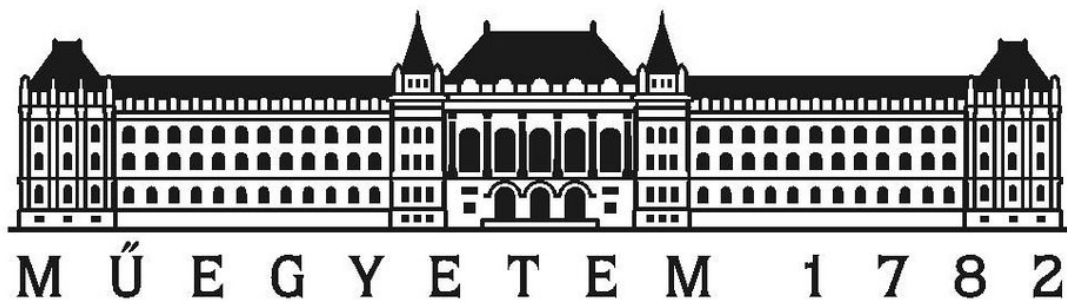




Testing of Pre-Compacted Bentonite Blocks for Radioactive Waste Disposal

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Abstract

Low-carbon energy production is a key direction in sustainable development. One significant contribution to energy balance is the use of nuclear power. Hazardous wastes are generated during the energy production and operation of nuclear power plants. The environment-friendly deposition of this waste is a crucial factor in producing green energy. Despite several research centres and efforts, no operating plants are at final disposal worldwide. It is well-known that final disposal in a deep-seated rock environment is feasible. The current research deals with one aspect of safe disposal: sealing radioactive waste from the environment in deep geological settings. For this purpose, bentonite (a water-tight clay mineral) is used. This study focuses on the use of bentonite in the form of pre-compacted clay bricks. These bentonite blocks are vital in maintaining structural integrity and preventing the water movement of released nuclides from waste canisters. This study evaluates the physical properties of these blocks under various loads and environmental conditions. The tests are performed under laboratory conditions. Preliminary results of density, uniaxial compressive tests and other physical properties of bricks with various compacted bentonites are presented. The research aims to determine whether these blocks can withstand the pressures and stresses they are expected to encounter in a nuclear waste repository over long periods, ensuring the mechanical stability of the storage environment.

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I. INTRODUCTION

People widely recognize nuclear energy as one of the most efficient and low-carbon energy sources available today. Nuclear energy is a lot better than a non-renewable fuel source because it has a high energy density, low greenhouse gas emissions, and it can produce a large amount of electricity without a lot of environmental impact. The good thing about nuclear energy, as opposed to the renewables (solar and wind) is that it is a constant and dependable source of energy that doesn't depend on weather. Ergo nuclear is the solution to the problem of global warming and the demand for clean energy in a world that desires energy. However, one of the drawbacks of nuclear energy is the disposal of the radioactive waste. Nuclear reactors discharge waste that is dangerous for tens of thousands of years, so some sort of permanent, safe storage method must be devised to keep it away from people and the environment to prevent radiation sickness and contamination. That's why, if we would like to keep this energy renewable and safe, we need to throw it away correctly.

One of the most promising approaches for managing radioactive waste is deep geological disposal which entails the isolation of waste in a stable geological formation at great depths. These types of repositories use natural geologic conditions as well as man-made barriers (pre-compacted bentonite blocks for example) to keep the waste contained and isolated for tens of thousands of years. Radioactive waste needs to be disposed of correctly, for the sake of the environment and for the sake of public health. Poor disposal or storage could lead to air, soil, and groundwater contamination, which may have adverse impacts on ecosystems and human populations. Also, if not properly secured, radioactive materials could pose long term security risks.

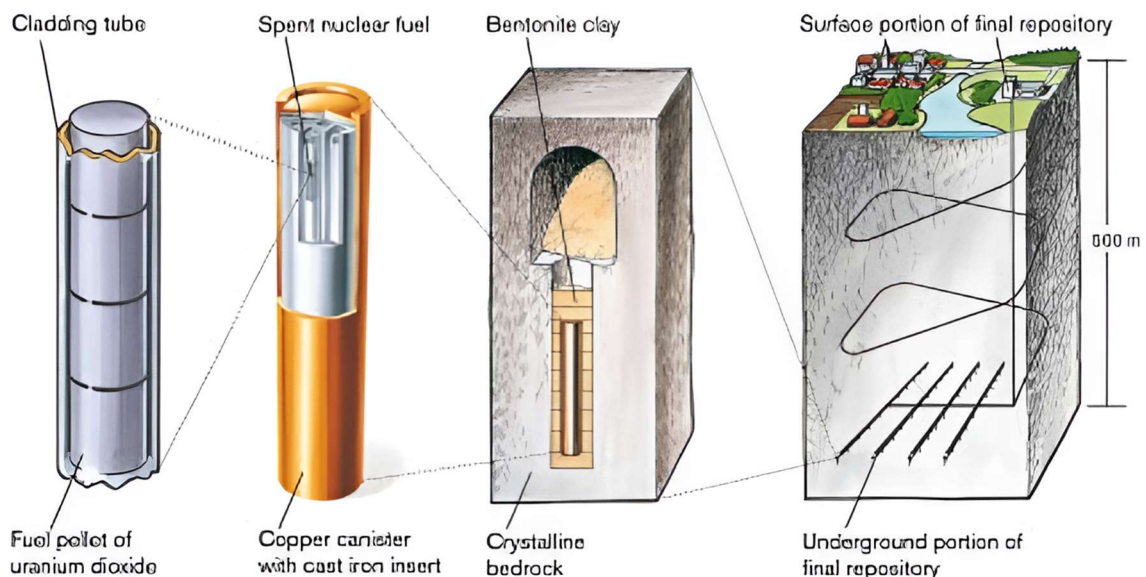


Figure 1: Example of disposal of radioactive waste (Keto, 2009)

During disposal, radioactive waste is isolated from the biosphere, which is typically accomplished by emplacement in stable geological formations in engineered containers. The idea is that it would contain the radiation for tens of thousands of years until it decomposes to

a level where it will not have any effect on the surrounding area. The creation of such deep repositories is being spearheaded by nations such as Finland and Sweden. According to SKB and Posiva's research, these repositories would rely on a combination of natural geological formations and engineered barriers (like bentonite clay) to ensure safe and long-term containment.

In the past decades, many nations have created nuclear waste repositories to lock away radioactive material. These sites are essential for ensuring the long-term environmental and public safety of nuclear waste. The main facilities are sited according to geological stability and distance from human populations, to minimise harm to human communities and natural systems. The map above shows where these disposal facilities are located around the world, with hotspots in North America, Europe and Asia. The particular properties and appropriateness of each site are described in the narratives accompanying the image, and these reveal some of the criteria for choosing and for containing.



Figure 2: Figure: Map with locations of active disposal sites (Storage and Disposal of Radioactive Waste, pp. 1-5)

Disposal facilities are currently in operation in:

- UK – Low Level Waist (LLW) Repository at Drigg in Cumbria operated by UK Nuclear Waste Management (a consortium led by AECOM with Studsvik UK, Serco, and Orano) on behalf of the Nuclear Decommissioning Authority.
- Spain – El Cabril LLW and ILW disposal facility operated by ENRESA.
- France – Centre de l'Aube operated by Andra.
- Japan – LLW Disposal Centre at Rokkasho-Mura operated by Japan Nuclear Fuel Limited.
- USA – five LLW disposal facilities:
 1. Texas Compact facility near the New Mexico border, operated by Waste Control Specialists.
 2. Barnwell, South Carolina operated by EnergySolutions.

3. Clive, Utah (EnergySolutions).
4. Oak Ridge, Tennessee (EnergySolutions)
5. Richland, Washington – operated by American Ecology Corporation. (Storage and Disposal of Radioactive Waste, pp. 1-10)

Bentonite clay is one of the materials used to construct these barriers because it has unique properties. Bentonite is a very compactable substance with low permeability, high swelling capacity and chemical stability making it an ideal sealing and buffering material in radioactive waste repositories. Its ability to expand when in contact with water allows it to fill voids and form an almost impervious layer around waste drums, thus minimizing the leaching of radioactive substances. Bentonite performs very well in the high pressure/high temperature conditions that would exist in a deep geological repository, especially when it is in the form of a pre-compacted block (as research shows). But the long-term periods of time that are required for the disposal of nuclear waste, which could be tens of thousands of years, will not change its chemical or structural stability.

This research is based on the testing of pre-compacted bentonite blocks for use in radioactive waste containment repositories. The whole point of these tests is to see how well these blocks would do in environments similar to those in a deep geological repository, testing such important properties as swelling pressure, hydraulic conductivity, and chemical stability. In this study an attempt is made to provide a comprehensive assessment of the role of bentonite in the long-term safety of radioactive waste disposal systems through laboratory testing and comparison with German, Finnish, and Swedish data. Thanks to some research in Sweden, Finland, and Germany, the properties of bentonite in repositories for radioactive waste can be understood a little bit better. These nations have come a long way in testing the performance of bentonite in a repository environment, and their findings will provide a good comparison point in this study. This study strives to provide a complete assessment of bentonite's use as a long-term geological barrier for high level radioactive waste by compiling information from around the world and conducting laboratory experiments on bentonite blocks.

II. APPLICATION OF BENTONITE AS A BUFFER MATERIAL

As it was said before, the storage of radioactive waste is one of the biggest challenges of environmental protection and long-term safety, demanding materials that can maintain their integrity for thousands of years under shifting and often hostile underground conditions. Of the many materials that have been investigated for use in radioactive waste containment, bentonite clay has become a particular focus of attention because of its special physical and chemical properties that render it especially effective at separating waste from the outside world.

The potential application of bentonite in geological repositories has stimulated research in many countries, including Finland, Sweden and Germany. Each nation has its own geological context and repository design, which would inform how bentonite is tested and used. Finland's disposal plan, for example, involves deep geological storage in crystalline rock, while Sweden uses the KBS-3 process, where waste is sealed inside copper containers, along with bentonite buffer, in a repository in granite. Germany, for its part, has concentrated on long-term studies of bentonite's thermal and mechanical stability within the framework of its salt and clay repository models.

To make sure bentonite stays effective in the long term, scientists have performed a range of tests in the laboratory that mimic repository conditions. These tests evaluate the mechanical, thermal and hydraulic performance of bentonite under stress, including its compressive strength, swelling pressure, density, and water absorption. Although laboratory experiments are somewhat closed and small in scale, they do help to understand the stability and behaviour of bentonite and yield important data for repository design and safety evaluations.

There are several studies worldwide, but European research uses bentonite materials that are locally available, therefore this section focuses on the best practices of three European countries. These three countries are Finland, Sweden and Germany. Each study helps to build the picture of the characteristics and behaviour of bentonite under different conditions - essential to proving its ability to isolate radioactive waste for the long-term.

2.1. Bentonite in Finland's Nuclear Waste Disposal Program

The bentonite method for radioactive waste disposal is largely based on the research done for the Posiva program, which runs the deep geological repository at Olkiluoto. Bentonite is a very important part of the KBS-3V concept in Finland where it is used as a buffer material next to the spent nuclear fuel canisters and as part of the backfill in the deposition tunnels. Much of the research that has been done so far (which is extensive) has dealt with testing bentonite under the unique geological and hydrological conditions of Finland, and more specifically its swelling characteristics, its hydraulic conductivity, and its long-term stability.

In the below table, properties of different types of bentonite clay are collected. Finish research focuses on testing MX-80, Ibeco RWC and Firedland clay. Testing of Firedland clay is important since I am using it as well for this research.

Property	MX-80	Ibeco RWC (Ca-N)	Friedland Clay
Bulk Density (g/cm ³)	1.93 - 2.05	1.85 - 1.95	1.9 - 2.24
Dry Density (g/cm ³)	1.58 - 1.8	1.6 - 1.75	1.6 - 1.95
Water Content (%)	12% - 17%	10% - 15%	6.3% - 11.7%
Swelling Pressure (kPa)	3000 - 4000	1500 - 2500	300 - 3571
Hydraulic Conductivity (m/s)	10 ⁻¹³ - 10 ⁻¹¹	10 ⁻¹² - 10 ⁻¹¹	10 ⁻¹¹ - 10 ⁻¹²
CEC (meq/100g)	80 - 95	70 - 90	28 - 33

Table 1: Physical and Chemical Properties of Different Bentonites (Mamunul, 2012)

The Finnish spent fuel repository at Olkiluoto is of the KBS-3V type, which is a concept developed in cooperation with Sweden. That entails plutonium waste being inserted into copper canisters, which are in turn enclosed in bentonite and lowered into vertical deposition holes. It's just that the bentonite acts as a buffer that expands when it comes in contact with groundwater and closes off the waste canisters and restricts the amount of water that flows through the repository. It is this swelling capability that is essential in keeping the integrity of the repository and preventing the radionuclides from migrating out of the disposal area.

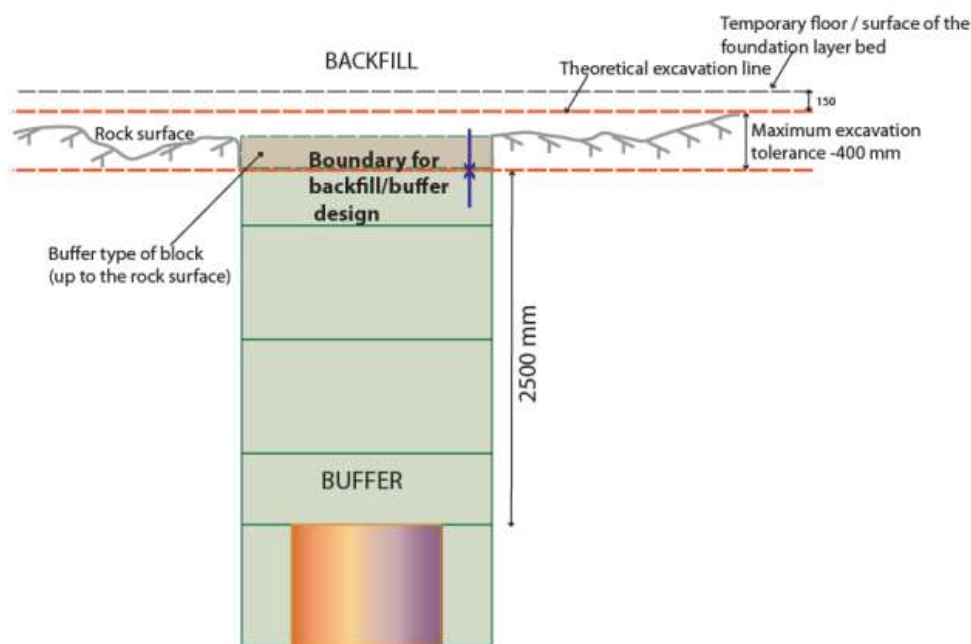


Figure 3: Design boundary between the buffer and the backfill (Mamunul, 2012)

The ground conditions at Olkiluoto are different because it contains saline groundwater, which will affect the performance of bentonite. Now the research that Posiva has done has been on the interaction of bentonite with groundwater of different salinities. The research shows that bentonite still has sufficient swelling pressure to provide a good seal around waste canisters, even in saline conditions (Mamunul, 2012). According to the Backfill Production Line 2012 Report by Posiva, the backfill is composed of Friedland clay and bentonite pellets, and the

smectite content in bentonite varies between 75-90% (Mamunul, 2012). These prevent the tunnels from collapsing in on themselves and keep the waste from having water seeping into it.

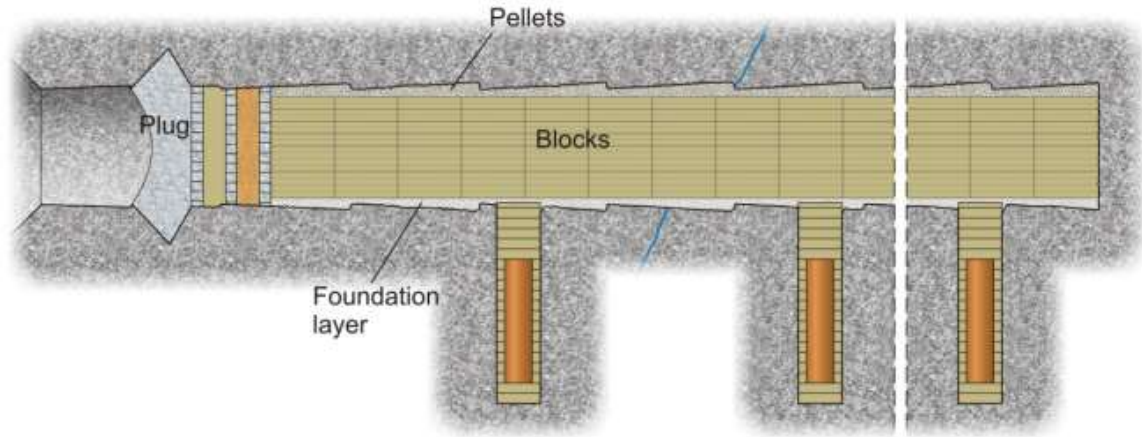


Figure 4: A schematic figure showing the main components of the backfill and the location of the deposition tunnel plug. (Mamunul, 2012)

One of the most important properties of bentonite is its swelling pressure because it allows it to fill the void spaces and create a close contact with the repository. Posiva tested the swelling capacity and hydraulic conductivity of bentonite, especially when exposed to the salty groundwater in the area (Kiviranta, 2018). It turns out that compacted bentonite blocks do not lose their swelling pressure even if they are in contact with saline water. The swelling index and hydraulic conductivity tests showed that the permeability of the material will remain low which means limited water flow and radionuclide migration (Mamunul, 2012).

Solution Type	Bentonite Type	Density (g/cm ³)	Hydraulic Conductivity (m/s)	Swelling Pressure (kPa)	Cation Exchange Capacity (meq/100g)
Distilled Water	MX-80	1.6	2.0×10^{-13}	4000	95
10% NaCl	Ibeco RWC	1.65	9.8×10^{-12}	1500	80
35% NaCl	Friedland	1.7	8.5×10^{-11}	3571	33
70% NaCl	Friedland	1.7	1.0×10^{-11}	520	32

Table 2: Influence of Saline Solutions on Bentonite Properties (Mamunul, 2012)

Bentonite's long-term thermal stability is the subject of extensive study in Finland, not least because it is used to contain spent nuclear fuel that heats up over the years. This heat might change the structure of the clay and affect its containment ability. However, research led by Posiva has shown that bentonite maintains both its swelling capacity and structural integrity even under prolonged thermal loads from radioactive decay. These results are important because they demonstrate that bentonite can hold up in the harsh conditions of a repository,

and safely contain the waste for the hundreds of thousands of years it takes for the radioactivity to decay. (Mamunul, 2012), (Holt, 2011).

Such durability in bentonite is essential because it guarantees that the material will not break down, lose structural integrity or cease to perform its barrier function over time. That swelling capacity in particular enables bentonite to keep permeability low, a trait that serves as a secondary containment layer, plugging up crevices and preventing the movement of contaminants. These characteristics make bentonite uniquely well-suited to long-term storage of nuclear waste, able to adjust to and live with the thermal extremes, thereby becoming a safe material for safety-critical purposes.

Finland's obsession with the manufacture and quality assurance of bentonite blocks and pellets also illustrates the need for material consistency in this use. When used as buffer and backfill material, bentonite is subject to stringent quality controls, including hydraulic tests, swelling pressure tests, dry density tests and compressive strength tests. These checks are there to guarantee that every batch passes very strict performance criteria, since inconsistencies would weaken the repository's performance. Also, the uniaxial compression technique is often employed to reach the desired density and permeability in bentonite blocks. Through such precise control of compression, bentonite maintains its critical properties, forming a strong, stable wall that can withstand the long-term requirements of radioactive waste isolation. (Holt, 2011)

Test Type	Year	Bentonite Type	Conditions	Key Findings
Swelling Pressure Test	2013	MX-80, Friedland	Tested with NaCl and CaCl ₂ solutions	Saline solutions reduce swelling pressure.
Hydraulic Conductivity Test	2015	MX-80, Ibeco RWC	Tested across dry densities	Conductivity decreases with increased dry density.
Compression and Shear Tests	2011	Friedland	Saturated and compacted samples	Shows higher resistance under saturation.
Triaxial Compression	2009	Ibeco RWC	Saturated with 10% NaCl solution	Lower hydraulic conductivity and moderate swelling pressure

Table 3: Laboratory Testing and Environmental Effects on Bentonites (Holt, 2011), (Mamunul, 2012)

Although Finland's geological situation is different from Sweden and Germany, many of the conclusions correspond with the findings from these countries. Sweden and Finland are concerned with the swelling properties of bentonite and its low permeability, and Germany is more interested in the thermal stability, and mechanical properties of the bentonite. The only "unique" aspect of Finland's contribution is that they test the bentonite in saline groundwater conditions, proving that it can still perform as a barrier material even under those conditions (Kiviranta, 2018), (Mamunul, 2012).

Finland has done a lot of research on bentonite (specifically through the Posiva Oy program) and they have found it to be a very suitable material for storing radioactive waste in deep

geological repositories. The research stresses the fact that bentonite will keep its swelling pressure and permeability low (even with saline groundwater) and therefore is a good barrier for long-term storage. By ensuring rigorous quality control and comprehensive testing, Finland contributes valuable insights into the use of bentonite as a crucial material in the safe and effective disposal of radioactive waste.

2.2. Bentonite in Sweden's Nuclear Waste Management

In Sweden, Svensk Kärnbränslehantering AB (SKB) has developed the KBS-3 concept, a disposal system for spent nuclear fuel that relies heavily on bentonite. The idea behind this is to put the used fuel rods in deep geological repository and ensure that bentonite blocks are compacted so that there is no water flow through and no migration of radionuclides (Gunnarsson D., 2006). The design of the repository consists of vertical disposal holes bored into the floors of tunnels and the canisters are placed in these holes with bentonite as a buffer. This is presented on the picture below. (Keto, 2009).

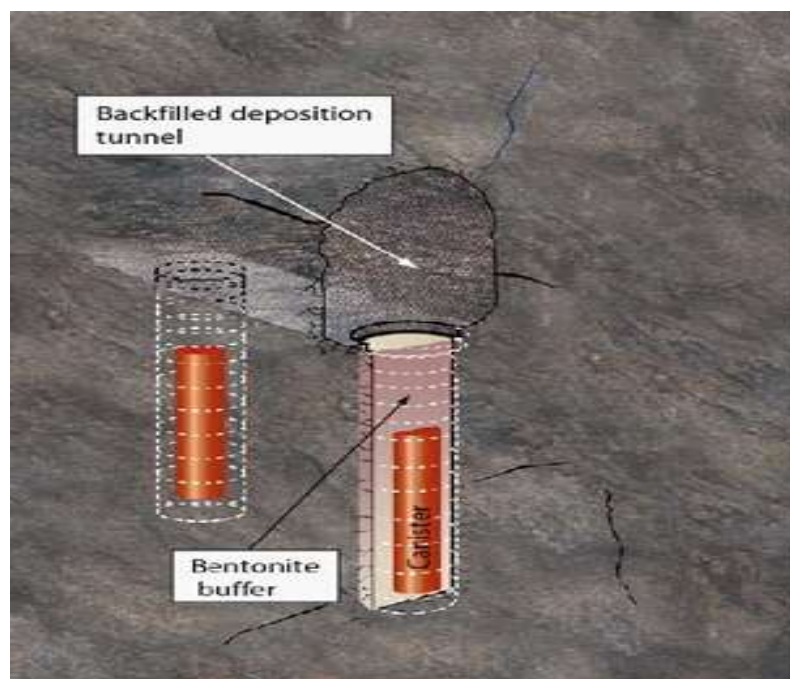


Figure 5: Illustration of the disposal method (Keto, 2009)

Much of the SKB research focuses on the swelling attributes of bentonite. Bentonite expands when it takes in water, and thus forms a very tight seal around the canisters and in between the buffer and the host rock (Pusch, 2001) (Keto, 2009). This expansion is a key part of the KBS-3 theory because it keeps the canisters pressed up against the rock and therefore prevents any large amount of water from coming in. SKB has shown in full scale field tests (like the ones at the Äspö Hard Rock Laboratory) that bentonite is capable of producing swelling pressures of over 200 kPa. Which is enough pressure to clog the water ways and greatly inhibit the migration of radionuclides (Pusch, 2001) (Gunnarsson D., 2006). So, for long term performance SKB has tested bentonite in various ground water conditions (high salinity etc).

Bentonite Type	Density (kg/m ³)	Water Content (%)	Permeability (m/s)	Swelling Capacity (MPa)	Hydraulic Conductivity (m/s)	CEC (meq/100g)
MX-80	1,950	10	4×10^{-13} (at 2000 kg/m ³)	1.5-2.3	$<1 \times 10^{-10}$	109.67
Friedland Clay	1,800-2,000	8.4-12	2×10^{-12} (at 2000 kg/m ³)	0.85-1.0 (at 2000 kg/m ³)	2×10^{-12} - 5×10^{-11}	40
Asha 230	1,700	17.3	3×10^{-12}	1.8	$<1 \times 10^{-10}$	62-109

Table 4: Properties of Bentonite Types from research in Sweden (Pusch, 2001), (Gunnarsson D., 2006)

Sweden's groundwater at repository depths is not of constant composition, so it is important to know how saline conditions will influence bentonite. Research states that even in saline conditions bentonite still has a very low hydraulic conductivity usually below 1×10^{-10} m/s. This ensures minimal water flow through the buffer, making diffusion the primary transport mechanism for any potential radionuclide release (Pusch, 2001), (Gunnarsson D., 2006), (Keto, 2009).

In SKB's backfill design, the void spaces around these blocks are filled with pre-compacted bentonite blocks and bentonite pellets. The backfill system is a product of the BACLO (Backfilling and Closure) program, which is designed to minimize void spaces and provide a high density (Keto, 2009). Backfilling with large bentonite blocks compacted under high pressures to densities greater than 1,900 kg/m³, and bentonite pellets to fill the void spaces too small for the blocks, thus providing uniform swelling pressure and sealing (Gunnarsson D., 2006). The blocks and pellets provide for an 80% full capacity and thus greater efficiency of the system (Keto, 2009). Backfilling is a big deal with water inflow and early saturation. The bentonite should be able to self-seal if water enters the tunnels when they are being installed, and SKB has proven in both lab and field tests that this is possible (Gunnarsson D., 2006), (Keto, 2009). It is also important that the bentonite have the ability to homogenize, so that the swelling pressure will be distributed evenly, and the barrier properties will be maintained over the long term (Keto, 2009).

Compaction Technique	Pressure Applied (MPa)	Target Density (kg/m ³)	Observations
Uniaxial Compaction	25	1,800-2,000	Effective for large blocks but requires careful water content control to achieve uniformity
Isostatic Compaction	50	>2,000	Yields very high densities but less feasible for field application due to equipment constraints

Table 5: Compaction technics used in Sweden's research (Keto, 2009)

In the long run, stability is the key because the bentonite buffer must last for thousands of years. SKB has conducted extensive tests to assess how bentonite interacts with groundwater over time, with a particular focus on its chemical stability. All of these studies have demonstrated that bentonite remains resilient even after extended contact with a variety of groundwater chemistries, including highly saline conditions (Pusch, 2001). The low hydraulic conductivity and high swelling pressure of the bentonite both contribute to the resistance of the bentonite to chemical changes that would otherwise impair its function (Gunnarsson D., 2006) (Keto, 2009).

As spent fuel canisters generate heat, it is important to understand how bentonite responds thermally. Research conducted by SKB shows that bentonite has a low enough thermal conductivity to release heat without compromising the bentonite's form or function (Gunnarsson D., 2006), (Keto, 2009). Which would make it a perfect material to endure the temperature changes of radioactive decay, so that the buffer would not be compromised.

The research done in Sweden, via SKB and the KBS-3 system, has given a complete picture of bentonite as a barrier material for radioactive waste. Bentonite has the unique ability to swell, maintain low permeability and resist long term chemical and mechanical stresses, thus insuring its use as a safe container for nuclear waste. And research and testing continue, in places like Äspö, to certify that the substance is still up to the rigorous standards set by Sweden's nuclear waste disposal program.

Year	Research Institution	Tests Performed	Bentonite Type	Key Findings
2006	SKB	Density, swelling pressure, permeability	MX-80	Achieved high swelling capacity (>1.5 MPa) and low permeability (4×10^{-13} m/s) at 2000 kg/m ³
2009	Posiva-SKB (BACLO)	Hydraulic conductivity, self-sealing	Friedland Clay	Demonstrated good self-sealing and low hydraulic conductivity under high-density conditions
2018	AECL-SKB	Saturation, swelling pressure, compressibility	Asha 230	High density blocks (>1,700 kg/m ³) maintained low hydraulic conductivity in saline environments

Table 6: Research on Bentonite Testing (Keto, 2009), (Gunnarsson D., 2006)

2.3. Bentonite in Germany as a material for sealing underground disposal sites

The literature review of the use of bentonite for nuclear waste disposal in Germany (based off of the GRS-300 report) revolves around how bentonite is a suitable engineered barrier material, mostly because of its physical, chemical, and geotechnical properties.

In Germany bentonite is used extensively as a sealing agent in underground repositories, such as those used for nuclear waste and hazardous chemical landfills. It's primarily used because it has low permeability, it's self-sealing, and it's very stable over long periods of time when it's in contact with water. This is with regard to bentonite and its use in nuclear waste repositories, where its main function is to prevent the migration of radionuclides and other hazardous substances from reaching the biosphere.

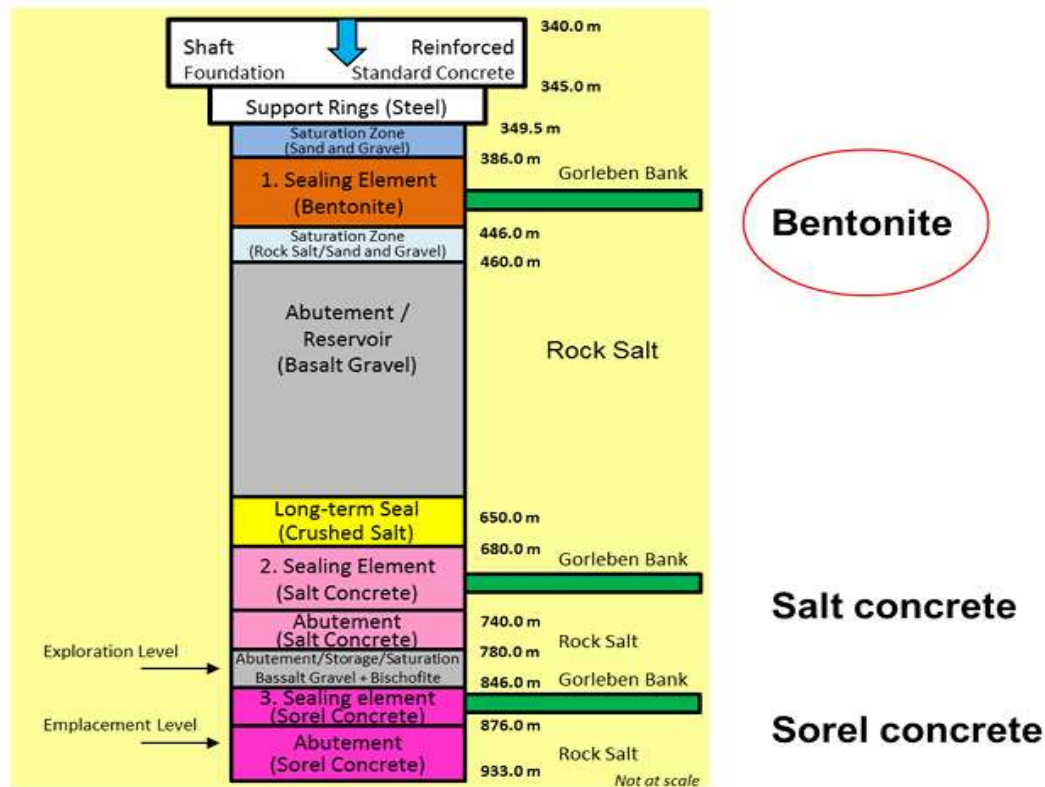


Figure 6: Bentonite as sealing material (Mingliang Xie, 2012)

Different types of bentonites and their properties were collected in the table below.

Bentonite Type	Density (kg/m ³)	Water Content (%)	Permeability (m ²)	Swelling Capacity (%)	Hydraulic Conductivity (m/s)	CEC (meq/100g)
MX-80	1200 - 1800	8% - 20%	10 ⁻¹¹ - 10 ⁻¹⁰	High	10 ⁻¹² - 10 ⁻¹⁰	80 - 100
IBECO RWC	1100 - 1600	7% - 18%	10 ⁻¹²	Medium	10 ⁻¹¹	70 - 90
FEBEX	1300 - 1700	9% - 15%	10 ⁻¹¹ - 10 ⁻⁹	High	10 ⁻¹¹ - 10 ⁻¹⁰	60 - 85

Table 7: Physical Properties of Bentonite in German research (Mingliang Xie, 2012)

Bentonite is mainly composed of smectite, a type of clay that expands greatly when in contact with water, which means it is good for sealing and buffering purposes. In Germany, various types of bentonites, such as Na-bentonite (MX-80) and Ca-bentonites, have been studied. These materials are tested under simulated deep geological repository conditions with emphasis on saline environments such as rock salt and potash formations which contain large amounts of NaCl (sodium chloride). Most of the bentonite deposits studied in German literature derive from volcanic ash which has been altered in a marine or lacustrine setting. The mineralogy of bentonite is a large factor in its use as a barrier material. Especially, the German researchers point out the smectite fraction which controls the swelling and retentive capacities of bentonite. The swelling capability of bentonite is a key factor in its function as a barrier material. Bentonite expands when water enters it, and it expands to fill any voids or cracks in the repository and acts as a seal.

Bentonite Type	Formation Environment	Parent Rock Type	pH Conditions	Impact on Properties
MX-80	Marine sedimentary deposits	Acidic	Neutral	High swelling; stable under saline conditions
IBECO RWC	Hydrothermally altered tuff	Mafic	Alkaline	Moderate swelling; sensitive to ion exchange
FEBEX	Submarine volcanic deposits	Rhyolitic	Neutral	Good stability in groundwater; effective sealant

Table 8: Environmental and Geological Conditions Affecting Bentonite Properties (Mingliang Xie, 2012)

German research has shown that bentonite is stable and retains its swelling capacity for extended times even when in contact with saline solutions. This is especially important at nuclear waste dump sites where the material must last for thousands of years. Bentonite is a buffer material used in high-level nuclear waste (HLW) repositories that is placed around the waste canisters. It stops the radionuclides from migrating and it also slows down the corrosion of the waste canisters. The interactions between bentonite and corrosion products, such as iron and copper, have been thoroughly investigated. Research done in Germany shows that bentonite is affected by high saline solutions that can alter its hydraulic properties, but not enough to make it lose its sealing capabilities. Gas formation is another critical issue in nuclear waste repositories. German research has been centred around the movement of gases (hydrogen, methane) produced by either the corrosion of waste canisters or the breakdown of organic material, and how they pass through bentonite. Bentonite is a good barrier to the diffusion of gases and will help keep the integrity of the repository. Bentonite also has really good sorption properties, meaning that it can soak up dangerous radionuclides like caesium (Cs) and cadmium (Cd) and keep them from moving into the biosphere.

Gas Type	Solvent	Gas Concentration (ppm)	Dissolubility (g/100 ml)	Ostwald Coefficient (v/v)
Hydrogen (H₂)	Pure Water	2.5	0.000223	0.00025
	15% NaCl	2	0.000144	0.000249
	50% NaCl	1.1	0.0000731	0.000148
	90% NaCl	0.8	0.00005453	0.000105
	90% IP21	0.7	0.00003868	0.000114
Methane (CH₄)	Pure Water	3.2	0.0022811	0.0003232
	15% NaCl	2.9	0.0016609	0.0003646
	50% NaCl	1.36	0.000748	0.0001754
	90% NaCl	1.1	0.00054276	0.000161
	90% IP21	0.9	0.0003728	0.0001564
Carbon Dioxide (CO₂)	Pure Water	8100	15.1322	0.8585
	15% NaCl	7450	14.2047	0.77365
	50% NaCl	3240	4.7152	0.44081
	90% NaCl	2840	3.9246	0.4069
	90% IP21	2280	2.5637	0.4015
Sulphur Hexafluoride (SF₆)	Pure Water	151.5	0.96404	0.01578
	15% NaCl	140	0.70344	0.01847
	50% NaCl	61	0.2944	0.0083
	90% NaCl	53	0.2944	0.00788
	90% IP21	45	0.1787	0.0075

Table 9: Gas Dissolution in Highly Saline Solutions at 0.1009 MPa and 298.16 K (Mingliang Xie, 2012)

A lot of the research is centred around the long-term stability of bentonite in German repositories. Bentonite is known to maintain its structure and characteristics for long periods of time as evidenced by tests run under simulated repository conditions. While it is true that contact with salt solutions can bring about certain mineralogical changes in bentonite, these changes are not so drastic that they would compromise the overall ability of bentonite to serve as a sealing agent.

In German research this question has been investigated using a number of experimental approaches, all with the aim of understanding the behaviour of bentonite in a repository. One of the main methodologies involve through-diffusion experiments, which basically entails the exposure of bentonite samples to different NaCl solutions and radionuclides, such as Cs and Cd. Because the experiments prove that the diffusion coefficients of these elements are smaller when the salinity is great, bentonite is still a good barrier material even in these extreme conditions.

Bentonite was also test for gas concentration, dissolubility, and diffusion coefficients for various heavy metals in saline solutions. Data from these tests can be seen in the table below.

Heavy Metal	Solution Type	Diffusion Coefficient (m ² /s)
Caesium (Cs)	50% NaCl	2.18×10^{-10}
	90% NaCl	5.19×10^{-11}
	90% IP21	2.10×10^{-11}
Cadmium (Cd)	90% NaCl	6.54×10^{-12}
	90% IP21	3.12×10^{-11}
Lead (Pb)	50% NaCl	3.56×10^{-11}
	90% NaCl	5.10×10^{-12}
	90% IP21	1.97×10^{-11}

Table 10: Results for diffusion coefficients (Mingliang Xie, 2012)

From these data, it can be concluded that bentonite's diffusion coefficients are within an acceptable range for a nuclear waste barrier, and also that as dry density increases, diffusion decreases.

All the research done in Germany shows that bentonite is a good sealant for nuclear waste dump sites. It has good geotechnical and mineralogical characteristics, and it has proven to be stable over the long term in adverse saline environments, so it would make a good barrier material. The bentonite has the properties of diffusion and sorption, and that way, the dangerous substances are kept within the repository, and the biosphere is less likely to become contaminated. (Mingliang Xie, 2012).

III. MATERIALS

Friedland clay was chosen for sample preparation in this study because it is widely regarded as a benchmark material in the radioactive waste disposal research community. Friedland clay is a naturally occurring, fine-grained clay that is composed of a mixture of montmorillonite, illite and kaolinite, endowing it with its unusual swelling, sealing and durable qualities. It is especially prized in geological and environmental engineering because of its low permeability and its superior ability to hold moisture, both of which make it a good barrier material for containment applications. Friedland clay swells dramatically under certain conditions, and that can plug up holes in repositories and slow down the flow of water around radioactive materials, in effect limiting the risk of contamination.



Figure 7: Friedland clay from our laboratory

This clay type is widely recognized as a “reference material” across several European countries, including Finland, Sweden, and Germany, where it is used as a baseline material in experiments assessing bentonite's efficacy for waste containment. The uniformity of the use of Friedland clay in these studies lends itself to useful cross-country comparisons in the literature, which enables an understanding of how differences in preparation conditions - for example, compaction and moisture content - influence its performance.

Not only will this paper detail the properties of Friedland clay, but a table will accompany this paper to detail the number and types of tests run on each sample. It is to make the report more transparent and to have the information there in an organized manner, especially since it is in table form, so it is easy to see the experimental data collected during the experiment.

Applied methods	Standards	Number of specimens	Number of results
Bulk density		Cylindrical samples 32	64
Bulk density		Cubic samples 5	5
Water content		Cylindrical samples 32	32
UPV test		Cylindrical samples 32	64
UPV test		Cubic samples 5	105
UCS test		Cylindrical samples 32	32
Total			302

Table 11: Number of total tests done in the laboratory

This table provides a comprehensive view of the testing process, showing that a total of 302 tests were conducted across all samples. To enhance readability, the table is color-coded: yellow cells indicate the tests performed on cylindrical samples, while red cells represent the tests conducted on cubic samples. This color-coding will allow for a quick and clear understanding of the distribution and frequency of tests, further supporting transparency in data presentation.

IV. SAMPLE PREPARATION

This section lays out the steps involved in conducting the research in a systematic and exhaustive way. It describes precisely the procedures, materials, and methods used to collect and process data on the properties of bentonite samples under different preparation conditions. By clearly defining each stage, from sample preparation to testing, the methodology helps to ensure that the research can be understood, replicated, and validated by others in the field. This part also explains why the selected methods have been used, demonstrating how each one fits the study's goals of determining the suitability of bentonite as a material for radioactive waste containment. Since bentonite is used as a lining in containment barriers, the procedure is key to analysing how various preparation conditions influence its structural and mechanical characteristics - essential for long-term storage uses.

In this study, 37 samples were prepared: 32 cylindrical samples and 5 cubic samples. Every sample was given a unique identification (ID) number to facilitate constant tracking, and pictures of each sample are to be added to give visual documentation for reference. Each sample was prepared under different conditions, with different values of water content, mixing time and applied compaction pressure being set during preparation. These parameters are so important because they directly affect bentonite's structural stability, density and mechanical strength, all of which are relevant to its function in nuclear waste containment.

4.1. Process of making the samples

The cubic blocks were originally made in a mould, which will be illustrated in supplementary figures. This mould allowed the samples to be kept a uniform shape while varying compaction and hydration in controlled ways.



Figure 8: Mould used for cubic samples

Once prepared, the cubic blocks were carefully drilled to extract cylindrical specimens, forming standardised test pieces. By this process, each cylindrical sample inherited the properties of the cubic block from which it was drilled, providing a spectrum of samples with varying compaction densities and water content.

In the below picture, 5 cubic samples that were used in this study are presented.



Figure 9: Cubic samples

As mentioned before, cylindrical samples were drilled from the cubic samples. This was done using a specific drilling machine in the laboratory. The used machine can be seen in the next picture.



Figure 10: Drilling machine

Finally, we get the cylindric samples that will be used for testing in this study. Each sample was carefully marked to make future references easier.



Figure 11: Cylindric samples

Once ready, each sample's physical characteristics were measured, from length and diameter to weight and density. These measurements serve as the initial characterisation needed to evaluate the influence of each preparation parameter on the bentonite's response, under test conditions.

Firstly, water content and density of each sample, cubic and cylindric, will be measured and checked.

After that, two key tests were performed on the samples to assess their behaviour in the conditions relevant to radioactive waste storage:

- Ultrasonic Pulse Velocity (UPV) Test:
- Uniaxial Compressive Strength (UCS) Test:

V. RESULTS AND DISCUSSION

The experimental tests are reported and analysed in this chapter to assess the suitability of Friedland clay as a containment material for radioactive waste disposal. The data gathered from the ultrasonic pulse velocity (UPV) tests and uniaxial compressive strength (UCS) tests, as well as the water content calculations, provide insight into how various preparation conditions—such as compaction pressure and initial water content—impact the physical and mechanical properties of the clay samples.

The UPV test results provide information about the internal quality and uniformity of the samples, and might identify defects or voids or other problems, while the UCS test results indicate the strength and strength of the material under uniaxial loading. What's more, water content analysis enables a comparison to be made between hydration levels and compressive strength, which adds a further dimension to the picture of how the material performs in containment.

The findings are presented in the context of literature findings, both in terms of similarities and discrepancies, and in the framework of the behaviour of Friedland clay under different conditions. The analysis is designed to assess if the characteristics of Friedland clay are consistent with the needs of long-term isolation of radioactive waste and to identify ideal preparation conditions to maximise its performance as a barrier material.

5.1. Results of water content

After the UCS test, water content was measured from each cylindrical sample to see the effect of moisture content on compressive strength. After each sample was broken under the UCS test, its weight was instantly measured and noted. The samples were then placed in an oven set to 110 degrees Celsius, where they remained for 24 hours to ensure complete drying. This temperature and time are standardised to get reliable water content results.

Once dry, each sample's dry weight was weighed to determine the dry density. With the original and dry densities, water content was determined. This measurement represents a useful proxy for moisture content in the samples prior to testing and can be used to investigate the impact of initial hydration on the material's performance under compressive load.

The whole water content determination was done with only cylindrical samples, and it was done so in accordance with the specifications of the UCS test. These measurements and calculations help to explain the relationship between water content and compressive strength, which are key data for determining the applicability of Friedland clay as a containment material for radioactive waste disposal.

The following graph will show the correlation between water content measured at the beginning and the compaction pressure exerted. Compared with this, the differences in preparation affect the structural integrity of Friedland clay in terms of its long-term integrity as a containment material. Additionally, to this table another table with my measured water content and applied pressure is presented below.

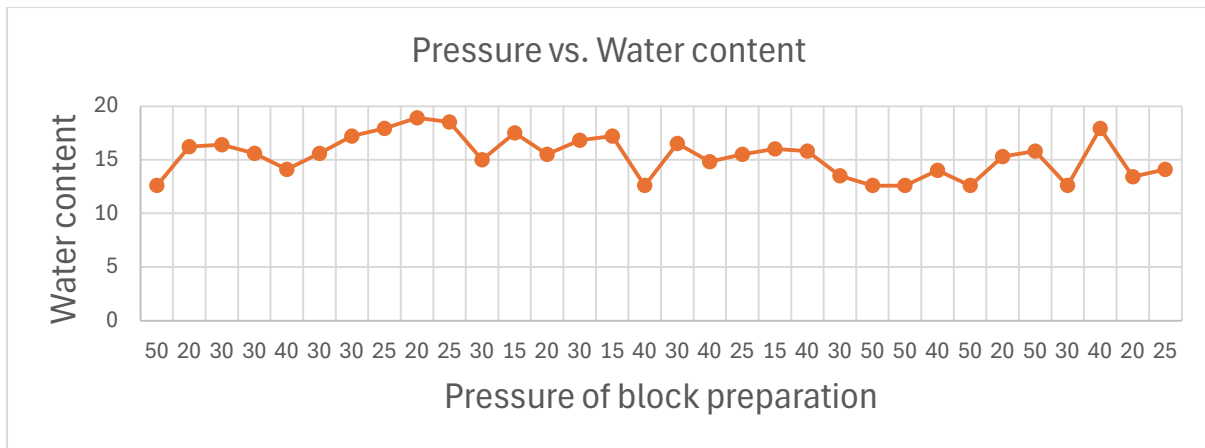


Figure 12: Measured water content of the sample before drilling and pressure applied at the making of the blocks.

For comparison, I plotted results from my water content calculations and applied pressure at the beginning of making the cubic samples.

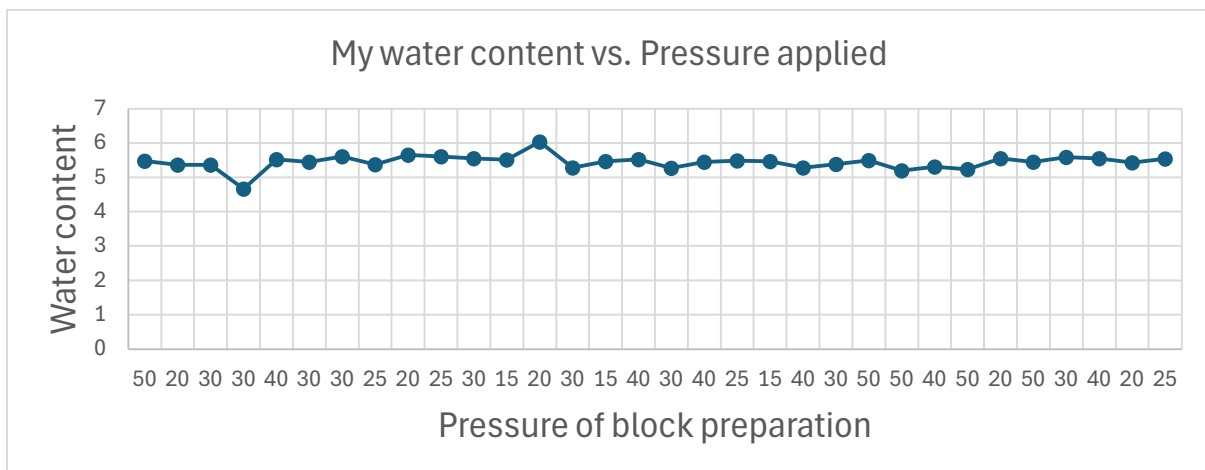


Figure 13: Measured water content by me and pressure applied at the making of the blocks.

The mean moisture content for this study was from 4.66 to 6.04 [%], a value substantial for this investigation. This value represents a relatively low level of moisture content that is not overwhelming but enough to dictate the swelling characteristics of the material, an important property for bentonite in containment barriers. When it comes to radioactive waste disposal, more water can cause more swelling, which could improve the sealing properties of the clay, but could also cause it to collapse under high pressures. On the other hand, low water content could also mean low swelling potential, which might mean that the material can't form a tight seal around waste and could be more permeable.

Thus, a stable water content, as realised here, is critical for Friedland clay to have the right balance of density and swelling properties to perform well as a barrier in radioactive waste

isolation. Such intermediate water content both strengthens the material and permits a degree of swelling that aids long-term sealing performance, in line with safe containment objectives.

When these results are analysed, they will also be compared with data from studies in Finland, Sweden and Germany, where similar research on bentonite-based materials has been carried out. This comparison enables an assessment of whether the trends found in this study correspond with those in the literature and forms the basis on which to compare the performance of Friedland clay with that of other materials commonly used for the confinement of radioactive waste.

Results from the Finland and Sweden are plotted with my results in the below figure. Germany did research on water content as well, but on the Friedland clay that was used in this research so for better analysis I excluded Germany from the plot.

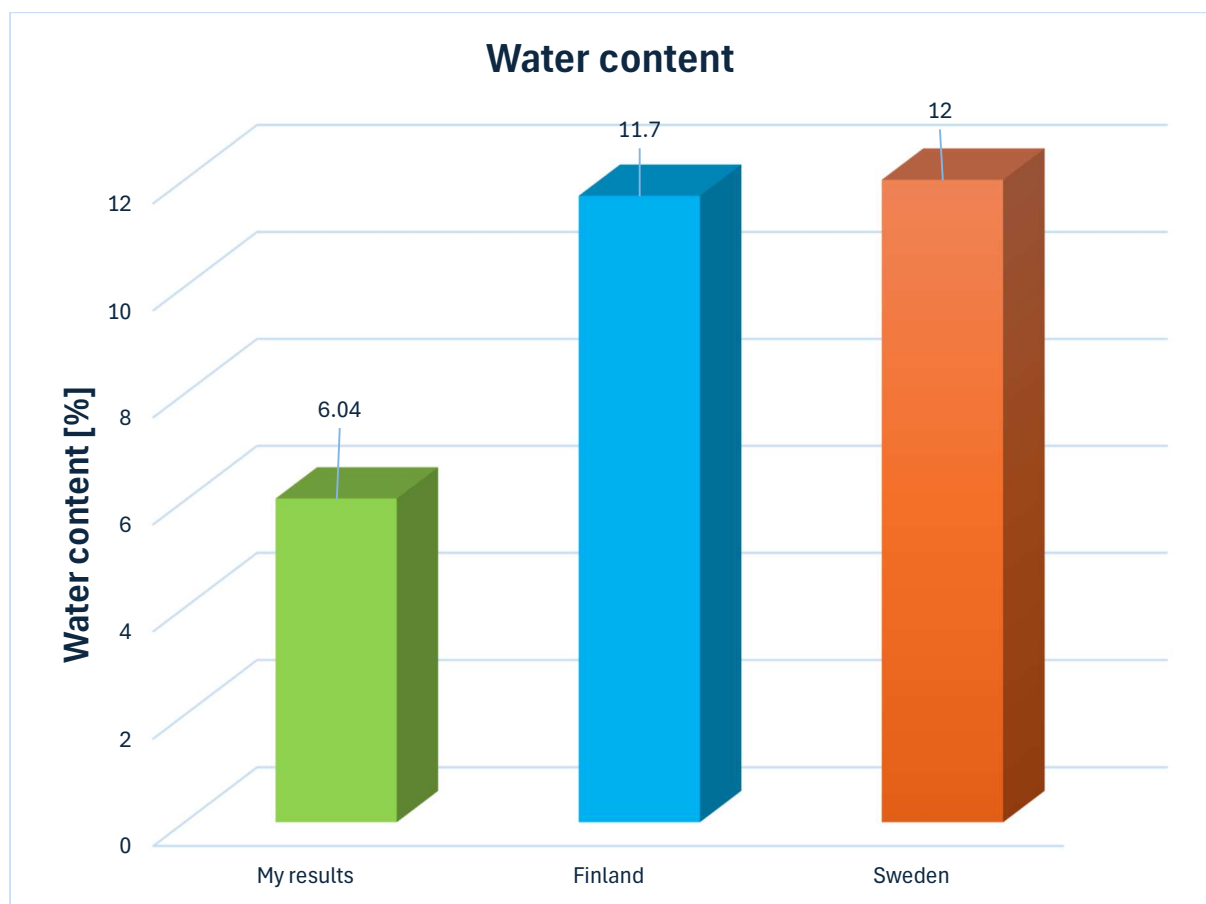


Figure 14: Comparison of water content with data from literature review.

5.2.Density

The density data from the cylindrical and cubic samples are analysed which should provide some information about the structural and mechanical integrity of Friedland clay under the different preparation treatments. Density is a key parameter in this study because it directly affects material strength, in terms of load-bearing capacity, compressive strength and sealing, all of which are important to the material's use as a containment barrier for radioactive waste.

- Measuring Density of cubic and cylindric samples:

In order to determine the density of the samples, the following procedure was used for both cylindrical and cubic sample geometries:

- Cubic Samples: For the cubic samples, density was similarly calculated by first determining the volume, using the length of each side to calculate $V=a*b*c$, where a, b, c are the side lengths. Each sample's mass was then divided by its calculated volume to obtain the density.
- Cylindrical Samples: The volume of each cylindrical sample was calculated based on its measured dimensions, specifically its diameter and height. Using these dimensions, the sample's volume was determined with the formula for the volume of a cylinder, $V=\pi r^2 h$, where r is the radius and h is the height. The mass of each sample was then measured with a precise scale, and the density was calculated by dividing the mass by the calculated volume.

Density is a key parameter in determining the applicability of Friedland clay as a barrier material. Increased density is frequently associated with decreased porosity and increased compressive strength, properties that are crucial for stability and permeability reduction in long-term containment. In a repository setting, dense materials build up a low-permeability barrier around the waste, reducing the migration of potentially harmful materials, and confining radioactive elements to the containment zone.

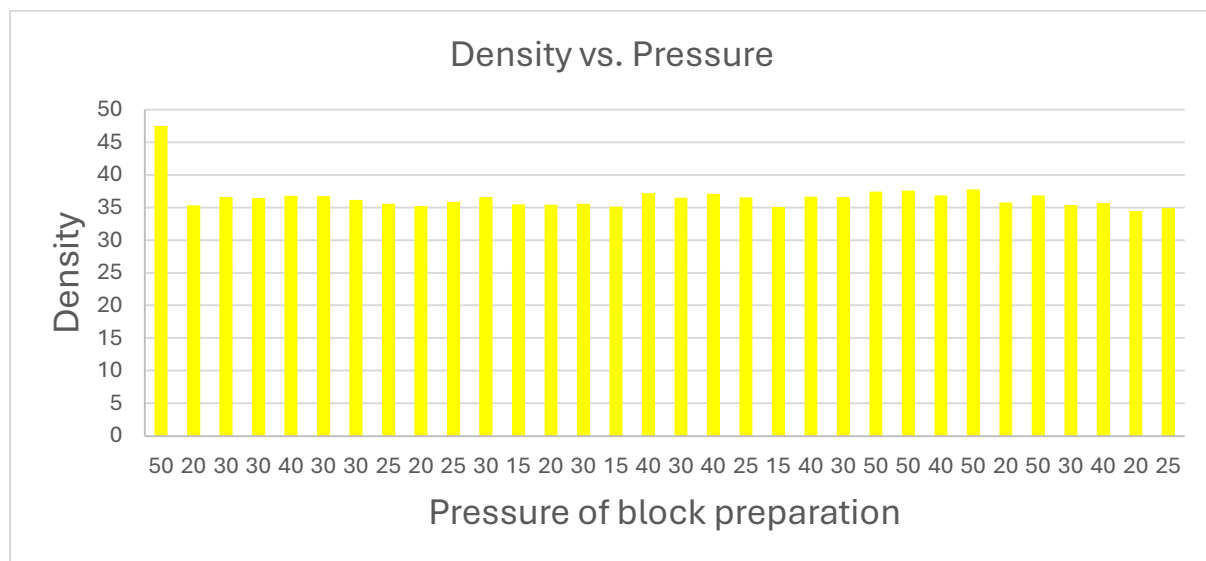


Figure 15: Density vs. Compaction Pressure for cylindric samples

For this research, the density of cubic samples was measured at approximately 2.24 g/cm³, a value that holds specific significance. A density of 2.24 g/cm³ means that the Friedland clay samples have been compacted to the point where they could possibly support structural integrity but not allow much water to pass through, as is necessary for a good containment material. This density also compares well with that seen in other studies cited in the literature, and further supports the validity and replicability of results obtained here.

In a word, a density of 2.24 g/cm³ or so indicates that the Friedland clay samples are sufficiently compacted as to be helpful in securing strength and sealing performance in a waste containment application. Such density is sufficient to achieve the dual objectives of mechanical stability under confinement and low permeability to restrict the leakage of leachate, a central objective for materials used in radioactive waste confinement barriers.

The density figures of this study are in good agreement with those reported in the literature from Finland and Sweden. In particular, this study reached an average density of 2.24 g/cm³ for cubic samples, on par with densities published in Finnish and Swedish studies. Finland's average density was 2.4 g/cm³, in line with this study, and Sweden's average density for comparable bentonite samples was slightly lower, at 2.0 g/cm³. This close correspondence to the results obtained in Finland leads us to infer that the Friedland clay in this study has the same compaction characteristics as bentonite materials tested in Finland. The lower density seen in Swedish studies might be a result of differences in sample preparation, compaction pressure, or water content, and illustrates how preparation methods can influence density results.

The consistency of density results between this study and the Finnish studies lends credibility to the results and suggests that Friedland clay, under the right circumstances, can obtain density values comparable to those in conventional bentonite uses in Europe. That consistency also gives the clay its promise as a good material to use for storing radioactive waste, providing consistent compaction and low permeability, which are crucial for preventing the movement of waste in a repository site.

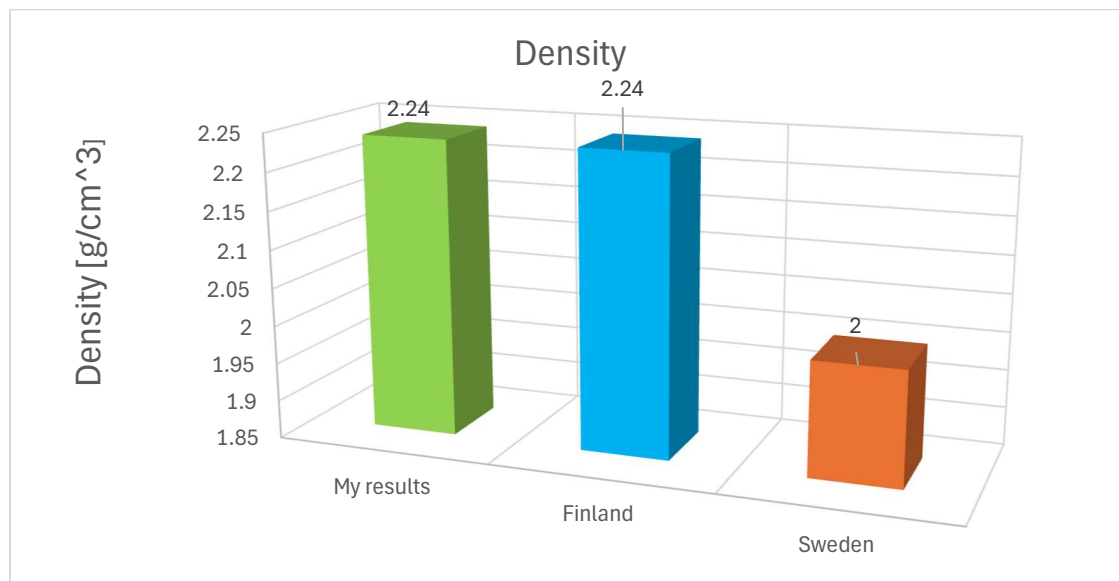


Figure 16: Density results compared with data from the literature review

5.3. Ultrasonic Pulse Velocity (UPV) Test

Firstly, the samples were subjected to Ultrasonic Pulse Velocity (UPV) test. The UPV test is a non-destructive way of examining the inner structure of the material, by sending ultrasonic pulses through it. Pulse velocity is a measure of the density, porosity and compactness of a material, and these factors are directly related to its strength and stability. The experiment consisted of loading the 32 cylindrical and 5 cubic bentonite samples between two transducers and sending an ultrasonic pulse through one end and receiving it on the other. The pulse velocity was measured in m/s, and the higher the pulse velocity the denser and less porous the material. The UPV results are significant for understanding the homogeneity and compactness of bentonite, both of which are essential for minimizing fluid transport and maintaining containment in radioactive waste disposal. In a repository, bentonite must be able to keep its structure for an extended time under stress and environmental conditions.



Figure 17: Ultrasonic machine used for the UPV testing. Cylindrical sample can be seen between two transducers

Testing of cubic samples for UPV test was made with more measures for ultrasonic travel time. Since the cubes are bigger, I measured more points for the UPV test. Top side was labelled as A, right side was labelled as B and left side was labelled as C. On the top side or A side I made 9 measures and 6 measures on B and C side. On the picture bellow, I showed where each measure was taken on the sample.



Figure 18: Cubic samples and points for the UPV test.

In the next tables, results from the UPV test for the cubic samples are collected. As mentioned before, measurements are done according to the above picture. First, I measured the dimensions of each sample and their weights.

	Sample ID	a [mm]	b [mm]	c [mm]	Weight [g]
1	G149130	148.02	148.8	97.76	4691.35
2	G150140	150.2	148.95	95.95	4749.19
3	G146115	152.28	149.52	84.44	4128.73
4	G147120	148.97	149.6	107	4837.61
5	G148125	151.26	149.75	95.79	4851.38

Table 12: Measurements of cubic samples

The UPV measurements on cubic samples will be displayed graphically to show the spread and distribution of measurements.

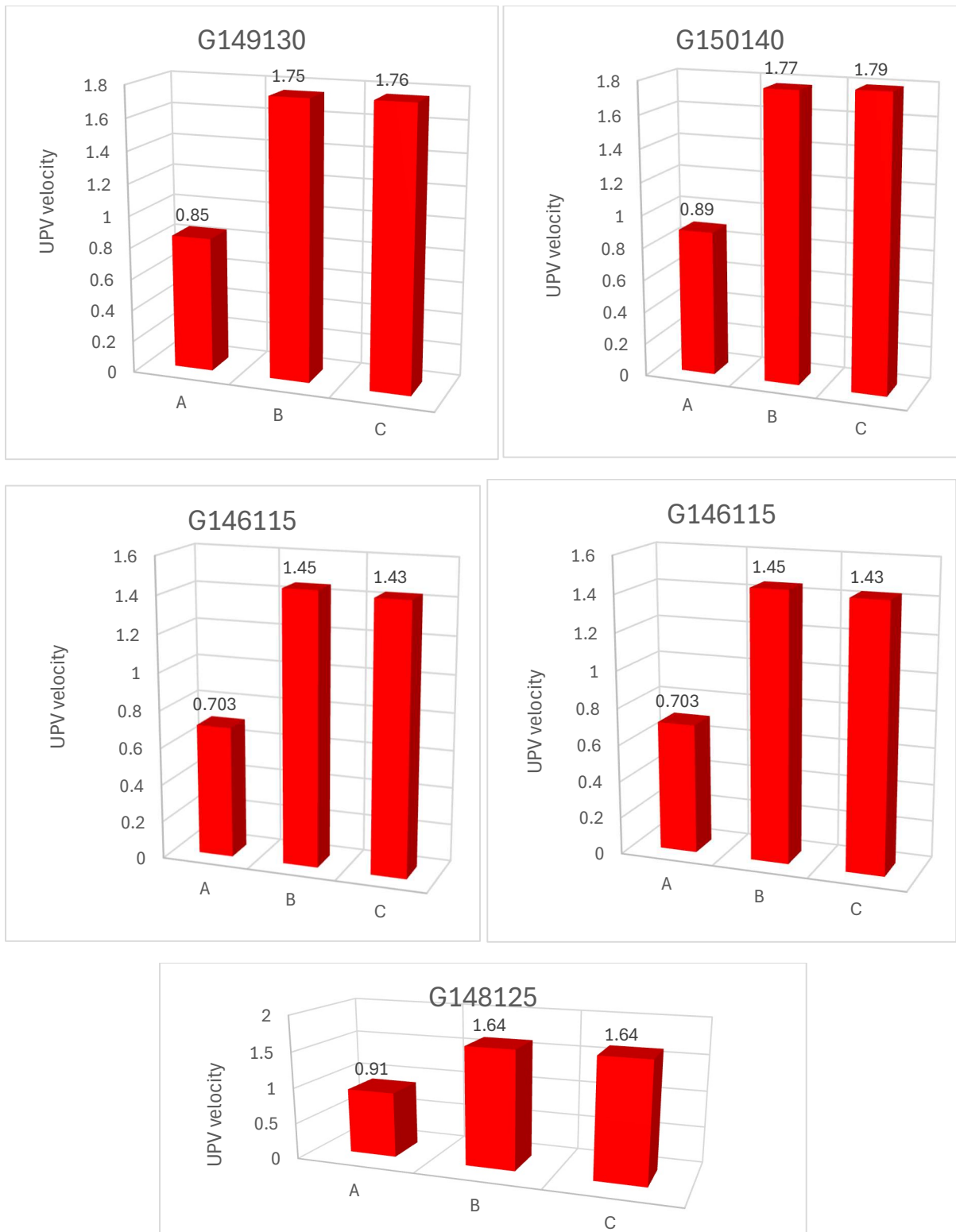


Figure 19: Measurements from the cubic samples graphically presented

Some cubic samples showed lower pulse velocities than anticipated in testing, suggesting that they were not fully uniform. This observation will be supported by images showing specific

areas of the samples where inconsistencies, such as voids or density variations, were visible. These heterogeneities may be the result of uneven compaction or spatial variability in moisture distribution during sample preparation, all of which are important factors to take into account when preparing clay blocks as containment barriers.



Figure 20: Cubic samples with visible inhomogeneous

The results of the UPV test are relevant to assessing Friedland clay's consistency and structural integrity as a containment material. When it comes to radioactive waste management, a material with a high pulse velocity is probably less prone to fracture, and less likely to have channels for water to flow through, which means it's better at containing waste. In particular, by comparing UPV data for cylindrical and cubic samples, we can better understand how various preparation conditions (for example, water content and compaction pressure) affect the internal structure of the clay, and its suitability for long-term containment.

After finishing the cubic samples, I continued the measurements for cylindric ones.

For this test, I measured samples length, weight and using the machine I measured ultrasonic travel time. I measured the travel time from both sides of the samples (top side (A) and bottom side (B)). With the collected data I could calculate the volume, density and ultrasonic pulse velocity. Using the length of the sample as path length and dividing it with measured travel time I got the ultrasonic pulse velocity of every sample.

The UPV results for cylindrical samples in this study ranged from 0.6999 to 1.7299 km/s. For comparison, UPV measurements taken on the cylindrical samples immediately after drilling, approximately 2-3 weeks prior, showed a range of 1.882 to 0.717 km/s. This variation in pulse speed with time implies that the structure of the material itself may have shifted slightly after the initial drilling, possibly because of some drying, settling, or internal stress readjustments in the clay. The decrease in velocity could indicate a slight reduction in sample homogeneity or an increase in microfractures over time, which may impact its sealing ability under prolonged containment conditions.

	Sample ID	Diameter [mm]	Length [mm]	Weight [g]
1	6/2	43.60	70.41	228.99
2	34/3	34.08	76.40	144.51
3	54/3	34.35	74.92	147.91
4	52/3	34.26	73.82	144.74
5	44/1	34.61	72.33	144.62
6	52/4	34.26	70.58	139.46
7	22/2	33.88	70.15	134.96
8	35/2	34.17	73.05	139.42
9	20/1	33.96	71.94	135.11
10	213	33.85	69	131.5
11	161	34.25	69.13	136.01
12	19/2	34.24	71.11	135.69
13	51/3	34.06	69.22	131.17
14	36/30-3	34.12	71.9	137.05
15	33/3	34.24	71.89	135.7
16	A5/3	34.4	65.68	132.02
17	54/4	34.38	64.74	127.6
18	173	34.4	67.06	134.31
19	C15/1	34.39	65.72	129.71
20	13/4	33.88	66.83	124.66
21	53/2	34.06	60.3	118.14
22	302	34.54	62.84	124.78
23	45/2	34.55	60.71	123.25
24	41/1	34.62	56.6	115.67
25	53/4	34.3	55.53	110.16
26	41/3	34.57	55.97	114.81
27	142	34.36	48.2	92.96
28	18/2	34.27	41.2	81.69
29	40/2	34.5	38.95	74.69
30	232	33.66	37.62	70.97
31	43/1	34.55	37.7	70.47
32	292	34.42	33.57	63.41

Table 13: Measurements of cylindric samples

Taken together, these UPV test results further support the use of Friedland clay as a barrier material, but also indicate that issues such as moisture content and internal stresses must be carefully considered. These findings underscore the need for consistent conditions during the installation and ongoing monitoring of the clay to ensure its effectiveness in radioactive waste containment over extended periods.

5.4. Uniaxial Compressive Strength (UCS) test

Uniaxial Compressive Strength (UCS) testing is a fundamental technique to determine the compressive strength of materials such as bentonite under stress, which will help explain how well the material can resist pressure in the long term. In this research, the UCS test was carried out only on cylindrical specimens, which are the standard because they offer uniform surfaces and dimensions that allow precise compressive strength determination.

The UCS test machine works by subjecting the specimen to a monotonically increasing uniaxial load in the direction of its long axis until failure. The machine is essentially a sturdy loading frame with a hydraulic piston that pushes gently, at controlled force, on the sample. A cylindrical specimen is put between two compression plates, and when the piston pushes down, it compresses the specimen, gradually increasing the load until the specimen can no longer bear the weight and breaks. The machine that tests is calibrated to exert force accurately and uniformly so that every sample is tested on the same terms, to get consistent and comparable results.

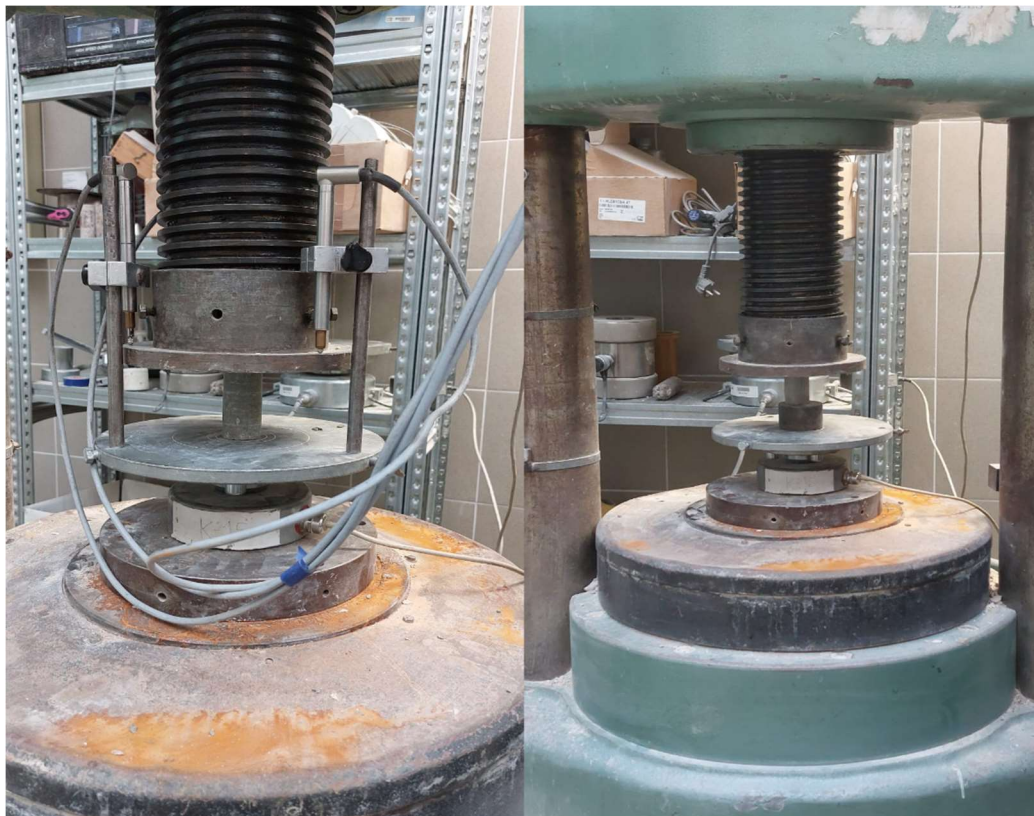


Figure 21: UCS test machine

When tested, sensors inside the machine record the ultimate load at failure, and other variables such as the lateral displacement and modulus of elasticity. Based on these measurements, the material's strength, elasticity and failure behaviour under uniaxial loading can be discerned. Every bit of information from the machine is sent to a tethered computer, where it's

automatically recorded and analysed. These measurements were then summed and tabulated in a table to clearly display the material's behaviour throughout the set of samples tested.

Because the UCS test captures data at failure, this enables us to study the effects of varying sample-preparation conditions such as the level of compaction pressure and moisture content on load-bearing capacity. The findings are vital to determining whether Friedland clay is suitable for use as a containment barrier in radioactive waste repositories, where it needs to stay structurally intact for millions of years under pressure. There is an image above of the UCS test machine and setup to illustrate the explanation of this testing procedure.



Figure 22: Examples of samples after UCS test

The Uniaxial Compressive Strength (UCS) Test, performed on cylindrical samples, was used to determine the compressive strength of Friedland clay - a parameter of importance for determining the load-bearing capacity and structural stability of the clay. This test determines the highest compressive force a sample can take before breaking, and thus gives us an idea of how tough the material is, and whether it would be a good barrier to contain radioactive waste. In storage of radioactive waste, for instance, materials need to be robust enough to ensure structural integrity for extended periods, which is why UCS testing is so important in assessing the integrity of Friedland clay under pressure.

UCS testing of cylindrical specimens varied from 7.6 MPa to 0.415 MPa, an observed strength variation presumably caused by variations in preparation conditions, including compaction pressure and initial water content. The higher the UCS values, the stronger the samples, meaning that these samples have a more dense and rigid structure that can support more weight. Smaller UCS values, on the other hand, signify weaker strength, and could make the material

more prone to deformation or failure under stress, with implications for its use as a containment barrier.

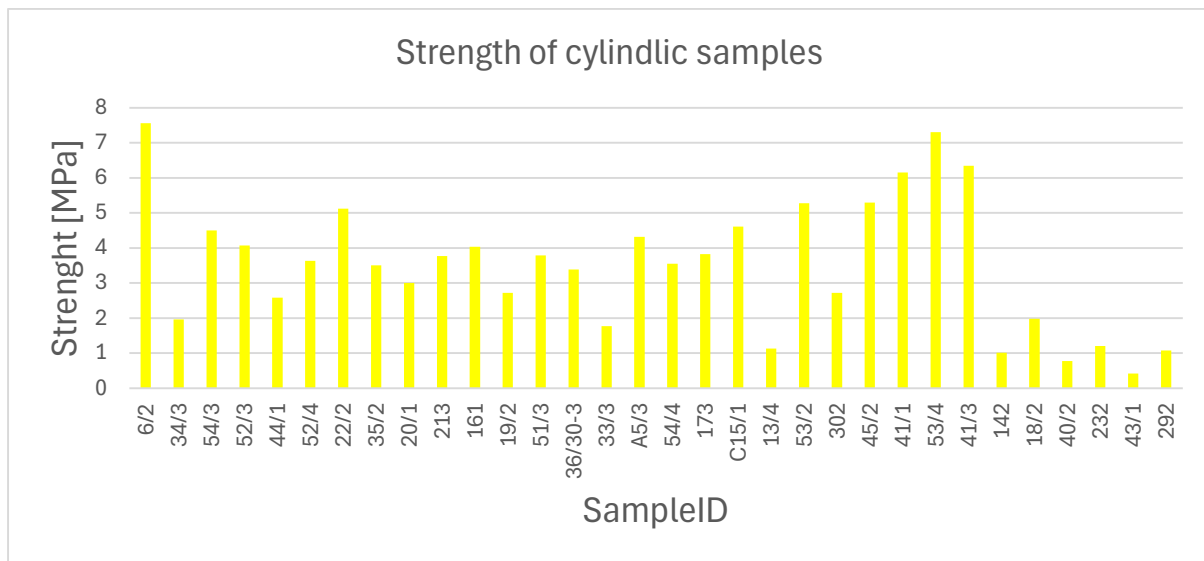


Figure 23: Results from the UCS test

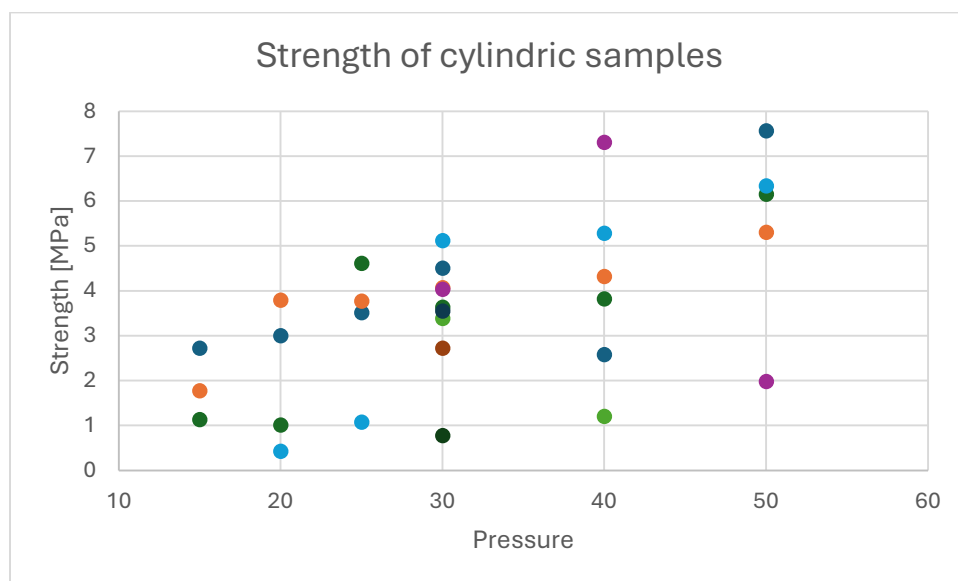


Figure 24: Pressure vs Strength graph

For six of the smallest cylindrical samples, the Brazilian test (an indirect method of measuring tensile strength) was performed instead of the UCS test, as their size was insufficient for standard compressive testing. The Brazilian test results are a useful adjunct for tensile properties, which, though secondary to compressive strength, also give some insight into the clay's integrity under various stress regimes.

All UCS and Brazilian test results are tabulated in order to succinctly summarise the variation in strengths observed. This spread of strength values is important because it shows that it is necessary to constrain preparation variables in order to obtain reproducible results, so that the clay structure can be made to conform to the properties needed for waste containment. Knowledge of these strength characteristics and their variability is immediately relevant to the design and preparation of containment barriers, and it underscores Friedland clay's potential, under the right conditions, to be a good barrier material in radioactive waste repositories.

The mechanical testing analysis using the Ultrasonic Pulse Velocity (UPV) and the Uniaxial Compressive Strength (UCS) tests has proved significant in understanding the structural integrity and suitability of Friedland clay as a host rock for radioactive waste disposal. The UPV test really brought out the need to get some homogeneity and density in the clay samples because the higher the pulse velocity, the more compact, less permeable, the structure. The measurements revealed some variation in UPV between cylindrical and cubic samples, highlighting the effects of preparation on the homogeneity of the material.

The UCS test again showed the compressive strength of Friedland clay, with values ranging from 7.6 MPa to 0.415 MPa. This spread implies that preparation variables, like compaction pressure and water content, play an important role in the mechanical stability of the clay. Samples with higher UCS values proved to be more resilient under stress, essential for maintaining structural integrity in a containment barrier. Moreover, the Brazilian test results on smaller specimens for the Brazil samples helped with a general understanding of the tensile properties of the clay, and the way it behaved under stress.

In summary, the mechanical test results support Friedland clay as a barrier material, while strength and uniformity are crucial for barrier performance during long-term containment. These observations highlight the importance of developing controlled preparation techniques that ensure consistency and reproducibility in practical applications. With optimised processing, Friedland clay can achieve the required properties of strength and low permeability, making it a more practical sustainable and robust option for radioactive waste storage.

VI. CONCLUSION

This study has reviewed the promise of Friedland clay as a containment material for radioactive waste disposal, drawing on a systematic literature review and experimental characterisation of those key physical and mechanical properties.

The literature review noted the proven application of bentonite-based clays in the containment of radioactive waste, owing to their low permeability, large swelling capacity and structural stability. Studies in Finland and Sweden, for example, confirmed the value of getting the best density, moisture content and structural homogeneity to promote these qualities. Studies also underscored the significance of preparation conditions—such as compaction pressure and initial moisture—in achieving stable, reliable clay barriers. Friedland clay could be compared with these studies and found that similar material properties would make it suitable for waste containment.

The experimental part of this research included tests on water content, density, ultrasonic pulse velocity (UPV) and uniaxial compressive strength (UCS) to assess the suitability of Friedland clay. All the tests yielded vital data on how preparation conditions affected the clay's ability to serve as a containment material.

Water Content: Measurements of water content in cylindrical samples varied from 4.66% to 6.04%, which suggests a moderate level of hydration across samples. This range is compatible with the clay's capacity to strike a balance between low permeability and structural integrity. The small change in water content reflects small differences in initial hydration of the samples, which could affect their swelling response and permeability. Compared with water content taken immediately after drilling, this study found a decline over time, probably because the samples dried out during the storage time before testing. This suggests that, over time, initial hydration levels plateau, a finding of great significance for practical applications where samples may dry out during the course of an experiment. The observed range of water content in my samples is in line with findings from Finland and Sweden, which indicate an optimal balance between water content and structural stability necessary for containment integrity.

Density: The average density found for the cubic samples was only 2.24 g/cm³, not much different than the 2.24 g/cm³ that Finland has reported and Sweden 2.0 g/cm³. Density is important in containment because it affects both mechanical integrity and permeability. The match with Finland's findings reinforces the consistency and reliability of Friedland clay in a controlled setting and lends it as a similarly strong barrier material. The higher density means low porosity - good for stopping waste leaks - bolstering Friedland clay as a long-term waste repository candidate.

UPV Test: The UPV measurements on cylindrical samples varied from 0.6999 to 1.7299 km/s, as compared to an initial range of 1.882 to 0.717 km/s measured shortly after drilling. This decline of UPV values during the 2–3-week period is probably due to a slight loss of moisture and small structural changes occurring during the time, both of which can affect material integrity. Because higher UPV values are typically associated with denser, more homogeneous material of higher structural consistency, the early decline indicates that Friedland clay needs tightly regulated conditions to maintain good integrity. These measured values are especially important in determining whether the clay makes a good containment material. The constant UPV spread over 1.7 km/s would indicate a material that is likely sufficiently tough to avoid

micro fracturing over time - a requirement for long-term stability in waste isolation. In this paper, though, the drop from the starting values suggests that further sample preparation is needed to eliminate long-term variability. In the case of cubic samples, the lower UPV values suggested a degree of heterogeneity in the clay matrix that could compromise containment integrity. Plotting these measurements in graphical form can reveal variations and highlight the need for consistent density, particularly in larger scale uses. Taken together, these results support the use of UPV testing in the characterisation of material homogeneity and structural integrity, which are essential for assessing the applicability of Friedland clay in radioactive waste repository settings.

UCS Test: UCS values for cylindrical specimens ranged from 7.6 MPa to 0.415 MPa, reflecting a large variation in compressive strengths due to preparation conditions. This spread illustrates the clay's capacity to resist compressive force but also suggests that particular compaction pressures are required to achieve the best strength. The Brazilian test, done on smaller specimens, added complementary tensile strength data, and so provided a broader picture of the toughness of Friedland clay. The UCS test findings are crucial as they validate Friedland clay's mechanical robustness, confirming its suitability as a material capable of maintaining structural integrity under stress—a fundamental requirement in waste containment.

To summarise, this study has shown that Friedland clay, prepared under tight control conditions, could satisfy the requirements for radioactive waste confinement. The results of the water content, bulk density, UPV and UCS tests all go together to show that it is a low permeability, stable, compressive material that can support structural loads for long periods. These properties are consistent with observations from Finland and Sweden and support the potential of Friedland clay as a sustainable and robust barrier material for radioactive waste disposal. Once the preparation variables are understood and manipulated, Friedland clay can be optimised for use in containment facilities and long-term waste storage solutions can be made safer and more effective.

References

- Gunnarsson D., L. M. (2006). *Deep repository – engineered barrier systems Assessment of backfill materials and methods for deposition tunnels.*
- Holt, E. J. (2011). *Buffer Component Manufacturing by Uniaxial Compression Method.*
- Keto, P. B. (2009). *Assessment of backfill design for KBS-3V repository.*
- Kiviranta, L. S. (2018). *Characterization of Bentonite and Clay Materials 20012-2015.*
- Mamunul, H. P.-T. (2012). *Backfill Production Line 2012 Design, Production and Initial State of the Deposition Tunnel Backfill and Plug.*
- Mingliang Xie, R. M.-J. (2012). *Bentonite as Barrier Material for the Sealing of Underground Disposal Sites.*
- Pusch, R. G. (2001). *The Buffer and Backfill Handbook, Part 2: Materials and techniques.*
- Web resources:
- Storage and Disposal of Radioactive Waste.* (2024, April 30). Retrieved from <https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste#near-surface-disposal> (accessed on 10th October)