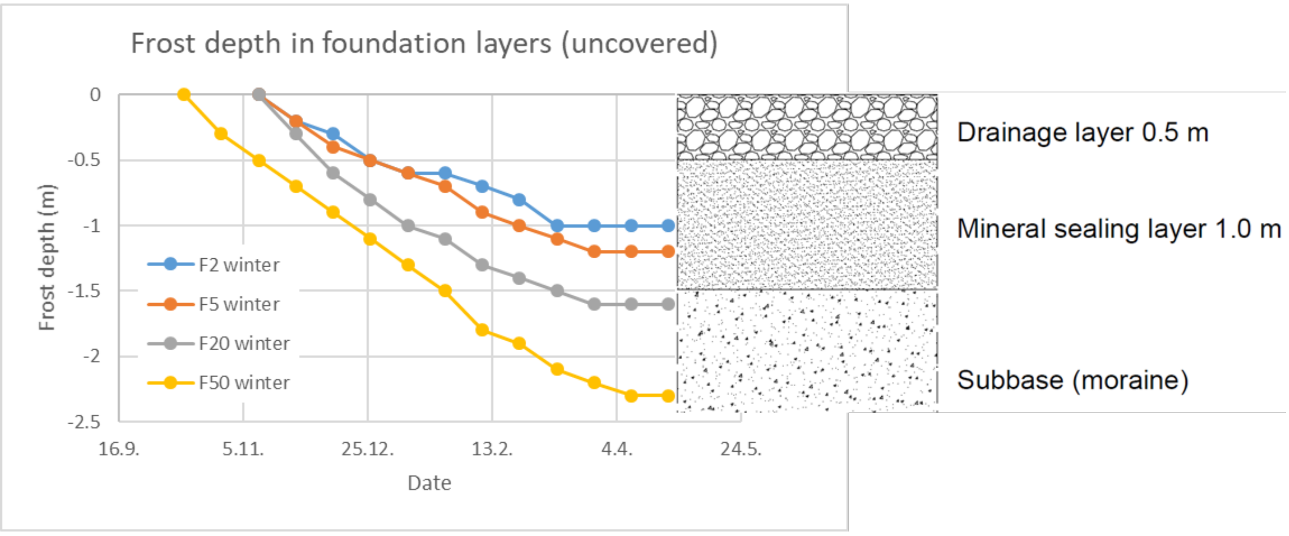
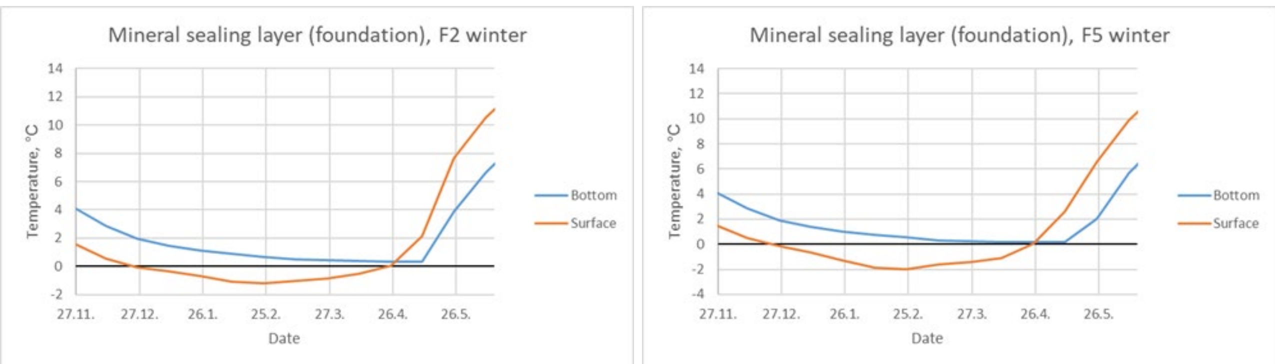
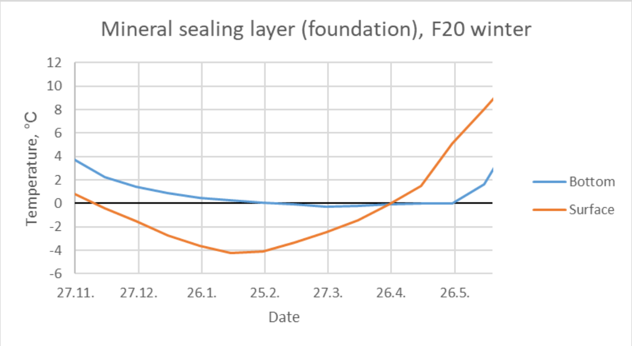


Figure 7-2. Frost depth (the level below which the temperature < 0°C) in the foundation layers during four different design winter periods.





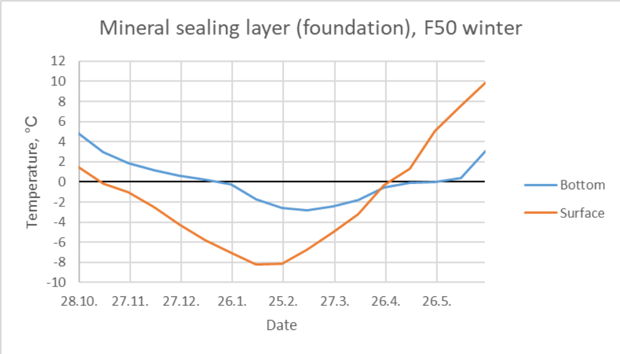


Figure 7-3. Temperatures in the bottom and surface of mineral sealing layer of the uncovered foundation layers during different winter periods (F2, F5, F20, and F50).

Table 7-2. Minimum temperatures at the surface and bottom of the mineral sealing layer of foundation structures during different design winter periods.

Minimum temperatures (°C) during different design winter periods					
Design winter		**F2**	**F5**	**F20**	**F50**
Mineral sealing layer (foundation structures)	Surface	-1.2	-2.0	-4.2	-8.2
	Bottom	0.3	0.2	-0.3	-2.8

Table 7-3. Minimum thickness of snow, expanded clay or polystyrene on top of the foundation layers with which the temperature is > 0°C at the surface of mineral sealing layer during winter for different design winters periods.

Thickness of thermal insulation to prevent freezing of the mineral sealing layer				
Design winter	**F2**	**F5**	**F20**	**F50**
Snow (cm)	30	30	50	90
Expanded clay (cm)	20	20	40	60
EPS/XPS (polystyrene) (cm)	5	10	10	15

7.1.3 Results - freezing of the cover layers

Similar types of simulations with the TEMP/W software were performed for the cover layers as were performed for the foundation layers. The analyses for the cover layers were performed also including the foundation layers and a 4 m thick backfill layer between the foundation and cover layers. Different thicknesses (1.0 m, 1.5 m, 2.0 m and 3.0 m) of a moraine top soil layer. The results are presented in Figure 7-4, Figure 7-5, Figure 7-6, Table 7-4 and Table 7-5.

The simulations showed that with the 1.0 m top soil layer, the mineral sealing layer was at least partly frozen with an average winter (F2). With F50 winter, the entire mineral sealing layer was frozen. If a thicker (1.5 m) moraine top soil layer was used, no freezing occurred with F2 and F5 winters. With F50 winter, the entire mineral sealing layer was frozen along with the 1.5 m top soil layer. It was also simulated that a 2.0 m thick moraine top soil layer was needed to prevent freezing of the mineral sealing layer during F20 winter and during F50, the required thickness was 3.0 m.

If snow was included in the simulations, it was found that with the 1.0 m top soil layer, 10 cm of snow was needed during F2 winter and 40 cm of snow during F50 to prevent any freezing of the mineral sealing layer. The 1.5 m top soil layer was sufficient to prevent freezing of the mineral sealing layer during F2 and F5 winters but 10 cm of snow was needed during F20 winter and 30 cm of snow during F50 winter.

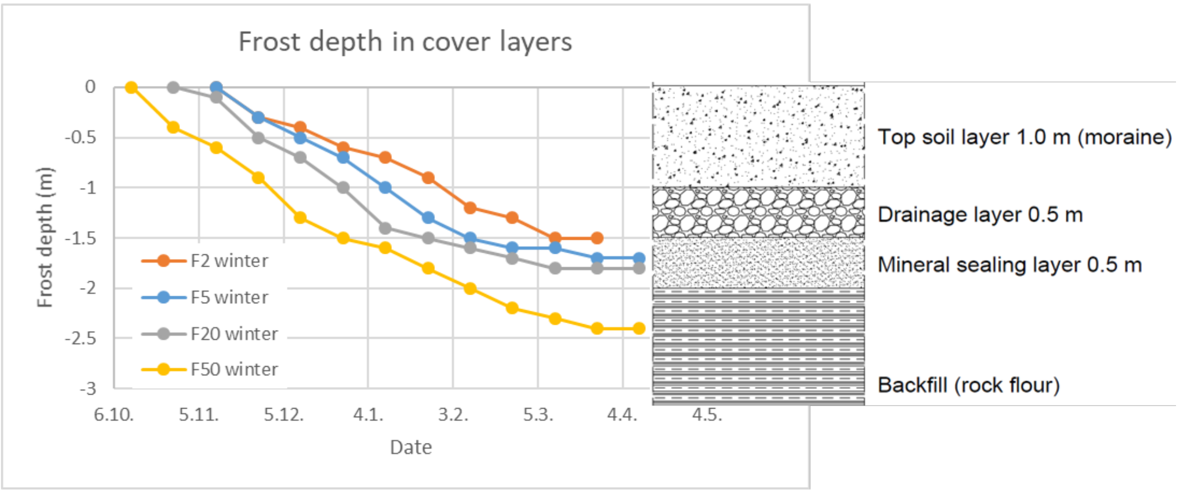


Figure 7-4. Frost depth (the level below which the temperature < 0°C) in the cover layers with a 1.0 m top soil layer during four different design winter periods.

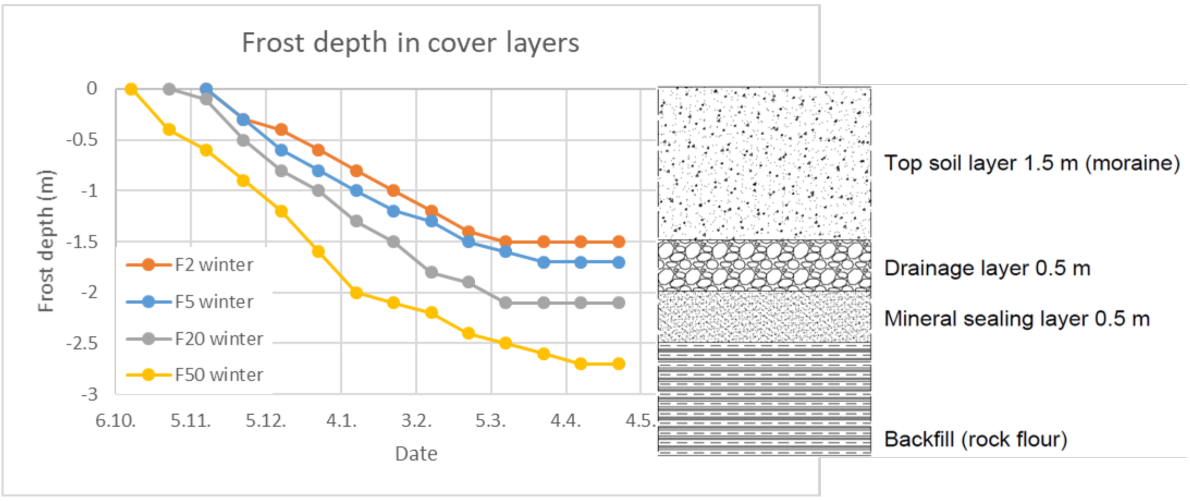
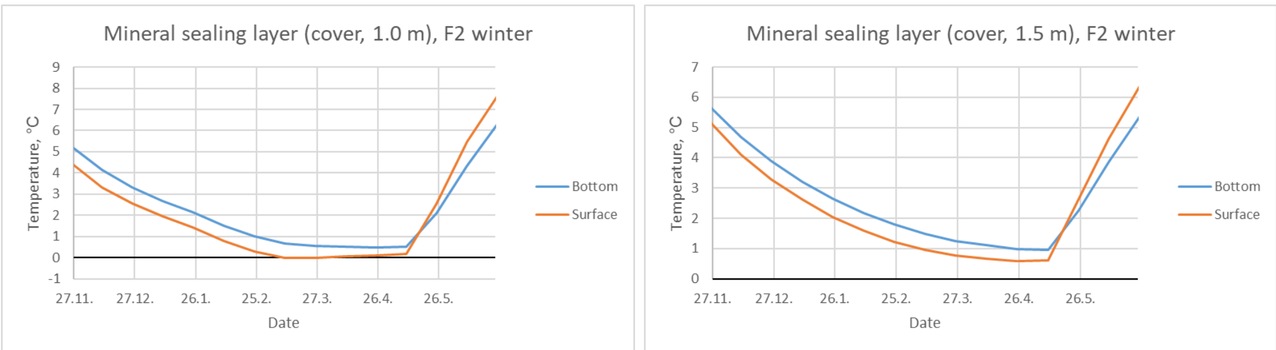


Figure 7-5. Frost depth (the level below which the temperature < 0°C) in the cover layers with a 1.5 m top soil layer during four different design winter periods.



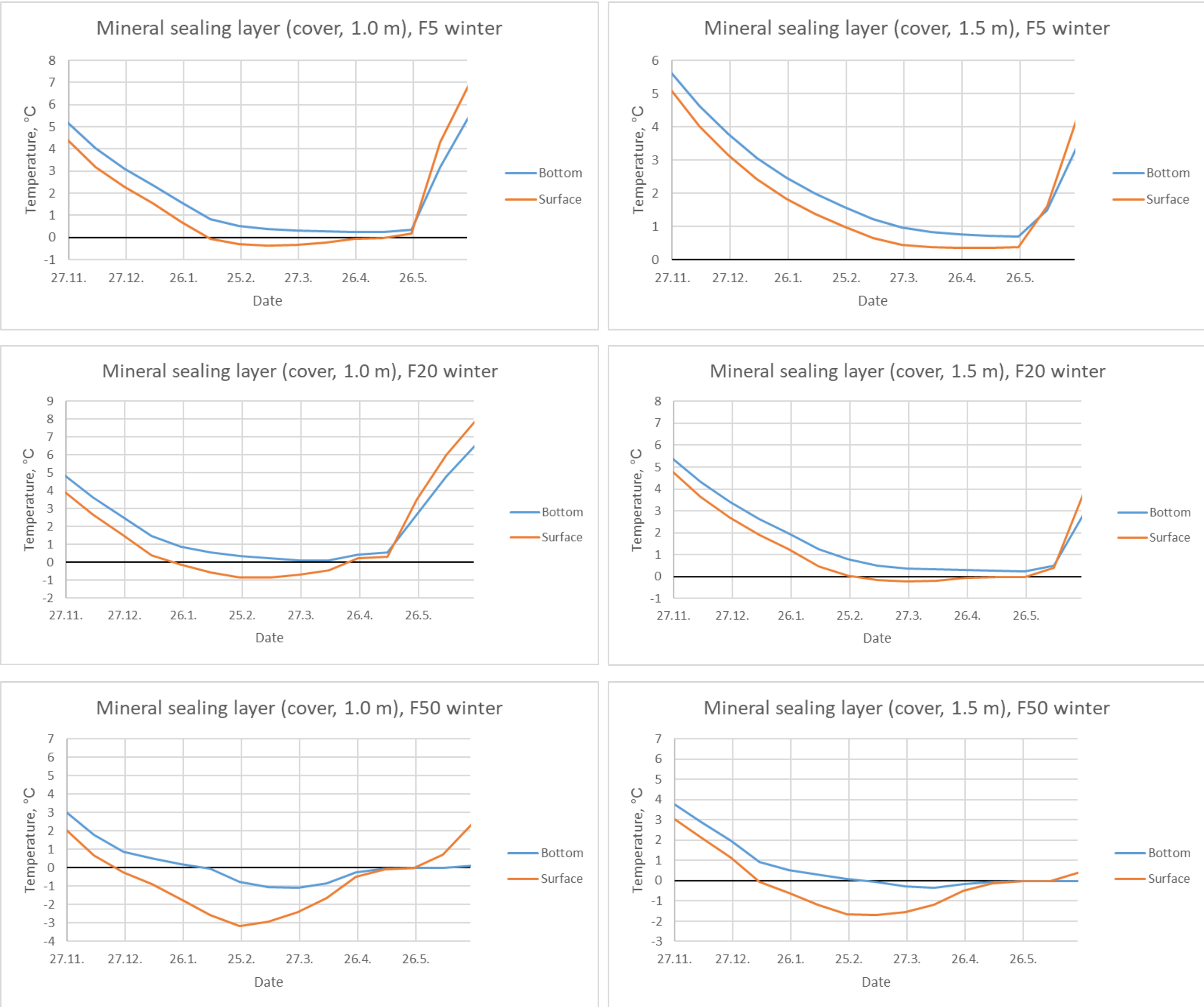


Figure 7-6. Temperatures in the bottom and surface of mineral sealing layer of the cover layers during different winter periods (F2, F5, F20, and F50). Simulations were performed for two different thicknesses (1.0 m and 1.5 m) of the top soil layer.

Table 7-4. Minimum temperatures at the surface and bottom of the mineral sealing layer in the cover layers with a 1.0 m top soil layer during different design winter periods.

Minimum temperatures (°C) during different design winter periods (top soil layer 1.0 m)					
Design winter		**F2**	**F5**	**F20**	**F50**
Mineral sealing layer (foundation structures)	Surface	-0.1	-0.4	-0.8	-3.1
	Bottom	0.3	0.2	0.1	-1.1

Table 7-5. Minimum temperatures at the surface and bottom of the mineral sealing layer in the cover layers with a 1.5 m top soil layer during different design winter periods.

Minimum temperatures (°C) during different design winter periods (top soil layer 1.5 m)					
Design winter		**F2**	**F5**	**F20**	**F50**
Mineral sealing layer (foundation structures)	Surface	0.6	0.3	-0.2	-1.7
	Bottom	1.0	0.7	0.3	-0.3

Table 7-6. Minimum thickness of the top soil layer (moraine) with which the temperature was > 0°C at the surface of the mineral sealing layer in the cover layers during different design winters periods.

Thickness of moraine (m) in the top soil layer to prevent freezing of the mineral sealing layer				
Design winter	**F2**	**F5**	**F20**	**F50**
Moraine in top soil layer (m)	1.5	1.5	2.0	3.0

Table 7-7. Minimum thickness of snow on the cover layers with which the temperature was > 0°C at the surface of the mineral sealing layer during different design winters periods and for two different thicknesses of the top soil layer (moraine).

Thickness of snow (cm) to prevent freezing of the mineral sealing layer					
Design winter		**F2**	**F5**	**F20**	**F50**
Thickness of top soil layer (m)	1.0	10	10	20	40
	1.5	0	0	10	30

7.1.4 Summary of the thermal analyses

It is recommended to perform analyses for the thermal behaviour of the near surface repository system during its design process. Freezing can lead to processes like frost heave of the subsoil, causing failures in the mineral sealing layers or drainage layers. These may lead to increased hydraulic conductivity of the mineral sealing layers. In this report, results of thermal modelling with GeoStudio's TEMP/W software for a generic near surface repository system was reported.

In the first phase of the thermal modelling, the possibility of freezing of the foundation layers was examined. It was obvious that without any additional thermal insulation the mineral sealing layer in the foundation layers would freeze during a winter period, especially if little or no snow was present. With snow, at least 30 cm would be needed for insulation. This is why it is recommended to construct the foundation layers outside the winter periods, during which there is a risk of freezing of the foundation layers. During the winter periods, the foundation layers should be protected from freezing by constructing the backfilled waste layer and cover layers on top of the foundation layers, or possibly using thermal insulation methods.

In the second phase of the thermal modelling, the entire near surface repository system was modelled and the possibility of freezing of the mineral sealing layer in the cover layers was examined. In long-term, the cover layers will be more prone to freezing and the mineral sealing layer in the cover layers will be protected from freezing by the covering layers. In the thermal modelling, the moraine topsoil layer with a thickness of 1.0 m did not prevent freezing of the mineral sealing layer. A tThickness of 1.5 m of moraine was sufficient during normal winter periods but not with more extreme winter periods which would require 3.0 m of moraine in the cover to prevent freezing. In these scenarios, no snow was taken into account, but based on the simulations a few tens of centimetres of snow would prevent freezing even in more extreme winter conditions.

It should be taken into account that the modelling presented in this report was performed for a generic near surface repository system with specific materials chosen for these modelling cases. For example, the top soil layer material in the cover layers should be examined separately for each individual design case, since thermal parameters vary depending on the material. In addition, the weather and climate scenarios are site specific and should selected checked for the actual site.

The recommendations based on these calculations are that in the expected lifetime of the repository, it is possible that all or at least some of the layers in the cover structure will undergo freezing and thawing, potentially affecting the performance of these layers, particulatly when low temperatures are combined with very little snow coverage. The risks related to the freezing and thawing can be mitigated by, e.g.:

- Installing a top layer with greater thickness than the minimum required for normal/hazardous waste landfills ≥ 1 m. Depending on the layer material thermal properties, the thickness could be in many cases ≥ 2 m. This would also mitigate the risk of tree roots puncturing the synthetic layers after closure of the facility. For example, Stoltz and Greger (2006) state that at mine sites, where the thickness of a low hydraulic conductivity cover layer was over 1.5 m, no root penetration had occurred.

- Using a combination of synthetic liner (HDPE geomembrane or bentonite mat) and mineral sealing layer in the cover layer (applying the principle of mutually complementing barriers), which is less vulnerable to increases in hydraulic conductivity. HDPE layers can also prevent root penetration as according to Dobson and Moffat (1995), tree roots are not able to penetrate HDPE-layers.

7.2 Laboratory studies for hydraulic conductivities with freezing and thawing

In the previous chapter, thermal conditions in the near surface repository were modelled. In particular, possibilities for freezing of the mineral sealing layers were examined. Based on the available literature, there is some evidence that hydraulic conductivity can possibly increase in different types of compacted soils or soil-mixtures after exposing the material to multiple freeze-thaw cycles. This may be due to changes that freezing can cause to the void ratio, structure, and fabric of the soil (Kim & Daniel, 1992). Increase in hydraulic conductivity after several freeze-thaw cycles have been found, e.g., by Kim & Daniel (1992) for compacted clay and by Wong and Haug (1991) for compacted clay and till. However, Wong and Haug (1991) found no changes in hydraulic conductivity after freeze-thaw cycles for compacted sand-bentonite mixture. Similarly, Kraus et al. (1997) found no changes in hydraulic conductivity of compacted sand-bentonite mixture after freeze-thaw cycles, both in the laboratory and in the field after 1-2 winters.

In KYT SURFACE phase 3, the effects of freezing and thawing on the hydraulic conductivity of compacted mixtures of bentonite and crushed rock were studied in a laboratory. The mixtures used simulated a compacted mineral sealing layer material in the near surface repository. The compacted mixtures of bentonite and crushed rock were exposed to multiple freeze-thaw cycles and hydraulic conductivity of the samples was measured after the freeze-thaw cycles. For comparison, similar samples without freeze-thaw cycles were tested for their hydraulic conductivity.

7.2.1 Materials

The materials studied in KYT SURFACE phase 3 are presented in Table 7-8. The geotechnical laboratory tests performed for these materials are discussed further in Sections 6.2 (Methods) and 6.3 (Results).

Table 7-8. Materials used in KYT SURFACE phase 3 task 3 (Performance of barrier materials).

Material	Product information given by the producer	Use and analysis performed in 2021
Crushed rock (0-16 mm)	Mineralogical composition: Felsic rock type, granitoid typically consisting of quartz, feldspars, mica and accessory minerals. Producer: RUDUS	Used in mixtures of crushed rock and bentonite (6%, 8% and 10%). Note that the grain size was reduced to 10 mm by dry sieving.
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	Used in mixtures of crushed rock and bentonite (6%, 8% and 10%).

Material	Product information given by the producer	Use and analysis performed in 2021
Mixture of crushed rock (10 mm) and bentonite (6%), water content 8 %	See above information on crushed rock and bentonite	Hydraulic conductivity tests
Mixture of crushed rock (10 mm) and bentonite (8%), water content 10 %		Hydraulic conductivity tests
Mixture of crushed rock (10 mm) and bentonite (10%), water content 11 %		Hydraulic conductivity tests

7.2.2 Methods

The samples for the hydraulic conductivity testing with or without freeze-thaw cycling were prepared by first mixing the dried bentonite and dried crushed rock and adding the correct amounts of water to the samples (see Table 7-8). The samples were manually compacted inside cylindrical moulds with 100 mm height and 100 mm inner diameter (Figure 7-7). These exact dimensions of the samples were due to requirements for the hydraulic conductivity testing. The compaction targeted to similar densities as was found using the Proctor compaction in KYT SURFACE phase 2 (Keto et al. 2020). With the Proctor compaction, the dry densities reached 1850-2100 kg/m^3 depending on the bentonite content as well the water content of the samples.

Figure 7-7. Compacted sample in the mould and released from the mould with required dimensions for hydraulic conductivity testing.

The hydraulic conductivity of fine-grained soils was determined with the falling-head method (ASTM, 2016). In the falling-head method, the soil sample was first saturated under a specific head condition. The water was then allowed to flow through the soil in a flexible wall permeability cell without adding any water, so the pressure head declined as water passed through the specimen.

The freeze-thaw cycling for the samples was conducted during a one-month period during which the samples were exposed to 10 freeze-thaw cycles. In one freeze-thaw cycle there was a 24 h period of freezing the samples at -5°C (based on modelling in chapter 6.1) followed by another 24 h period for thawing at room temperature.

7.2.3 Results

Hydraulic conductivity tests for different bentonite contents in crushed rock/bentonite mixtures were presented previously in KYT SURFACE phase 2 (Keto et al. (2020). Three samples with bentonite contents of 6%, 8% and 10% were analysed and named O248_V1, O248_V2 and O248_V3 respectively. The values of the tests are presented in Table 7-9. Parameters from the measurements are presented in detail in Appendix 1. The measured hydraulic conductivities corresponding to measured dry densities are presented in Figure 6-1 and corresponding to bentonite contents in Figure 6-2.

Values for samples tested during KYT SURFACE phase 3 with methodology presented in the previous section are also presented in Table 7-9 and in Appendix 1. Two sets of samples are presented, with both sets containing one sample of 6%, 8% and 10% bentonite contents in crushed rock/bentonite mixtures. The first set (P182_V1, P182_V2 and P182_V3), were measured without freeze-thaw cycles and the second set (P182_V4, P182_V5 and P182_V6), were measured after exposure to the freeze-thaw cycles. Again, the measured hydraulic conductivities corresponding to measured dry densities are presented in Figure 7-8 and corresponding to bentonite contents in Figure 7-9.

Table 7-9. Measured hydraulic conductivities and corresponding dry densities of the tested crushed rock and bentonite mixtures. O248_V1, O248_V2 and O248_V3 correspond to measured values from Keto et al. (2020), P182_V1, P182_V2 and P182_V3 to values measured without freeze-thaw cycles and P182_V4, P182_V5 and P182_V6 to values measured with the cycles.

Sample name	Bentonite content of the mixture (%)	Dry density (kg/m^3)	Dry density, kN/m^3	Hydraulic conductivity (m/s)
O248_V1	6	1892	18.56	5.90E-10
O248_V2	8	1903	18.67	3.30E-10
O248_V3	10	1915	18.79	1.90E-10
P182_V1	6	2018	19.8	3.10E-10
P182_V2	8	1996	19.58	2.40E-10
P182_V3	10	1999	19.61	2.90E-10
P182_V4	6	2055	20.16	2.20E-10
P182_V5	8	2059	20.2	1.00E-10
P182_V6	10	1968	19.31	1.50E-10

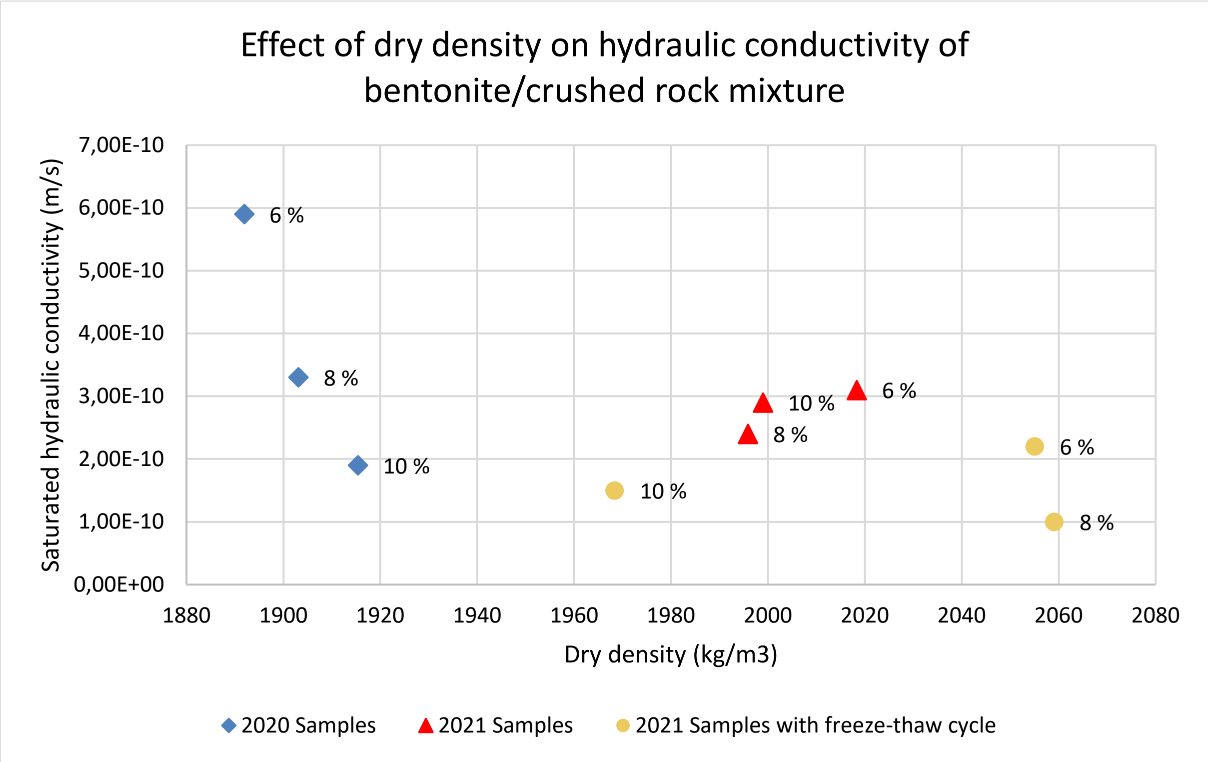


Figure 7-8. Measured dry densities of bentonite/crushed rock mixtures and corresponding hydraulic conductivities of Keto et al. (2020) and values measured in this study. Bentonite content of the samples is displayed adjacent to the data points in %.

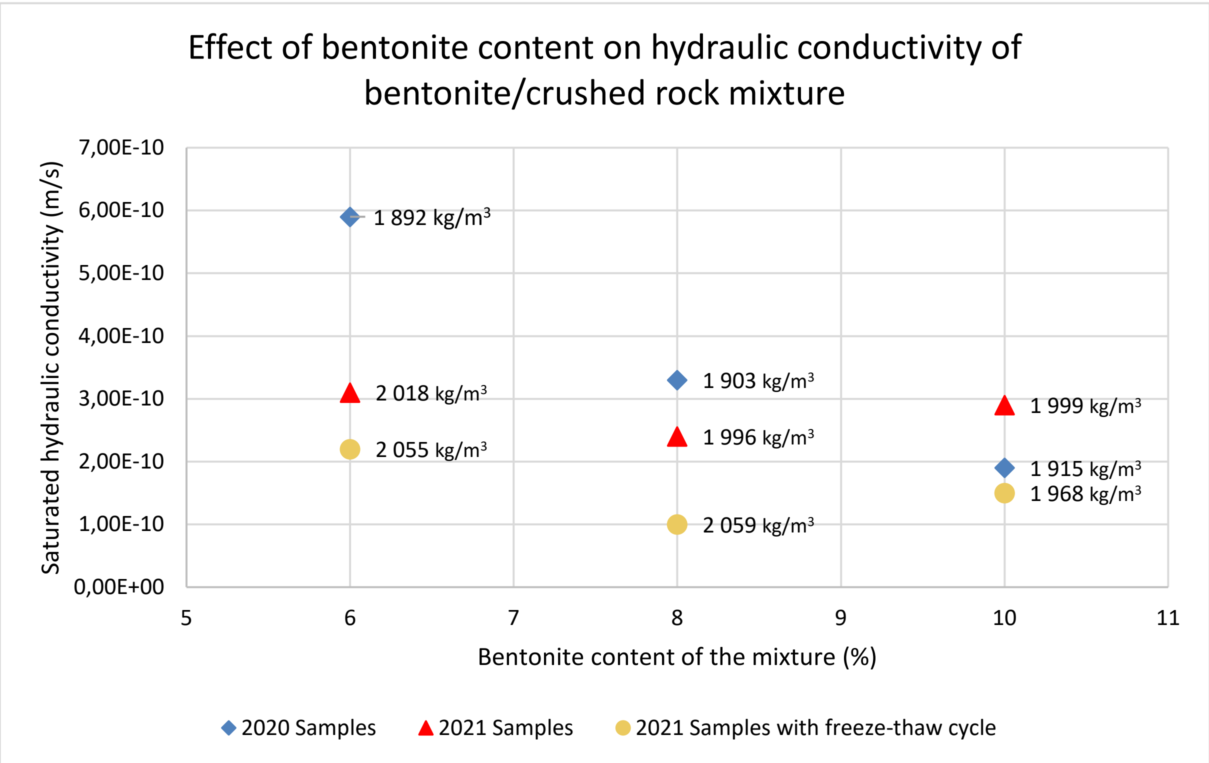


Figure 7-9. Bentonite contents of bentonite/crushed rock mixtures and corresponding measured hydraulic conductivities of Keto et al. (2020) and values measured in this study. Dry densities of the samples is displayed adjacent to the data points in kg/m^3.

7.2.4 Conclusions for the laboratory studies

The hydraulic conductivity tests for mixtures of bentonite and crushed rock with or without freeze-thaw cycles were performed in KYT SURFACE phase 3. Hydraulic conductivity test results from phase 2 were included in the results of this report. In total, nine samples were tested for their hydraulic conductivity. Three of these samples went through freeze-thaw cycles before the hydraulic conductivity test. The bentonite content in the samples was 6, 8 or 10%.

The results showed that the hydraulic conductivities of all the samples were $1x10^{-10}$ m/s to $6x10^{-10}$ m/s with dry densities corresponding to Proctor maximum dry densities achieved in Keto et al. (2020). Some expected trends were obtained from the results. Low hydraulic conductivity is achieved by installing the material to sufficient dry density and by having sufficient bentonite content in the mixture. There were no clear differences in the hydraulic conductivities between the samples with freeze-thaw cycles and samples without them. Samples exposed to the freeze-thaw cycles had slightly lower hydraulic conductivities but density differences and possible margins of error in the measurements should be taken into account. Another source of uncertainty is the number of freezing cycles, which was limited to 10 cycles in the present studies.

It should be noted that the dry densities of the samples were quite high and considered that typically the dry densities achieved in the field are at maximum 90% of the Proctor maximum dry densities for the material (varying from 1850-2100 kg/m^3), similarly high dry densities will not be achieved on site. This means that the hydraulic conductivities of the mineral sealing layers will in practice be lower, as well. However, when combined with synthetic liners (bentonite mat, HDPE geomembrane), the performance obtained with a combined layer should be on the order of approximately $<1x10^{-10}$ m/s or less. It is expected that this performance will undergo some degradation in time due to possible processes taking place in the surface repository that would deteriorate the quality of the sealing layers. In addition, evidence of the performance of synthetic materials over very long time scales does not exist, since these types of materials have only been in use for some decades and not centuries.

For the design, the preliminary recommendations are:

- Use a combination of a synthetic barrier (bentonite mat or HDPE geomembrane) and mineral sealing layer for ensuring better long-term performance, robustness against processes taking place in surface repository (including freezing and thawing) and fulfilling the principle of mutually complementing barriers.

- Use a mixture of crushed rock (or moraine) and bentonite in the mineral sealing layer with the amount of bentonite optimised based on the void volume of the crushed rock (Keto et al. 2020). This value is likely to be somewhere between 6 and 10%.

- Compact the mineral sealing layer to a dry density corresponding to at least 90% of the Proctor maximum determined for the material (Keto et al. 2020).

8. Discussion, recommendations and remaining uncertainties

Design basis and performance targets for a landfill type near surface repository have been discussed as part of the KYT2022 SURFACE project. This interim report further discusses how these performance targets and the processes expected in near surface conditions for the next 300 years can be taken into account in the design. In comparison to the requirements set for solid or hazardous waste landfills, the main differences between a landfill and a repository are the applied legislation, expected service life and passive post-closure safety. The safety of a repository should not rely on active post-closure monitoring or maintenance; passive safety functions provided by the surrounding structures are critical for its long-term performance. Formation of ground frost and frost heave is a process that has the potential to degrade the properties of the engineered barriers in time. In a normal or hazardous waste landfills, frost is not allowed to penetrate the level of the mineral sealing structures. Numerical modelling performed on the frost penetration depth during an average winter (F2) and cold winters occurring once in 20 years (F20) and once in 50 years (F50) indicates that all the layers of the cover structure may freeze during the F20 and F50 winters if the top soil layer is not thick enough or there is not sufficient snow coverage to provide insulation. This freezing implies that there is a risk for some deterioration of the cover structures due to frost upheave or deterioration of the clay-based barriers in the repository service life. These risks can be mitigated by increasing the thickness of the topmost cover layer from the minimum 1 m up to, e.g., 1.5-2 m. However, the frost penetration modelling should be repeated case by case based on the site specific scenarios for development of winter temperatures and taking into account the thermal properties (including also target densities) of the materials used in the design.

Post-closure site reforestation, especially considering pine trees, leading to root penetration deep into the soil and presenting a puncture risk to the synthetic layers is a long-term aspect that should be discussed further. This risk could also perhaps be mitigated by a thicker top layer, if no active post closure measures are required for preventing harmful vegetation to grow on top of the repository. HDPE layers also could prevent root penetration in the cover layer.

Calculations for the worst-case gas generation rates per kg of organic waste are not yet available and will be discussed further in the final year of the project. However, the key to minimise generation of gases in organic waste is keeping the waste as dry as possible. Considering the long-term performance, a combination of structures is recommended for the sealing layer at the cover consisting of a synthetic liner (bentonite mat or HDPE geomembrane) and a mineral sealing layer. The target k value for the mineral sealing layer is $<1x10^{-9}$ m/s, but in a combined structure the k-value in the initial state should be significantly lower, ($<1x10^{-10}$ m/s or lower), which would effectively decrease the infiltration of the water into the repository. Another possible measure would be to place the organic waste into metallic packages with watertight lids. This packaging would have at least two positive effects on the performance of the repository. The packages would keep the organic waste dry and provide better mechanical performance for the repository (less settlement of the cover layer due to soft waste and better support when installing the structures of the cover layer). Based on preliminary results from the migration of studies, interactions with metallic waste packages may reduce the mobility of some radionuclides through the disposal volume. However, this result will be confirmed in the final phase of the project. A process understanding of the radionuclide/waste package interaction, particularly with regard to reversibility, will need to be established.

There are also systems for collecting landfill gas, but the effects of these collection systems on the long-term performance due to their penetration through the landfill structure is unclear. Many of these systems also require active maintenance and handling of the discharged gases. A system could be installed for one part of the repository for study purposes. However, gases might not be produced until late in post-closure times if the water flow into the repository can be efficiently limited. Thus, an early gas monitoring program might not reveal whether or not such a system is needed. The ability of the cover structure and waste packages to limit contact of water with the waste is therefore considered important. The question of gas generation is discussed further in the next phase of the project based on the estimations on the worst-case gas generation within the repository (results available later in 2022).

The role of the drainage and leachate water collections systems on the long-term performance was discussed considering post-closure safety. Landfill drainage systems typically rely on active maintenance in terms of flushing of the drainage pipes for keeping them open. In a repository, this maintenance is possible while the repository is in the operational phase but not after closure. Similarly, active leachate monitoring and handling can be performed during the operational phase and possibly also during the post closure phase (even though the safety of the system shall not rely on active post-closure safety). In any case, some drainage function is in the foundation layer is needed after closure to avoid accumulation of water in the repository, even if the effectiveness of the drainage system decreases over time due to clogging. The importance of the performance of the cover layer is also clearly emphasised from this perspective.

It should also be remembered that any systems, including a leachate collection and a gas collection system that penetrate either through the cover or bottom layers can act as a potential means for water transport to and from the repository. Therefore, before any of such systems are planned, a thorough evaluation on their necessity and design should be performed.

Double HDPE geomembranes in the foundation layer were also suggested for more effective leachate collection. This idea was rejected based on the requirement for passive post closure safety of the repository, but could instead be applied for the cover layer.

9. List of Appendices

Appendix 1. Hydraulic conductivity results

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Appendix 1

APPENDIX 1

Tampereen yliopisto
Tutkimuskeskus TERRA Geo Road Rail

Nuutti Vuorimies, puh. 040 720 3050

TESTAUSSELOSTUS MPR/248/2020

1 (2)

9-12-2020

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 paino-%	*tiivistysvesipitoisuus* w_{opt} %	γ_d 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 alkuhalkaisijaa. 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/m³	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)

MPR/248/2020 Liite 1. 1/ 3

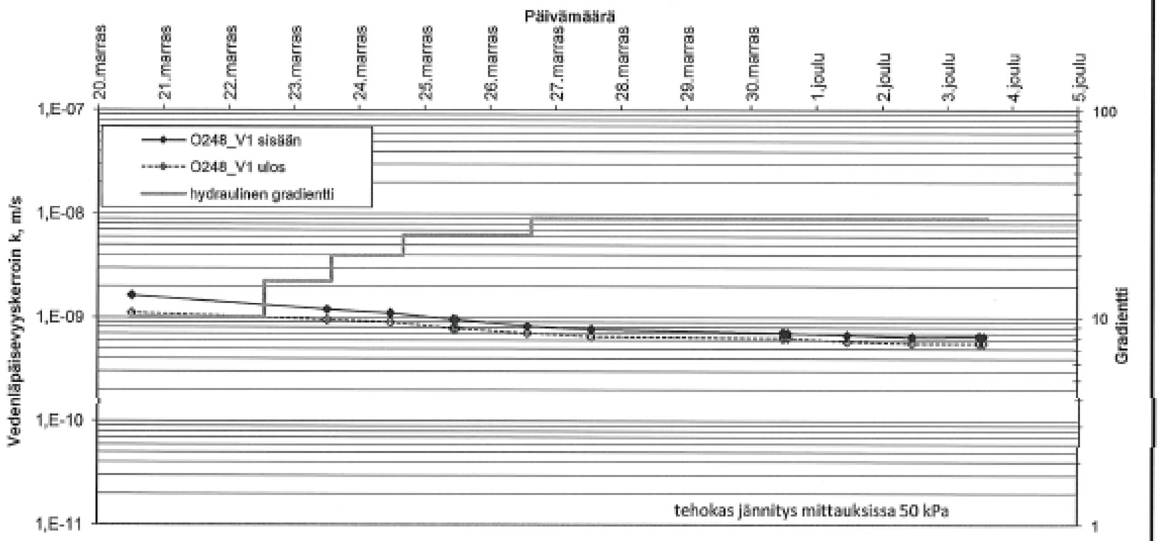
VEDENLÄPÄISEVYYDEN MÄÄRITYS PEHMEÄSEINÄMÄISELLÄ MENETELMÄLLÄ KOLMIAKSIAALIKOESELLISSÄ

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

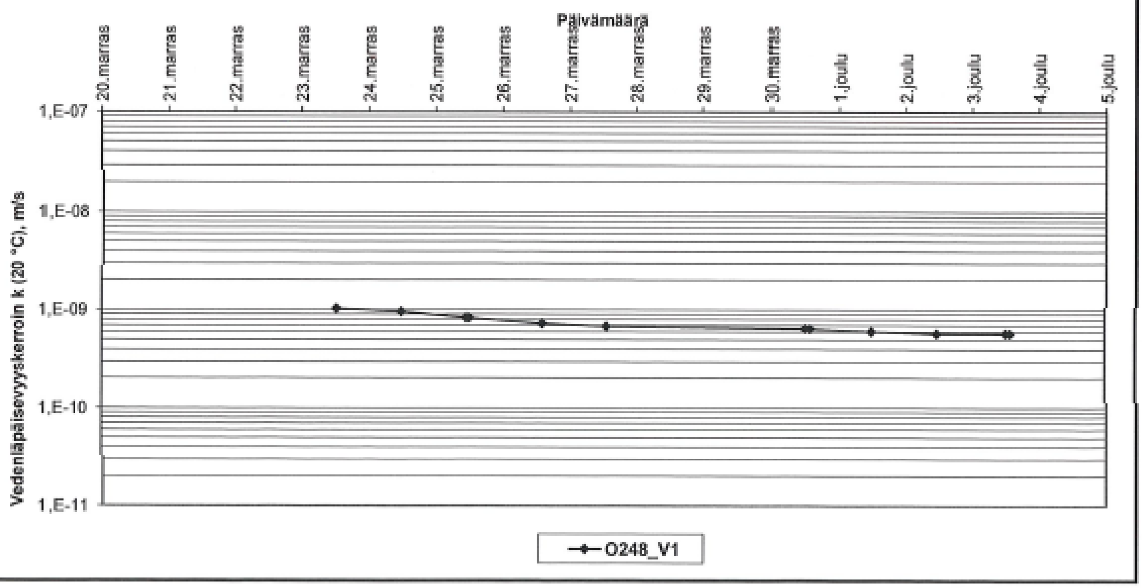
TIEDOT ENNEN KOETTA		
Näytteen korkeus	100,0	mm
Näytteen halkaisija	100,0	mm
Näytteen pinta-ala	78,5	cm²
Tilavuus	785	cm³
Paino ennen koetta	1576,4	g
Vesipitoisuus ennen koetta	6,1	%
Näytteen märkäirtotiheys	2007	kg/m³
Märkätilavuuspaino	19,7	kN/m³
Näytteen kuivairtotiheys	1892	kg/m³
Kuivatilavuuspaino	18,56	kN/m³
Kokoonpuristuma	0,0	mm
Korkeus konsolidoituneena	100,0	mm

TIEDOT KOKEEN JÄLKEEN (lask ρ_s=2,65 g/cm³)		
Näytteen korkeus konsolidoituneena	100,0	mm
Näytteen halkaisija (mitattu)	100,0	mm
Näytteen pinta-ala	78,5	cm²
Tilavuus	785	cm³
Näytteen paino kokeen jälkeen	1684,6	g
Näytteen kuivapaino	1486,1	g
Vesipitoisuus kokeen jälkeen	13,4	%
Näytteen märkäirtotiheys	2145	kg/m³
Märkätilavuuspaino	21,0	kN/m³
Näytteen kuivairtotiheys	1892	kg/m³
Kuivatilavuuspaino	18,56	kN/m³
Näytteen kyllästysaste	88	%

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

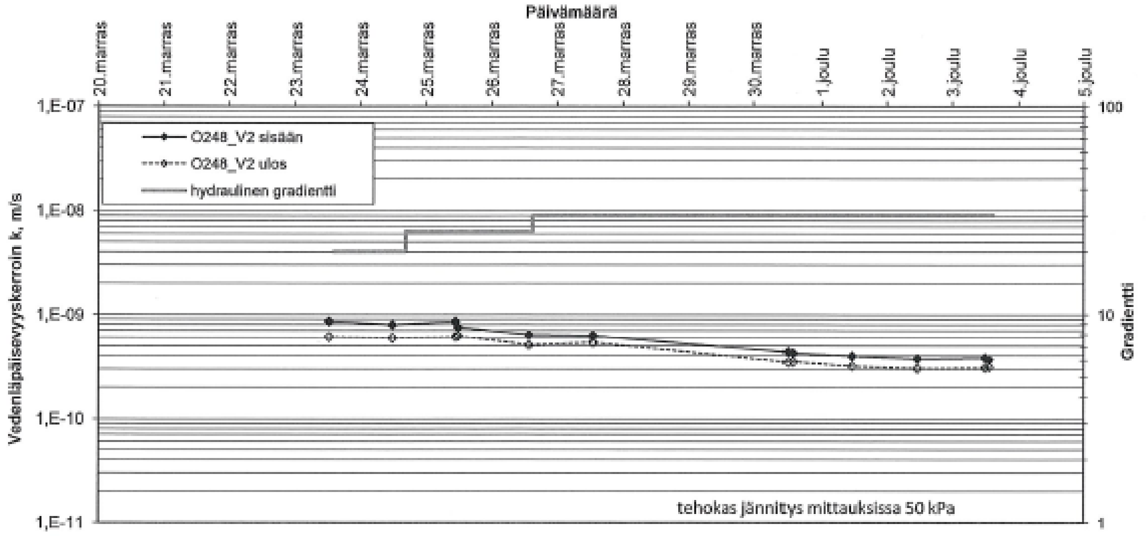


MPR/248/2020 Liite 1. 2/ 3

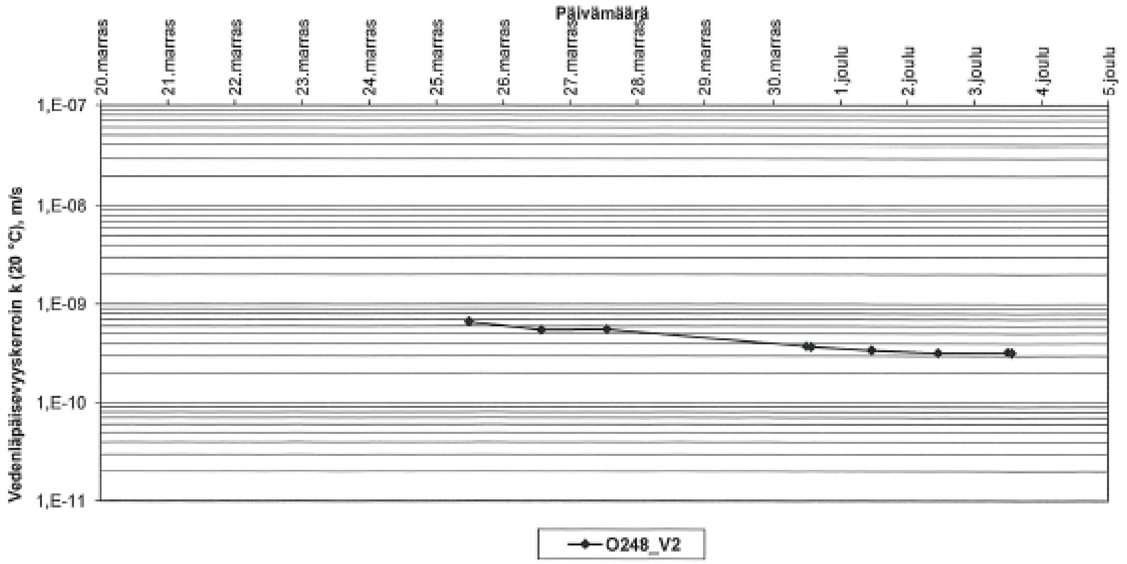
VEDENLÄPÄISEVYYDEN MÄÄRITYS PEHMEÄSEINÄMÄISELLÄ MENETELMÄLLÄ KOLMIAKSIAALIKOESELLISSÄ

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 tunnus	O248_V2	
Näytteen korkeus	99,9	mm	Näytteen korkeus konsolidoitunee	99,8	mm	Piste:	8 % bentoniitti	
Näytteen halkaisija	100,0	mm	Näytteen halkaisija (mitattu)	100,0	mm	Syvyys:	-	
Näytteen pinta-ala	78,5	cm²	Näytteen pinta-ala	78,5	cm²	Valmistuspvm:	17.11.2020	
Tilavuus	785	cm³	Tilavuus	784	cm³	VEDEN VIRTAUS: Q1= näytteeseen menevä tislattu vesi Q2=näytteestä tuleva vesi		
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	mediaani k (20 °C)	**3,2E-10**	m/s
Kuivatilavuuspaino	18,65	kN/m³	Kuivatilavuuspaino	18,67	kN/m³	keskim. k (20 °C)	**3,3E-10**	m/s
Kokoonpuristuma	0,1	mm	Näytteen kyllästysaste	86	%	Mittaaja:	NL, ES	
Korkeus konsolidoituneena	99,8	mm						



Vedenläpäisevyys, hyväksytyt tulokset

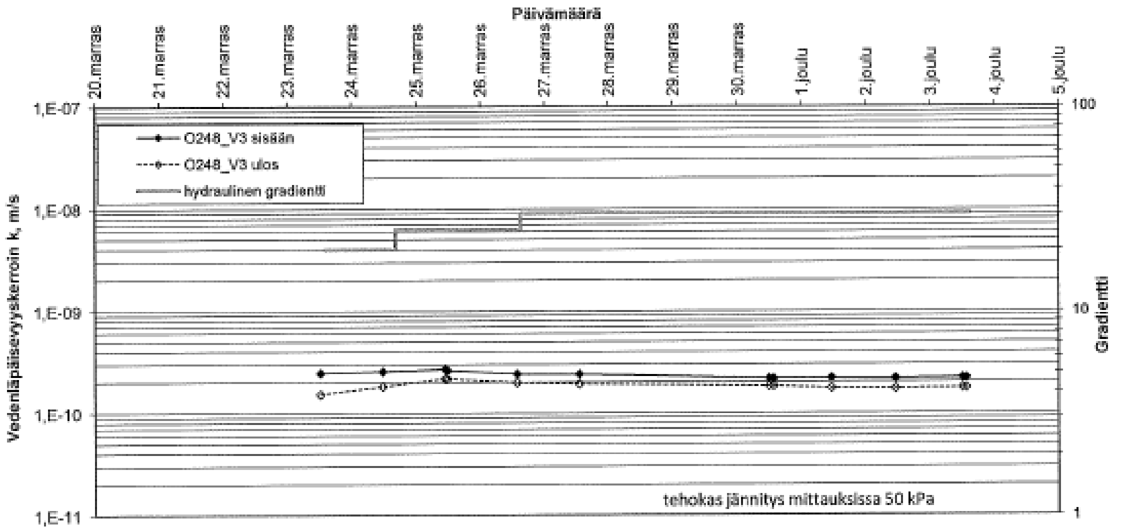


MPR/248/2020 Liite 1. 3/ 3

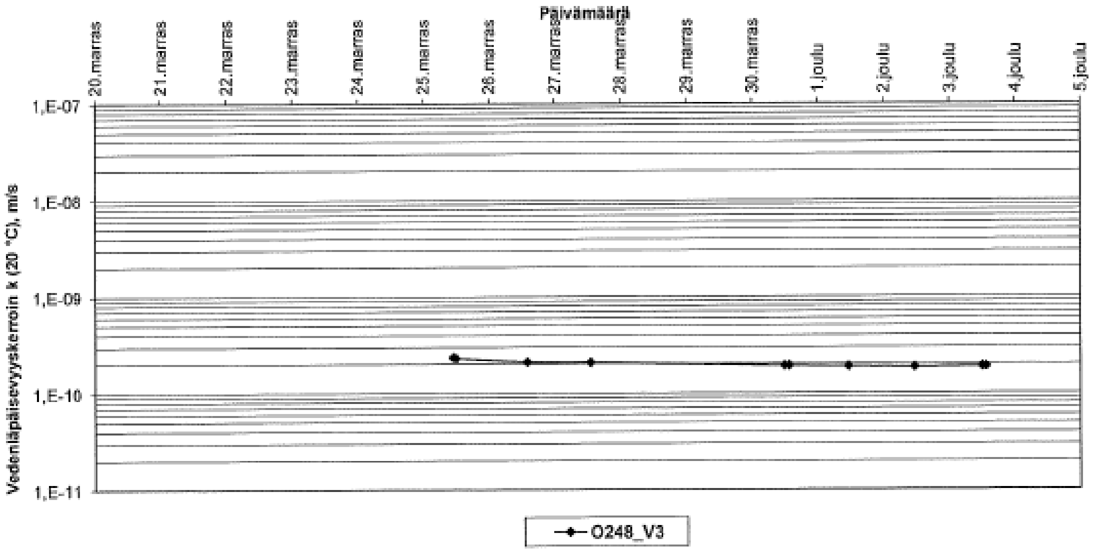
VEDENLÄPÄISEVYYDEN MÄÄRITYS PEHMEÄSEINÄMÄISELLÄ MENETELMÄLLÄ KOLMIAKSIAALIKOESELLISSÄ

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 tunnus	O248_V3
Näytteen korkeus	99,8	mm	Näytteen korkeus konsolidoitunee	99,6	mm	Piste:	10 % bentoniitti
Näytteen halkaisija	100,0	mm	Näytteen halkaisija (mitattu)	100,0	mm	Syvyys:	-
Näytteen pinta-ala	78,5	cm^2	Näytteen pinta-ala	78,5	cm^2	Valmistuspvm:	17.11.2020
Tilavuus	784	cm^3	Tilavuus	782	cm^3	VEDEN VIRTAUS: Q1= näytteeseen menevä tislattu vesi Q2=näytteestä tuleva vesi	
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/m^3	Näytteen märkäirtotiheys	2160	kg/m^3		
Märkätilavuuspaino	20,4	kN/m^3	Märkätilavuuspaino	21,2	kN/m^3		
Näytteen kuivairtotiheys	1912	kg/m^3	Näytteen kuivairtotiheys	1916	kg/m^3	mediaani k (20 °C)	**1,9E-10** m/s
Kuivatilavuuspaino	18,75	kN/m^3	Kuivatilavuuspaino	18,79	kN/m^3	keskim. k (20 °C)	**1,9E-10** m/s
Kokoonpuristuma	0,2	mm	Näytteen kyllästysaste	88	%	Mittaaja:	NL, ES
Korkeus konsolidoituneena	99,6	mm					



Vedenläpäisevyys, hyväksytyt tulokset



Tampereen yliopisto
Tutkimuskeskus TERRA Geo Road Rail

Nuutti Vuorimies, puh. 040 720 3050

10-1-2022

VTT Oy
Paula Keto

Tilaus 15.11.2021
KYT, vedenläpäisevyyskokeet

Näytteet

Tilaaja toimitti koekappaleet muovisylintereissä, joiden päät oli suljettu vanerilevyillä. Muovisylinteri ja päiden sulut oli ympäröity muovikelmulla ja kukin koekappale oli vielä omassa muoviämpärissä. Koekappaleet olivat projektista KYT ja niiden tiedot on esitetty taulukossa 1. Näytteet otettiin vastaan Tampereen yliopistolla 9.9. ja 19.11.2021. Toimitettujen näytteiden edustavuus on tilaajan vastuulla. Tampereen yliopistolla näytteille tehtiin kokeet työnumerolla 182/2021.

Taulukko 1. Näytteet kohteesta KYT.

	bentoniittiä	Sarja
ei J-S	6 %	1
ei J-S	8 %	1
ei J-S	10 %	1
J-S	6 %	2
J-S	8 %	2
J-S	10 %	2

J-S tarkoittaa, että toimitetut koekappaleet olivat käyneet läpi jäädytys-sulatussyklit

Näytteiden esikäsittely

Koekappaleet säilytettiin jääkaapissa ennen testausta.

Testausmenetelmät

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

Tulokset

Vedenläpäisevyyskokeiden tulokset ovat liitteessä 1 ja niissä on esitetty koekappaleiden vedenläpäisevyyskuvaajat ja taulukossa 2 on esitetty määritetty vedenläpäisevyyskerroin 20 °C lämpötilassa. Vedenläpäisevyyskerroin määritettiin neljän viimeisen mittaustuloksen keskiarvona. Mittauksissa koekappaleen korkeutena ja halkaisijana käytettiin kokeen alussa määritettyjä arvoja. Koekappaleisiin ei muodostunut kokoonpuristumaa vedenläpäisevyyden mittauksen aikana ja koekappaleiden laajeneminen ylöspäin oli estetty. Kokeessa käytettiin ionivaihdettua vettä. Koekappaleen keskimääräinen tehokas jännitys oli 50 kPa sellipaineen ollessa 200 kPa. Mittausten aikana keskimäärinen lämpötila oli 21,7 °C. Kyllästysasteen laskemisessa käytettiin oletuskiintotiheyttä ja B-arvoa ei mitattu.

Tampereen yliopisto
Tutkimuskeskus TERRA Geo Road Rail

Nuutti Vuorimies, puh. 040 720 3050

10-1-2022

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

Koekappale (bentoniittiä)	γ_d kN/m³	k_s, (20°C) m/s	k_u, (20°C) m/s	i
P182_V1 (6 %)	19,9	$3,1*10^{-10}$	$2,4*10^{-10}$	41
P182_V2 (8 %)	19,5	$2,4*10^{-10}$	$1,8*10^{-10}$	42
P182_V3 (10 %)	19,5	$2,9*10^{-11}$	$1,5*10^{-12}$	47
P182_V4 (6 %)	20,2	$2,2*10^{-10}$	$1,8*10^{-10}$	29
P182_V5 (8 %)	20,2	$1,0*10^{-10}$	$0,9*10^{-10}$	30
P182_V6 (10 %)	19,3	$1,5*10^{-10}$	$1,2*10^{-10}$	29

Koekappaleet P182_V4-P182_V6 olivat käyneet läpi jäädytyssulatussyklit ennen niiden toimittamista vedenläpäisevyysmääritykseen

Kokeet tehtiin 24.9.2021 – 3.1.2022. Alustavasti osa koetuloksista lähetettiin 2.12.2021. Tulokset pätevät ainoastaan testatuille näytteille. Testausselostuksen saa kopioida ainoastaan kokonaisuudessaan. Mahdollisesti jäljelle jääneitä näytteitä säilytetään kolme kuukautta testausselostuksen päiväyksestä.

Projektipäällikkö, DI — Nuutti Vuorimies

Laboratoriomestari — Mirka Pietiläinen

JAKELU — Tilaaja
Tampereen yliopisto

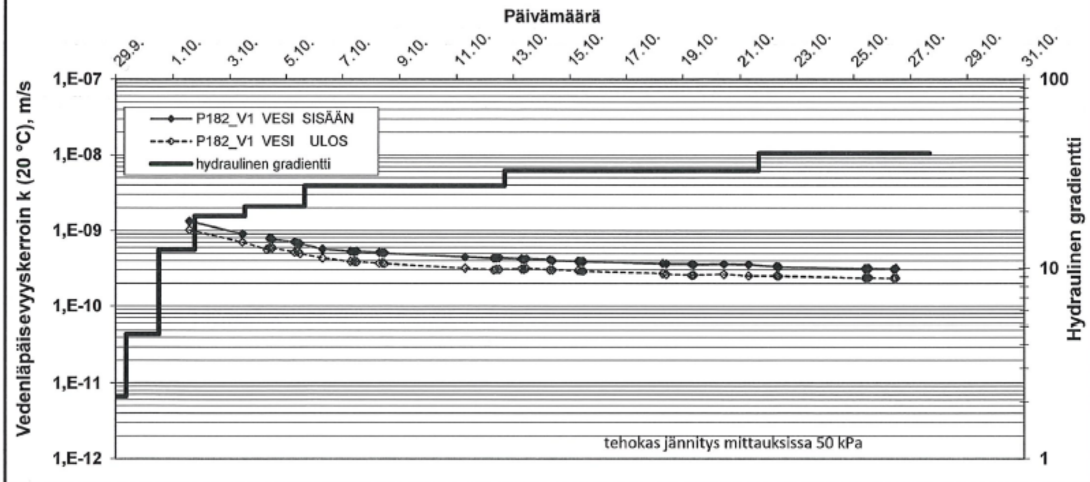
LIITTEET: — Liite 1. Vedenläpäisevyyskokeiden tulokset (6 sivu)

Testausselostus GeoLa/182/2021 Liite 1. 1 / 6

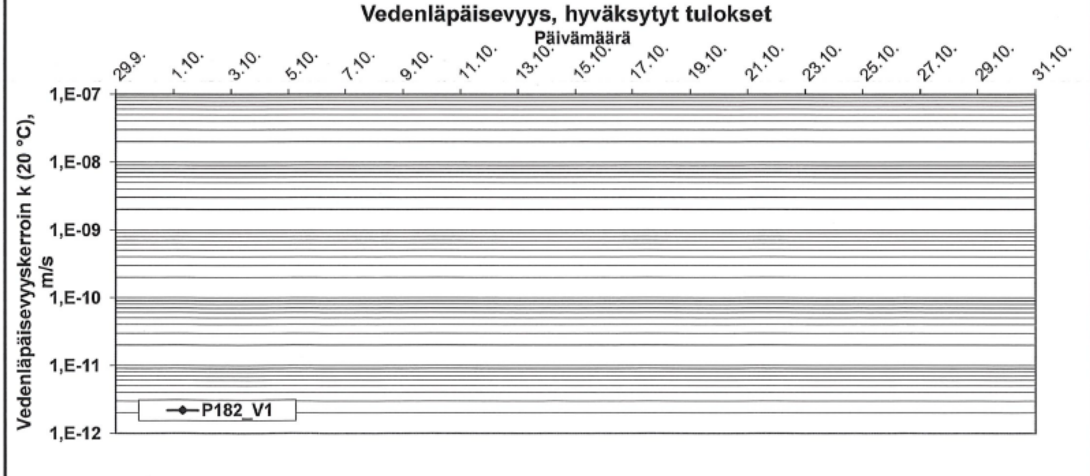
VEDENLÄPÄISEVYYDEN MÄÄRITYS VAKIOPAINEMENETELMÄ: PEHMEÄSEINÄMÄINEN KOENÄYTE

Tampereen yliopisto	**ASIAKAS**	**VTT Oy**
Tutkimuskeskus Terra	**KOHDE**	**KYT**
PL 600, 33014 Tampereen yliopisto	**TYÖNUMERO**	**182/2021**

Koenäytteen tunnus:	**P182_V1**		**Piste ja syvyys / materiaali:**	**6 % bentoniitti**			
KOENÄYTE ENNEN KONSOLIDOINTIA			**ja MITATTAESSA** (lask ρ_s=2.65 g/cm³)			**sekä PURETTAESSA**	
Valmistettu: pvm & tekijä	24.9.-21 MP/NV		Kokoonpuristui konsolidoinnissa	0,2	mm	Purettu pvm	24.11.-21
Koenäytteen korkeus	103,3	mm	Korkeus konsolidoituneena	103,1	mm	Korkeus, mm	103,3
Koenäytteen halkaisija	99,5	mm	Halkaisija	99,4	mm	Halkaisija, mm	99,4
Pinta-ala	77,8	cm²	Pinta-ala	77,6	cm²	Astia, g	48,5
Tilavuus	804	cm³	Tilavuus	800	cm³	A+ märkä näyte, g	1847,5
Paino ennen koetta	1765,4	g	Paino kokeen jälkeen	1799,0	g	A+ kuiva näyte, g	1670,4
			Kuivapaino	1621,9	g	**HUOM!** Sisään 3,1E-10 m/s ja	
Vesipitoisuus ennen koetta	8,8	%	Vesipitoisuus kokeen jälkeen	10,9	%	ulos 2,4E-10 m/s	
Märkäirtotiheys	2197	kg/m³	Märkäirtotiheys	2248	kg/m³	**Vedenläpäisevyyskerroin**	
Märkätilavuuspaino	21,6	kN/m³	Märkätilavuuspaino	22,1	kN/m³		**k (20 °C), m/s**
Kuivairtotiheys	2018	kg/m³	Kuivairtotiheys	2026	kg/m³	**mediaani**	**#NUM!**
Kuivatilavuuspaino	19,80	kN/m³	Kuivatilavuuspaino	19,88	kN/m³	**keskiarvo**	**#DIV/0!**
Kyllästysaste	75	%	Kyllästysaste	94	%	Mittaajat:	MP, NV



Vedenläpäisevyys, hyväksytyt tulokset



Päivittäjä: NL
Päivitetty: 10.3.2021

Tarkastaja: 11.3.2021 NV

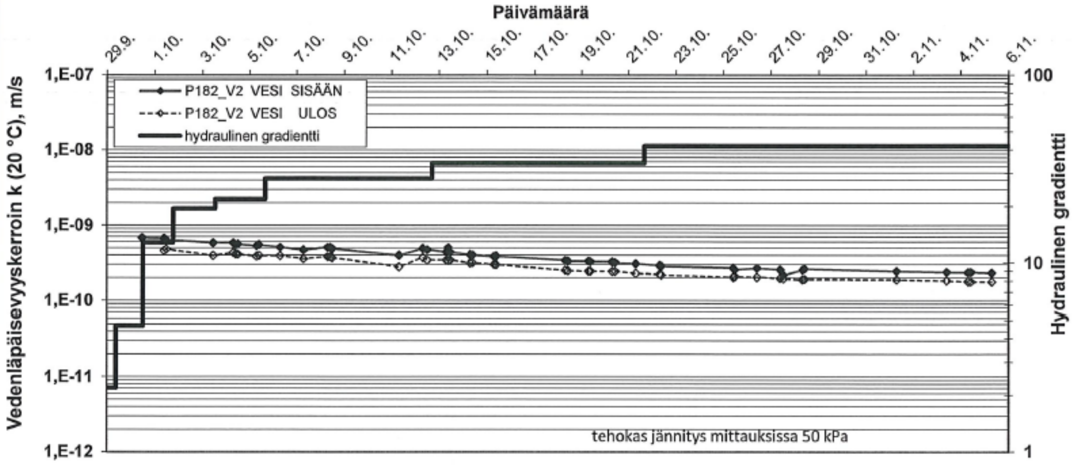
Tulostettu:
2.12.2021

Testausselostus GeoLa/182/2021 Liite 1. 2 / 6

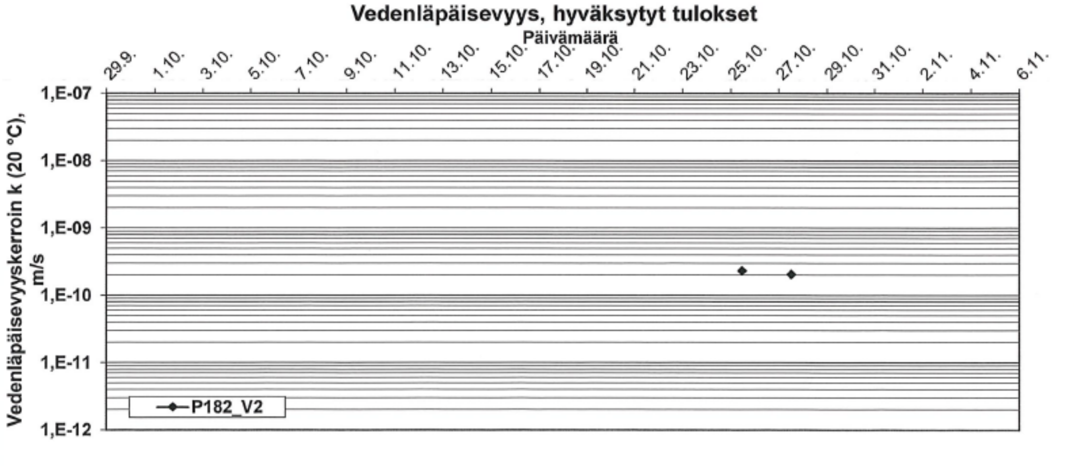
VEDENLÄPÄISEVYYDEN MÄÄRITYS VAKIOPAINEMENETELMÄ: PEHMEÄSEINÄMÄINEN KOENÄYTE

Tampereen yliopisto	**ASIAKAS**	**VTT Oy**
Tutkimuskeskus Terra	**KOHDE**	**KYT**
PL 600, 33014 Tampereen yliopisto	**TYÖNUMERO**	**182/2021**

Koenäytteen tunnus:	**P182_V2**		**Piste ja syvyys / materiaali:**	**8 % bentoniitti**			
KOENÄYTE ENNEN KONSOLIDOINTIA			**ja MITATTAESSA** (lask ρ_s=2.65 g/cm^3)			**sekä PURETTAESSA**	
Valmistettu: pvm & tekijä	24.9.-21 MP/NV		Kokoonpuristui konsolidoinnissa	0,0	mm	Purettu pvm	24.11.-21
Koenäytteen korkeus	100,3	mm	Korkeus konsolidoituneena	100,3	mm	Korkeus, mm	101,4
Koenäytteen halkaisija	99,5	mm	Halkaisija	99,6	mm	Halkaisija, mm	100,0
Pinta-ala	77,8	cm^2	Pinta-ala	77,9	cm^2	Astia, g	49,0
Tilavuus	780	cm^3	Tilavuus	782	cm^3	A+ märkä näyte, g	1811,1
Paino ennen koetta	1735,3	g	Paino kokeen jälkeen	1762,1	g	A+ kuiva näyte, g	1606,0
			Kuivapaino	1557,0	g	**HUOM!** Sisään 2,4E-10 m/s ja	
Vesipitoisuus ennen koetta	11,5	%	Vesipitoisuus kokeen jälkeen	13,2	%	ulos 1,8E-10 m/s	
Märkäirtotiheys	2225	kg/m^3	Märkäirtotiheys	2255	kg/m^3	**Vedenläpäisevyyskerroin**	
Märkätilavuuspaino	21,8	kN/m^3	Märkätilavuuspaino	22,1	kN/m^3		**k (20 °C), m/s**
Kuivairtotiheys	1996	kg/m^3	Kuivairtotiheys	1992	kg/m^3	**mediaani**	**#NUM!**
Kuivatilavuuspaino	19,58	kN/m^3	Kuivatilavuuspaino	19,54	kN/m^3	**keskiarvo**	**#DIV/0!**
Kyllästysaste	93	%	Kyllästysaste	106	%	Mittaajat:	MP, NV



Vedenläpäisevyys, hyväksytyt tulokset



Päivittäjä: NL
Päivitetty: 10.3.2021

Tarkastaja: 11.3.2021 NV

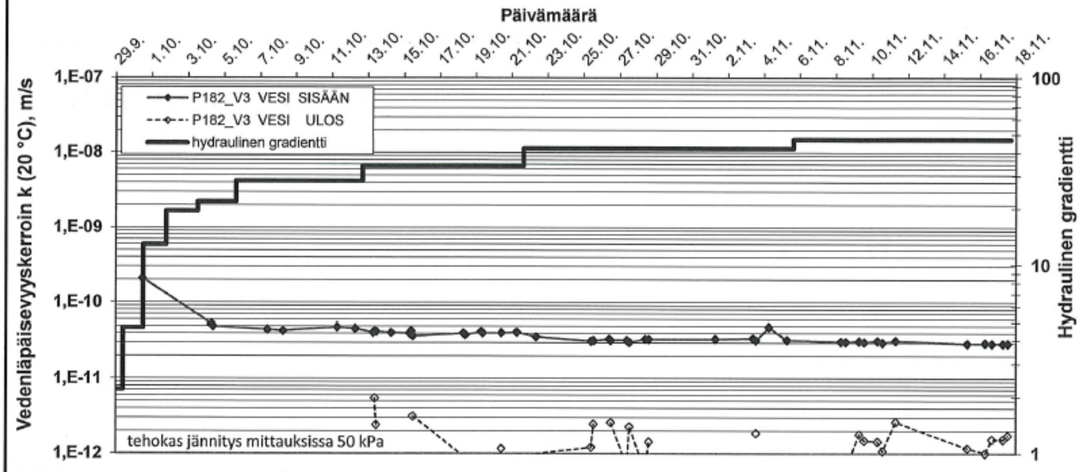
Tulostettu:
2.12.2021

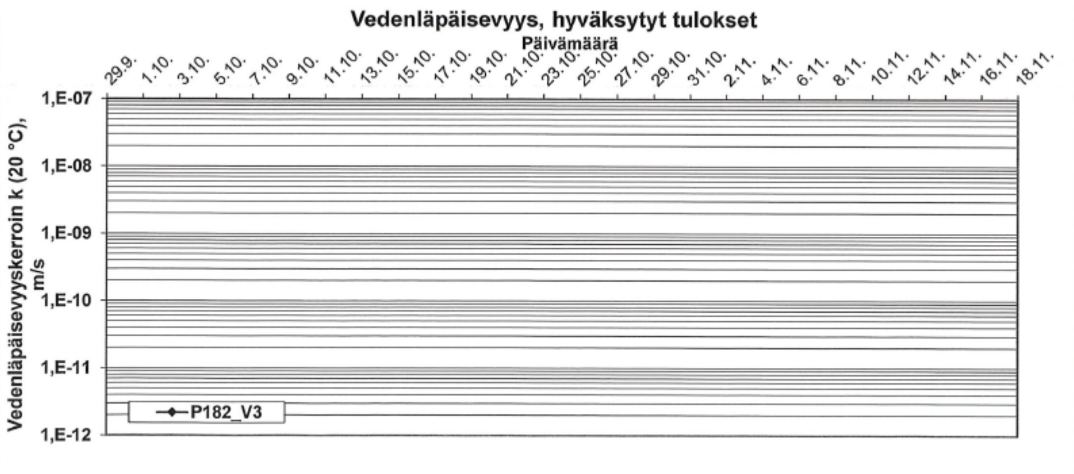
Testausselostus GeoLa/182/2021 Liite 1. 3 / 6

VEDENLÄPÄISEVYYDEN MÄÄRITYS VAKIOPAINEMENETELMÄ: PEHMEÄSEINÄMÄINEN KOENÄYTE

Tampereen yliopisto	**ASIAKAS**	**VTT**
Tutkimuskeskus Terra	**KOHDE**	**KYT**
PL 600, 33014 Tampereen yliopisto	**TYÖNUMERO**	**182/2021**

Koenäytteen tunnus:	**P182_V3**		**Piste ja syvyys / materiaali:**	**10 % bentoniitti**			
KOENÄYTE ENNEN KONSOLIDOINTIA			**ja MITATTAESSA** (lask ρ_s=2.65 g/cm^3)			**sekä PURETTAESSA**	
Valmistettu: pvm & tekijä	24.9.-21 MP/NV		Kokoonpuristui konsolidoinnissa	0,0	mm	Purettu pvm	24.11.-21
Koenäytteen korkeus	100,5	mm	Korkeus konsolidoituneena	100,5	mm	Korkeus, mm	103,2
Koenäytteen halkaisija	99,5	mm	Halkaisija	99,7	mm	Halkaisija, mm	99,8
Pinta-ala	77,8	cm^2	Pinta-ala	78,1	cm^2	Astia, g	48,3
Tilavuus	781	cm^3	Tilavuus	785	cm^3	A+ märkä näyte, g	1824,0
Paino ennen koetta	1753,5	g	Paino kokeen jälkeen	1775,7	g	A+ kuiva näyte, g	1610,7
			Kuivapaino	1562,4	g	**HUOM!** Sisään 2,9E-11 m/s ja ulos 1,5E-12 m/s	
Vesipitoisuus ennen koetta	12,2	%	Vesipitoisuus kokeen jälkeen	13,7	%		
Märkäirtotiheys	2244	kg/m^3	Märkäirtotiheys	2263	kg/m^3	**Vedenläpäisevyyskerroin**	
Märkätilavuuspaino	22,0	kN/m^3	Märkätilavuuspaino	22,2	kN/m^3		**k (20 °C), m/s**
Kuivairtotiheys	1999	kg/m^3	Kuivairtotiheys	1991	kg/m^3	**mediaani**	**#NUM!**
Kuivatilavuuspaino	19,61	kN/m^3	Kuivatilavuuspaino	19,54	kN/m^3	**keskiarvo**	**#DIV/0!**
Kyllästysaste	100	%	Kyllästysaste	109	%	Mittaajat:	MP, NV





Päivittäjä: NL
Päivitetty: 10.3.2021

Tarkastaja: 11.3.2021 NV

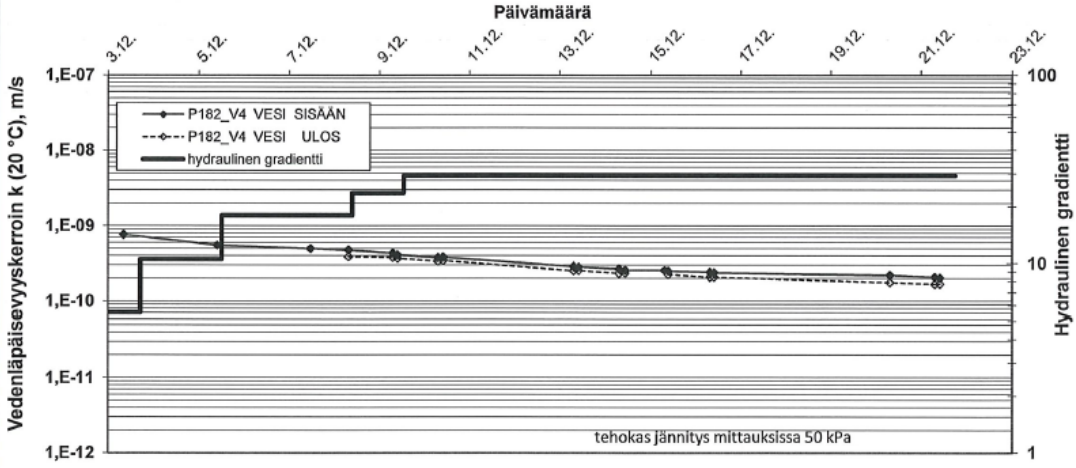
Tulostettu: 2.12.2021

Testausselostus GeoLa/182/2021 Liite 1. 4 / 6

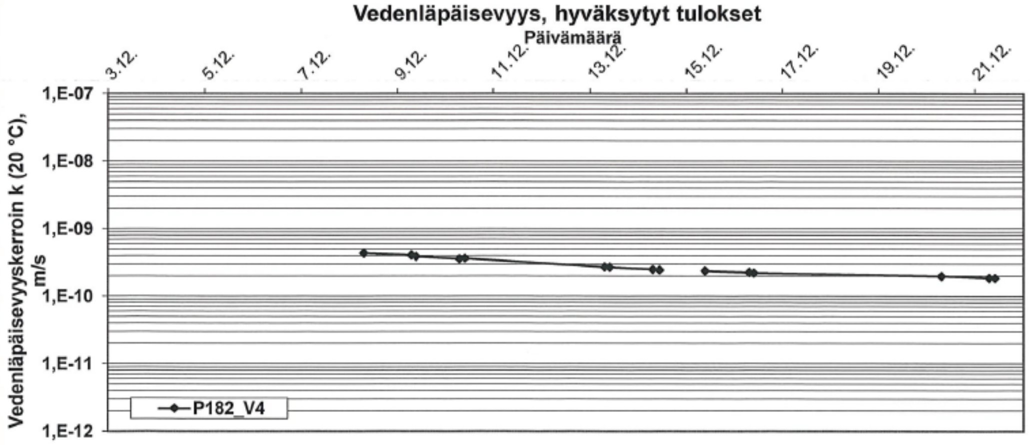
VEDENLÄPÄISEVYYDEN MÄÄRITYS VAKIOPAINEMENETELMÄ: PEHMEÄSEINÄMÄINEN KOENÄYTE

Tampereen yliopisto	**ASIAKAS**	**VTT Oy**
Tutkimuskeskus Terra	**KOHDE**	**KYT**
PL 600, 33014 Tampereen yliopisto	**TYÖNUMERO**	**182/2021**

Koenäytteen tunnus:	**P182_V4**		**Piste ja syvyys / materiaali:**	**6 % bentoniitti** (Jäädytys-sulatussyklien jälkeen)			
KOENÄYTE ENNEN KONSOLIDOINTIA			**ja MITATTAESSA** (lask ρ_s=2.65 g/cm^3)			**sekä PURETTAESSA**	
Valmistettu: pvm & tekijä	29.11.-21 MP		Kokoonpuristui konsolidoinnissa	0,0	mm	Purettu pvm	29.12.-21
Koenäytteen korkeus	101,8	mm	Korkeus konsolidoituneena	101,8	mm	Korkeus, mm	100,9
Koenäytteen halkaisija	99,0	mm	Halkaisija	99,0	mm	Halkaisija, mm	99,4 - 100,0
Pinta-ala	77,0	cm^2	Pinta-ala	77,0	cm^2	Astia, g	48,2
Tilavuus	783	cm^3	Tilavuus	783	cm^3	A+ märkä näyte, g	1827,2
Paino ennen koetta	1698,0	g	Paino kokeen jälkeen	1779,0	g	A+ kuiva näyte, g	1658,2
			Kuivapaino	1610,0	g	**HUOM!**	
Vesipitoisuus ennen koetta	5,5	%	Vesipitoisuus kokeen jälkeen	10,5	%		
Märkäirtotiheys	2167	kg/m^3	Märkäirtotiheys	2271	kg/m^3	**Vedenläpäisevyyskerroin**	
Märkätilavuuspaino	21,3	kN/m^3	Märkätilavuuspaino	22,3	kN/m^3		**k (20 °C), m/s**
Kuivairtotiheys	2055	kg/m^3	Kuivairtotiheys	2055	kg/m^3	**mediaani**	**1,9E-10**
Kuivatilavuuspaino	20,16	kN/m^3	Kuivatilavuuspaino	20,16	kN/m^3	**keskiarvo**	**2,0E-10**
Kyllästysaste	50	%	Kyllästysaste	96	%	Mittaajat:	MP, NV



Vedenläpäisevyys, hyväksytyt tulokset



Päivittäjä: NL
Päivitetty: 10.3.2021

Tarkastaja: 11.3.2021 NV

Tulostettu:
10.1.2022

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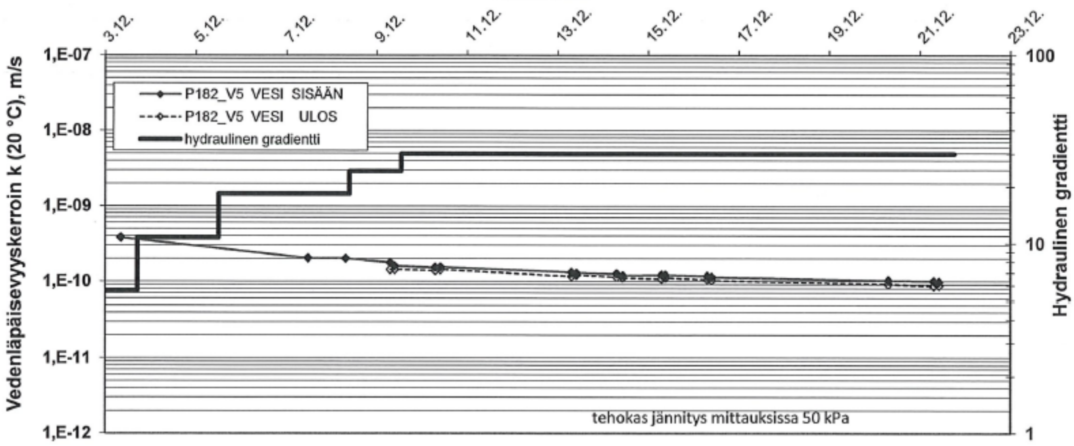
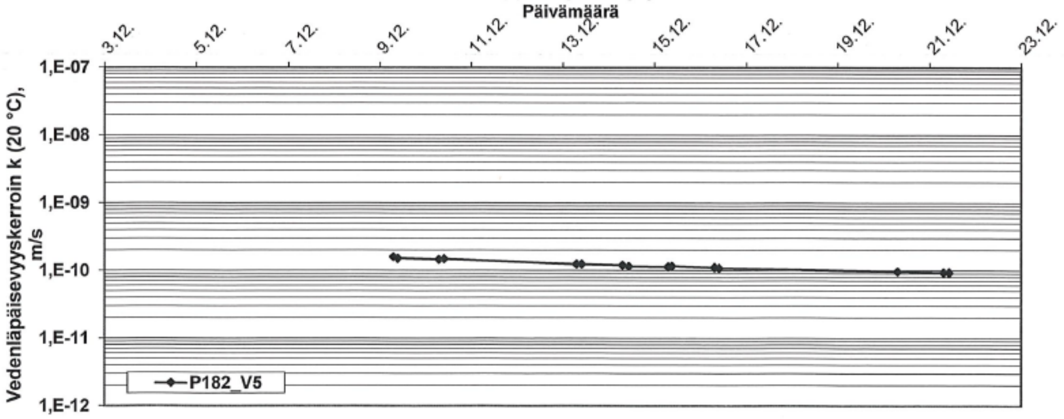
VEDENLÄPÄISEVYYDEN MÄÄRITYS VAKIOPAINEMENETELMÄ: PEHMEÄSEINÄMÄINEN KOENÄYTE

Tampereen yliopisto	**ASIAKAS**	**VTT Oy**
Tutkimuskeskus Terra	**KOHDE**	**KYT**
PL 600, 33014 Tampereen yliopisto	**TYÖNUMERO**	**182/2021**

Koenäytteen tunnus:	**P182_V5**		**Piste ja syvyys / materiaali:**	**8 % bentoniitti** (Jäädytys-sulatussyklien jälkeen)			
KOENÄYTE ENNEN KONSOLIDOINTIA			**ja MITATTAESSA** (lask ρ_s=2.65 g/cm^3)			**sekä PURETTAESSA**	
Valmistettu: pvm & tekijä	30.11.-21 MP		Kokoonpuristui konsolidoinnissa	0,0	mm	Purettu pvm	29.12.-21
Koenäytteen korkeus	99,4	mm	Korkeus konsolidoituneena	99,4	mm	Korkeus, mm	99,8
Koenäytteen halkaisija	99,3	mm	Halkaisija	99,3	mm	Halkaisija, mm	99,3-100,4
Pinta-ala	77,4	cm^2	Pinta-ala	77,4	cm^2	Astia, g	47,9
Tilavuus	769	cm^3	Tilavuus	769	cm^3	A+ märkä näyte, g	1802,4
Paino ennen koetta	1703,5	g	Paino kokeen jälkeen	1754,5	g	A+ kuiva näyte, g	1632,6
			Kuivapaino	1584,7	g	**HUOM!**	
Vesipitoisuus ennen koetta	7,5	%	Vesipitoisuus kokeen jälkeen	10,7	%		
Märkäirtotiheys	2214	kg/m^3	Märkäirtotiheys	2280	kg/m^3	**Vedenläpäisevyyskerroin**	
Märkätilavuuspaino	21,7	kN/m^3	Märkätilavuuspaino	22,4	kN/m^3		**k (20 °C), m/s**
Kuivairtotiheys	2059	kg/m^3	Kuivairtotiheys	2059	kg/m^3	**mediaani**	**9,5E-11**
Kuivatilavuuspaino	20,20	kN/m^3	Kuivatilavuuspaino	20,20	kN/m^3	**keskiarvo**	**9,8E-11**
Kyllästysaste	69	%	Kyllästysaste	99	%	Mittaajat:	MP, NV



Vedenläpäisevyys, hyväksytyt tulokset



Päivittäjä: NL
Päivitetty: 10.3.2021

Tarkastaja: 11.3.2021 NV

Tulostettu:
10.1.2022

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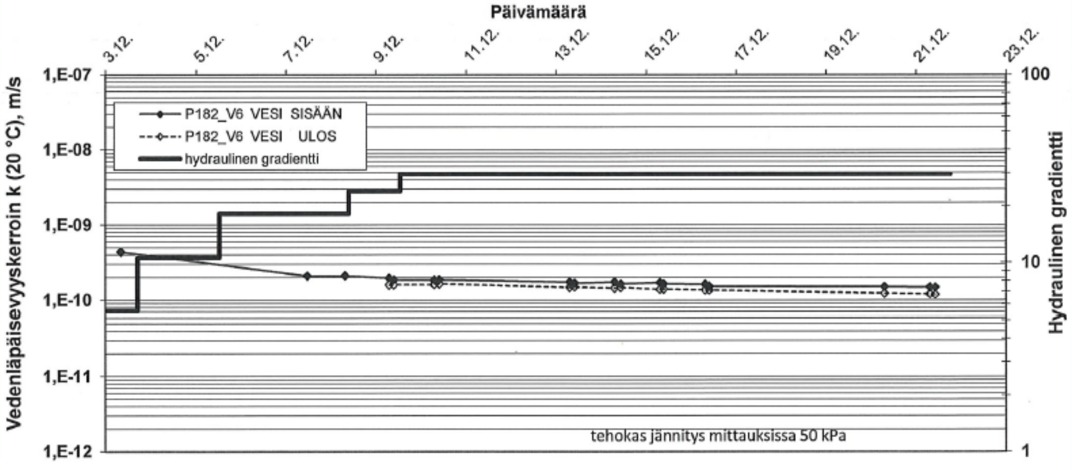
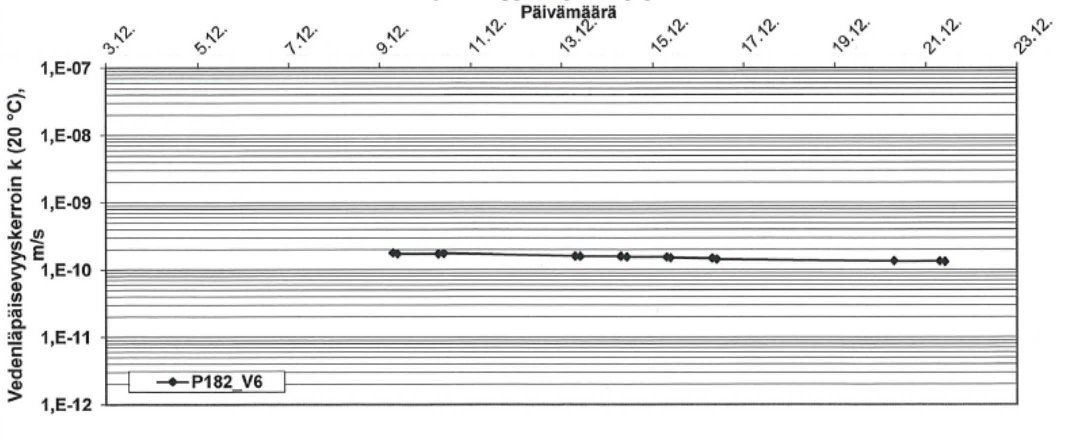
VEDENLÄPÄISEVYYDEN MÄÄRITYS VAKIOPAINEMENETELMÄ: PEHMEÄSEINÄMÄINEN KOENÄYTE

Tampereen yliopisto	**ASIAKAS**	**VTT Oy**
Tutkimuskeskus Terra	**KOHDE**	**KYT**
PL 600, 33014 Tampereen yliopisto	**TYÖNUMERO**	**182/2021**

Koenäytteen tunnus:	**P182_V6**		**Piste ja syvyys / materiaali:**	**10 % bentoniitti** (Jäädytys-sulatussyklien jälkeen)			
KOENÄYTE ENNEN KONSOLIDOINTIA			**ja MITATTAESSA** (lask ρ_s=2.65 g/cm^3)			**sekä PURETTAESSA**	
Valmistettu: pvm & tekijä	30.11.-21 MP		Kokoonpuristui konsolidoinnissa	0,0	mm	Purettu pvm	29.12.-21
Koenäytteen korkeus	100,9	mm	Korkeus konsolidoituneena	100,9	mm	Korkeus, mm	99,6
Koenäytteen halkaisija	99,2	mm	Halkaisija	99,2	mm	Halkaisija, mm	99,8-100,8
Pinta-ala	77,3	cm^2	Pinta-ala	77,3	cm^2	Astia, g	48,9
Tilavuus	779	cm^3	Tilavuus	779	cm^3	A+ märkä näyte, g	1781,3
Paino ennen koetta	1677,2	g	Paino kokeen jälkeen	1732,4	g	A+ kuiva näyte, g	1583,4
			Kuivapaino	1534,5	g	**HUOM!**	
Vesipitoisuus ennen koetta	9,3	%	Vesipitoisuus kokeen jälkeen	12,9	%		
Märkäirtotiheys	2152	kg/m^3	Märkäirtotiheys	2223	kg/m^3	**Vedenläpäisevyyskerroin**	
Märkätilavuuspaino	21,1	kN/m^3	Märkätilavuuspaino	21,8	kN/m^3		**k (20 °C), m/s**
Kuivairtotiheys	1969	kg/m^3	Kuivairtotiheys	1969	kg/m^3	**mediaani**	**1,3E-10**
Kuivatilavuuspaino	19,31	kN/m^3	Kuivatilavuuspaino	19,31	kN/m^3	**keskiarvo**	**1,4E-10**
Kyllästysaste	71	%	Kyllästysaste	99	%	Mittaajat:	MP, NV



Vedenläpäisevyys, hyväksytyt tulokset



Päivittäjä: NL
Päivitetty: 10.3.2021

Tarkastaja: 11.3.2021 NV

Tulostettu:
10.1.2022