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Water uptake of buffer and backfill

Laboratory tests

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Abstract

The KBS-3V concept for a repository for spent nuclear fuel consists of an underground facility, where hundreds of meters long tunnels contain eight-meter-deep deposition holes bored vertically in the tunnel floor. The spent fuel is encapsulated in copper canisters, which are placed in the deposition holes. The canisters are surrounded by highly compacted buffer blocks. Backfilling of the deposition tunnels above the deposition holes will be made with pre-compacted blocks placed in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls.

The water uptake of the buffer and the backfill in the repository is to a large extent expected to occur through localized inflow from water-bearing fractures in the adjacent near-field rock. It is therefore likely that the water uptake will be distinguished by the formation of channels and a relatively rapid water transport in pellets-filled slots, at least during the initial phase when the buffer or the backfill still is relatively dry, and especially so if the pressure of the inflowing water is high.

This report presents laboratory experiments that were designed and carried out with the objective to investigate these water uptake processes, how these are affected by different inflow rates, the pressure build-up, and the occurrence of channel formation in the pellet filling. These results can be used for the development and validation of material models that are used to predict the time-scale to saturate the bentonite components in the repository.

The laboratory experiments were performed with a simulated deposition tunnel (d=300 mm, L=2100 mm) filled with compacted blocks and pellets. A water inflow was applied via a filter from one of the tunnels ends. Two tests were made, one with a constant applied water pressure of 4 MPa, and one with a constant water inflow rate of 0.2 mL/min, but with a maximum applied water pressure of 4 MPa. The test duration was for both tests set to a maximum of 200 days, alternatively when 90 % of the available pore space was filled with water. A comprehensive sampling of the bentonite was made in conjunction with the dismantling to determine the water content and dry density distribution.

Sammanfattning

KBS3-V konceptet för ett slutförvar för utbränt kärnbränsle består av en underjordsanläggning med hundratals meter långa deponeringstunnlar, längs vilka åtta meter djupa deponeringshål skall borras i tunnelgolvet. Kärnbränslet skall placeras i kopparkapslar som i sin tur skall placeras i deponeringshålen. Kopparkapslarna skall omges av högkompakterade buffertblock tillverkade av bentonit. Deponeringstunnlarna ovanför deponeringshålen är planerade att återfyllas med förkompakterade block som placeras i tunneln och bentonitpellets som fyller upp utrymmet mellan blocken och tunnelväggarna.

Vattenupptaget i kärnbränsleförvarets buffert och återfyllning förväntas till stor del ske genom lokalt inflöde från vattenförande sprickor i intilliggande berg. Det är därför troligt att vattenupptaget kommer att utmärkas av kanalbildning och relativ snabb vattentransport i pelletsfyllda spalter, åtminstone under den initiala fasen när bufferten eller återfyllningen är förhållandevis torr, och i synnerhet om trycket hos det inflödande vattnet är högt.

I denna rapport presenteras laboratorieförsök som designats och genomförts med syftet att undersöka dessa vattenupptagsprocesser, hur de påverkas av olika inflödeshastigheter, tryckuppbyggnaden, och förekomsten av kanalbildning i pelletsfyllningen. Dessa resultat kan användas för utveckling och validering av materialmodeller som används för att prediktera vattenmättnadsförloppet för bentonitkomponenterna i kärnbränsleförvaret.

Laboratorieförsöken genomfördes i en simulerad deponeringstunnel (d=300 mm, L=2100 mm) fylld med kompakterade block och pellets. Två försök har genomförts, ett med ett konstant högt vattentryck på 4 MPa, och ett med ett konstant inflöde på 0,2 mL/min, men där det maximala vattentrycket var 4 MPa. Testerna kördes under maximalt 200 dagar alternativt till dess att 90 % av den tillgängliga porvolymen var fylld med vatten. En omfattande provtagning av bentoniten gjordes i samband med brytningen av försöken för att bestämma vatteninnehåll och densitetsfördelning.

Contents

1 Introduction

The KBS-3V concept for a repository for spent nuclear fuel consists of an underground facility, where hundreds of meters long tunnels contain eight-meter-deep deposition holes bored vertically in the tunnel floor. The fuel is encapsulated in copper canisters, which are placed in the deposition holes. The canisters are surrounded by highly compacted buffer blocks. Backfilling of the deposition tunnels above the deposition holes will be made with pre-compacted blocks placed in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls.

The water uptake of the buffer and the backfill in the repository is to a large extent expected to occur through localized inflow from water-bearing fractures in the adjacent near-field rock. It is therefore likely that the water uptake will be distinguished by the formation of channels and a relatively rapid water transport in pellets-filled slots, at least during the initial phase when the buffer or the backfill still is relatively dry, and especially so if the pressure of the inflowing water is high. Earlier investigations regarding water transport in pellet-filled gaps were presented by Åkesson et al. (2020).

This report presents laboratory experiments that were designed and carried out with the objective to investigate these water uptake processes, how these are affected by different inflow rates, the pressure build-up, and the occurrence of channel formation in the pellet filling. These results can be used for the development and validation of material models that are used to predict the time-scale to saturate the bentonite components in the repository.

The laboratory experiments were performed with a simulated deposition tunnel filled with compacted blocks and pellets. The test equipment consisted of cylindrical steel tubes with flanges (d=300 mm) that were mounted together to achieve a total test length of the simulated tunnel of 2100 mm. One shorter tube was equipped with a cylindrical filter on the inner periphery where it was possible to apply a water inflow. Two tests were made, one with a constant applied water pressure of 4 MPa, and one with a constant water inflow rate of 0.2 mL/min, but with a maximum applied water pressure of 4 MPa. The test duration was set to a maximum of two hundred days, alternatively when 90 % of the available pore space was filled with water.

A detailed description of the test equipment is provided in Chapter 2. The bentonite material, blocks and pellets, used in the tests are described in Chapter 3. The test preparation, the registered data and the result from the sampling are provided in Chapter 4 (Test 1) and in Chapter 5 (Test 2). Comments and conclusions of the tests are presented in Chapter 6.

2 Test description

2.1 Test matrix

Two tests were performed in this test series:

1. Water inflow at constant pressure of 4 MPa. The access to water should continue until the cumulative water uptake reaches 90 % of the available pore volume. Maximum test time was set to two hundred days.
2. Water inflow at constant inflow rate of 0.2 mL/min (0.288 liter/24h) but with a maximum pressure of 4 MPa. The access to water should continue until the cumulative water uptake reaches 90 % of the available pore space. Maximum test time was set to two hundred days.

It should be noted that the maximum water pressure in the tests was 3.8 MPa rather than 4 MPa due to limitations of the pump equipment used.

2.2 Test equipment

The tests were performed using a steel tube simulating a section of a deposition tunnel. Four steel tubes, three with a length of 600 mm and one with a length of 300 mm, were connected to each other via flanges and two steel lids were bolted at the ends, see the schematic drawing in Figure 2-1. The total length of the simulated tunnel was thus 2100 mm. The tunnel was filled with bentonite. Compacted blocks with a diameter of 260 mm were positioned in the center of the tunnel and the gap between the blocks and the tunnel walls was filled with bentonite pellets. Water was injected into a circular filter (simulated fracture) positioned at the tunnel periphery in the first short section. The filter was positioned on the steel surface i.e., the filter was not recessed into the tube. The filter had a thickness of 2 mm and a width of 90 mm. Sensors for measuring total pressure and pore pressure were installed at five positions. One total pressure sensor and one pore pressure sensor were placed at the top of each of the three tubes with a length of 600 mm, and at both ends of the simulated tunnel. The total pressure was measured using pistons, d=20 mm, which were transferring the pressure in the tunnel to an external loadcell (T1-T5). The pore pressure in the tunnel was measured by leading water through a steel filter to an external sensor (P1-P5). The applied water pressure at the inflow point was also registered. The injected water volume was registered either by a balance or by a so-called GDS APVC (Advanced Pressure/Volume Controller), see description in Section 2.4.

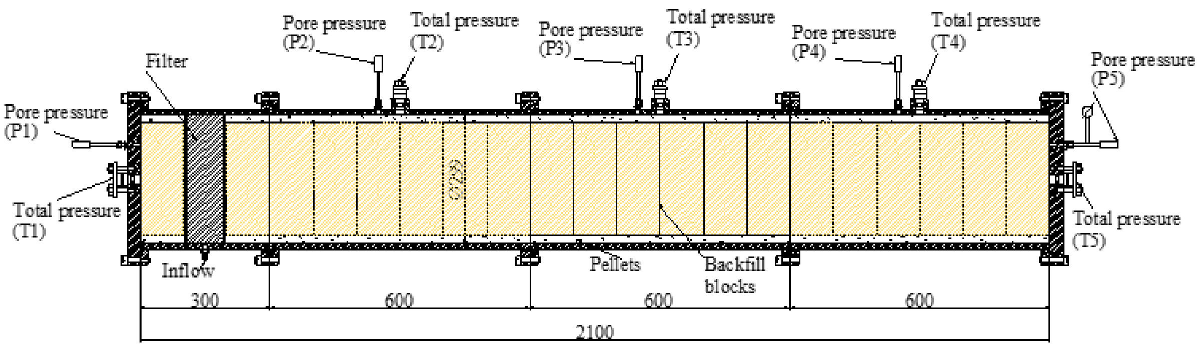


Figure 2-1. Schematic overview showing the design of the test equipment.

2.3 Water and pump equipment

2.3.1 Water

The water used in the tests had a salt content of 1 % by weight (50/50, Na/Ca) and contained $CaCl_2$ and NaCl at a mass ratio of 1:1. The total dissolved solids (TDS) content was 10 g/l.

2.3.2 Pump equipment

Different methods were used to achieve the desired applied water pressure and water flow rate:

Test 1 (4 MPa)

The chosen inflow condition, with a constant water pressure of 4 MPa, made it necessary to use a special High-Pressure Pump, which could maintain a relatively high inflow rate, especially during the initial phase of the test. The pump lifted water from a vessel placed on a laboratory balance. When the injection pressure exceeded 4 MPa, a pressure relief valve opened and let the water out back to the vessel. By manual readings of the weight of the vessel it was possible to measure the injected water volume with time. A photo of the test setup including pump and balance is provided in Figure 2-2 (left).

Test 2 (0.2 mL/min, 4 MPa)

A constant flow rate of 0.2 mL/min (0.288 L/24h) was achieved by using a special equipment, a so-called GDS APVC (Advanced Pressure/Volume Controller). With this equipment, it was possible to apply a constant flow rate with an at the same time increasing water pressure. When the water pressure had increased and was close to 3.8 MPa, the pump settings were changed to instead apply a constant water pressure of 3.8 MPa. A photo showing the GDS is provided in Figure 2-2 (right).

Figure 2-2. *Left: Photo showing the pump system used in Test 1 to inject water with high pressure, 4 MPa. Right: Photo showing the GDS APVC (Advanced Pressure/Volume Controller) used to apply a constant flow rate of 0.2 mL/min in Test 2.*

3 Material

3.1 Block manufacturing

The buffer blocks used in the tests were manufactured using a material with the trade name BARA-KADE 1002. The material is a natural sodium bentonite originating from Wyoming, USA.

The as-delivered material had a water content of 12 %. Before compaction to blocks, the material was mixed with water in an Eirich-mixer, to achieve a target water content of 17 %. The mixing was made at Äspö Laboratory. The target dry density for the compacted blocks was 1650 kg/m^3.

The blocks were compacted in a large press available at Lund University, Faculty of Engineering (LTH) in Lund, see left photo in Figure 3-1. The compaction pressure was set to approximately 22 MPa. The blocks had after manufacturing, a height of 100 mm and an outer diameter of 275/280 mm (slightly conical). The blocks were after manufacturing machined to have an outer diameter of 260 mm (varied between 258 and 262 mm). The machining was made using a bandsaw, where the block was rotated slowly against the saw blade. A photo of a block after adjustment of the diameter is provided in Figure 3-1 (right photo).

Figure 3-1 *Left: Manufacturing of blocks with an outer diameter of 275/280 mm using the 1000-ton press at LTH Lund. Right: Photo showing a manufactured block after adjustment of the diameter.*

3.2 Pellets

The pellets used in the tests were manufactured using the same material as was used for the buffer blocks (BARA-KADE 1002). The pellets used in the tests were manufactured by extrusion. This method includes that the bentonite material is squeezed through a hole-matrix, which results in pellets shaped as rods with varying length, Figure 3-2. The diameter of the pellets used in the tests was 6 mm and the length varied mainly between 5 and 25 mm. The pellets had a water content of 14.1 %. The pellet manufacturing was made at Äspö Laboratory.

Figure 3-2 *Photo showing pellets manufactured by extrusion.*

4 Test 1 (4 MPa)

4.1 Test preparation

4.1.1 Bentonite blocks

In total twenty-one blocks were used in this test plus a thin disc (thickness 21 mm). The thin disc was necessary to completely fill up the test cell with blocks (the length of the tunnel was 2100 mm, and the installed blocks had a height of between 98 to 99 mm). All blocks were measured and weighed before installation, see data provided in Appendix 1.

4.1.2 Bentonite pellets

Pellets were installed in the outer gap between the blocks and the tunnel walls. After installation of between one to three blocks, pellets were filled up in the outer gap. The weight of the installed pellets was determined, see data provided in Appendix 1. It should be noted that in the calculation of the achieved pellet density, the height of the pellet filling was set to the same as the block height since it was difficult to measure the actual height.

4.1.3 Assembly

The bottom end plate was mounted on one of the 600 mm long tube sections. The tube section was thereafter placed on the floor standing on the end plate. The installation of blocks and pellets was made with the tube sections standing vertically. After installation of two blocks, the outer gap between the installed blocks and the outer test cell wall was filled with pellets, see photo provided in Figure 4-1. Blocks and pellets were installed up to a height of 600 mm before the next tube section was mounted. A fork-lift was used to lift the tube sections in conjunction with the mounting. The assembly continued according to this procedure until all tube sections were mounted together. After mounting of the top end plate, the complete test setup was turned by use of a forklift and lifting straps. The test setup was then placed horizontally on the floor. The photo provided in Figure 4-2 shows the complete test setup including the high- pressure pump and the balance used to determine the amount of injected water.

Figure 4-1 *Blocks and pellets have been installed.*

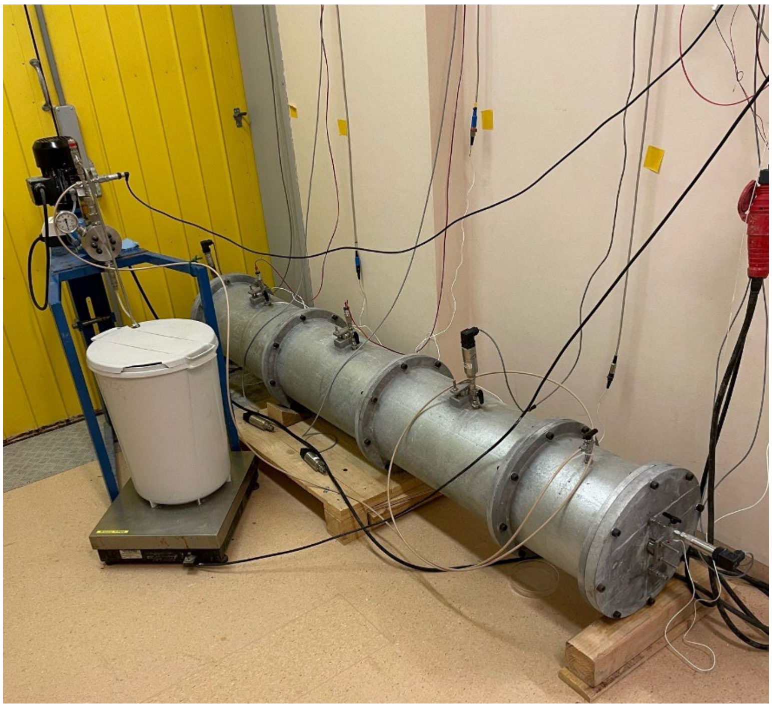


Figure 4-2 *The complete test setup including the pump and the balance.*

4.1.4 Installation data

Detailed data regarding the block dimensions, block weight, and pellets weight is provided in Appendix 1. A compilation of the most important data is provided below.

Blocks

The average bulk density of the blocks was 1968 kg/m^3. The bentonite had a water content of 17.4 % which means that the average dry density of the blocks was 1676 kg/m^3. The installed height of all blocks was calculated to 2093.4 mm which indicated that there was a total space between the blocks of 6.6 mm, probably rather evenly distributed along the test tunnel.

Pellets

The average bulk density of the installed pellet filling was 1099 kg/m^3. The pellets had a water content of 14.1 % which means that the average dry density of the pellet filling was 964 kg/m^3.

Dry density in the test volume

The total test volume was 0.14745 m^3. In total 220.714 kg dry mass bentonite was installed in the test volume (blocks=186.069 kg and pellets=34.645 kg). This resulted in an installed average dry density in the test volume of 1497 kg/m^3.

Available pore volume

The determined bulk density, water content and dry density of the block filling and pellet filling respectively is provided in Table 4-1. The porosity (n) of the block filling and pellet filling was calculated:

$$n = 1 - \frac{\rho}{\rho_s\ (w+1)} \qquad \text{4-1}$$

where ρ is the bulk density, ρ_s is the density of the solids, and w is the water content. The available pore volume, $PV_{available}$, could then be calculated:

$$PV_{available} = n \times V_{block}\ (1 - Sr) \qquad \text{4-2}$$

where V_{block} is the volume of the blocks (or pellets) and Sr is the degree of saturation of the bentonite.

The available pore volume in the blocks was calculated to 0.01218 m^3 and in the pellets to 0.01861 m^3, see details in Table 4-1. The total available pore volume was thus 0.03079 m^3. To achieve a filling of the available pore volume of 90 %, a water volume of 0.02771 m^3 should be injected.

Table 4-1. Installation data for Test 1 and the calculated available pore volume.

Test 1	
Test equipment	
V tunnel, m^3	0.14745
Installation	
Block	
w, %	17.4
Installed bulk mass, kg	218.445
Block volume (d=260 mm), m^3	0.11149
Bulk density, kg/m^3	1959
Dry mass, kg	186.069
Dry density, kg/m^3	1669
Density of solids, kg/m^3	2780
Void ratio	0.666
Sr, %	72.7
Porosity, %	0.400
Available pore volume, m^3	**0.01218**
Pellets	
w, %	14.1
Installed bulk mass, kg	39.530
Pellet volume, m^3	0.03596
Bulk density, kg/m^3	1099
Dry mass, kg	34.645
Dry density, kg/m^3	964
Density of solids, kg/m^3	2780
Void ratio	1.885
Sr, %	20.8
Porosity, %	0.653
Available pore volume, m^3	**0.01861**
Water uptake	
Total available pore volume, m^3	0.03079
Desired part of pore volume to be filled, %	90
Water volume to inject, m^3	**0.02771**

4.2 Registered data during test time

4.2.1 Injected water volume and applied water pressure

The measured injected water volume and water injection pressure for Test 1 are plotted versus time in Figure 4-3. It took approximately 2.5 hours to reach an injection pressure of 4 MPa. At this time had about 22 liters been injected. A small dip in pressure could be seen after 12 days of test duration in conjunction with an attempt to adjust the pressure relief valve. The adjustment was done to avoid water injection pressures above 4 MPa.

The test duration was approximately 33 days. After this time, a water volume of 28.128 liters had been injected into the test cell, corresponding to 91.33 % of the volume available at test start.

The injection pressure varied during the test, between 3.5 to 4.3 MPa. The variation was partly due to the pump strokes and partly due to the accuracy of the pressure relief valve.

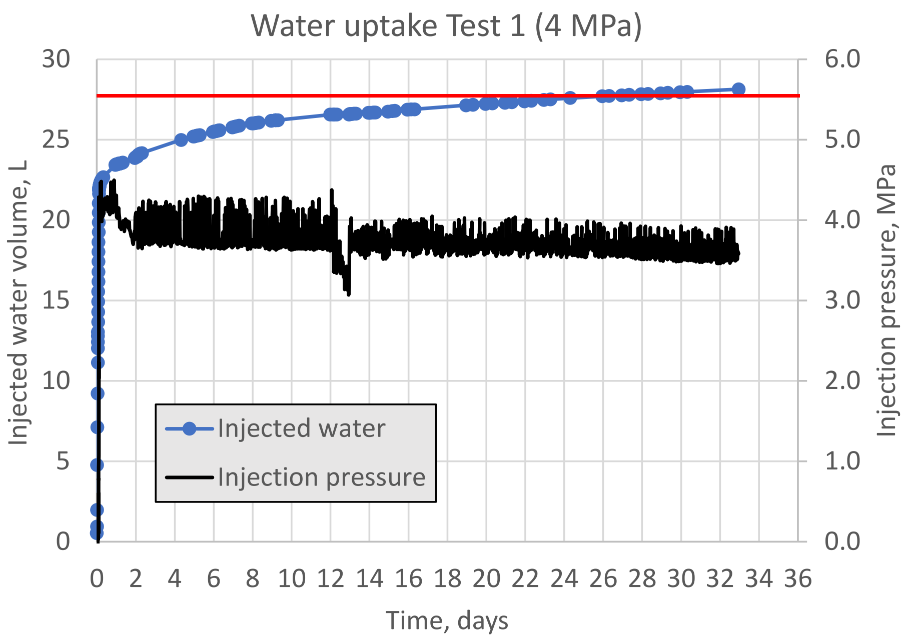


Figure 4-3. Injected water volume (blue) and water injection pressure (black) plotted versus time for Test 1. The red line indicates the volume needed to achieve a filling of the available pore volume of 90 %.

4.2.2 Registered total pressure and pore pressure

The graph provided in Figure 4-4 shows the registered water injection pressure (black line), the total pressure (full lines) and the pore pressure (dotted lines) plotted versus time in Test 1.

The fast filling of water in the beginning of the test resulted in registration of increased total pressure and pore pressure at all sensor positions. The registered pressure was at most positions at the same level as the applied injection pressure. However, after about one week, the pressure started to decrease at almost all positions, except the total pressure in position 1 and both total pressure and pore pressure at position 2. This was probably caused by swelling of the bentonite blocks, which thereby would compress the pellet-filled slot and increase the flow resistance along the periphery, which in turn would lead to the pore pressure decrease at sensor positions far from the water inlet and on the tube endings.

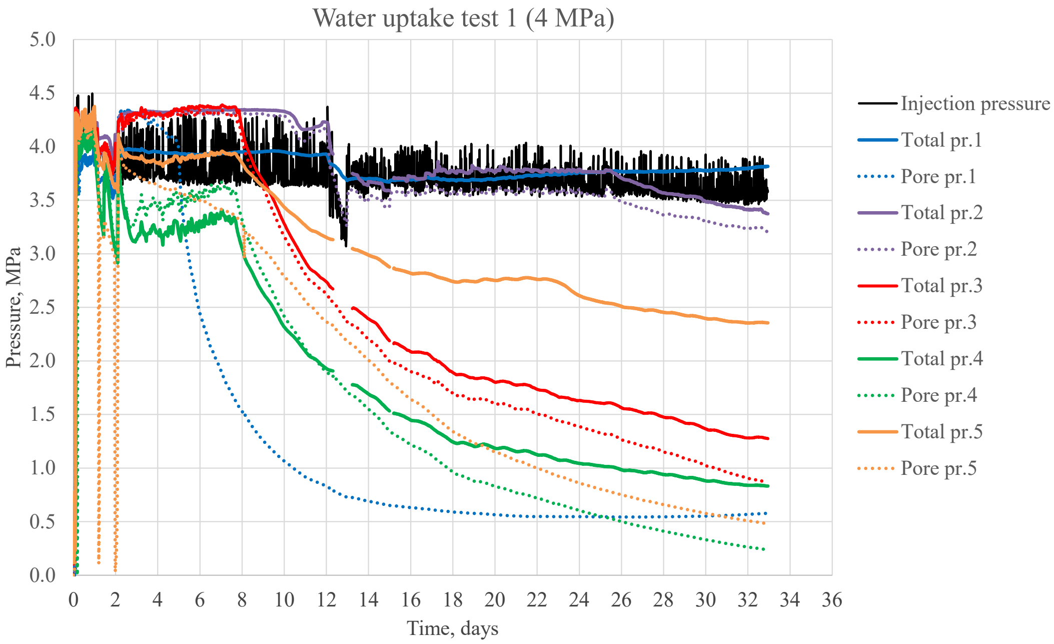


Figure 4-4. *Graph showing the registered water injection pressure (black line), the total pressure (full lines) and the pore pressure (dotted lines) in Test 1.*

4.3 Dismantling

4.3.1 General

When the amount of injected water had reached more than 90 % of the available pore volume at test start, it was decided to stop the test and start the dismantling. The total test duration was 33 days.

The water content and bulk density were determined in the bentonite at 264 positions. This data was then used to calculate the dry density and the degree of saturation.

4.3.2 Water content, density, and degree of saturation

Water content

The water content is defined as mass of water per mass of dry substance. The dry mass is obtained by drying the wet specimen at 105 °C for 24 hours.

The sample was placed in an aluminum tin and the bulk mass (m_b) of the sample was determined by use of a laboratory balance. The sample was placed in an oven for 24 h at a temperature of 105 °C. The dry mass of the sample (m_s) was determined immediately after removal from the oven. From these measurements the water mass (m_w) was calculated:

$$m_w = m_b - m_s \qquad 4\text{-}3$$

and the water content (w) of the sample determined:

$$w = \frac{m_w}{m_s} \qquad 4\text{-}4$$

Bulk density, dry density, and degree of saturation

The bulk density (ρ_b) was determined by hanging the sample in a thin thread under a balance. The sample was then weighed, first in air (m_b) and then submerged into paraffin oil (m_{bp}). The volume of the sample was then calculated:

$$V = \frac{(m_b - m_{bp})}{\rho_p} \quad \text{4-5}$$

Where ρ_p is the paraffin oil density. The bulk density of the sample was then calculated:

$$\rho_b = \frac{m_b}{V} \quad \text{4-6}$$

After determining the water content and the bulk density of each sample it was possible to calculate the dry density (ρ_d):

$$\rho_d = \frac{\rho_b}{1+w} \quad \text{4-7}$$

Since the grain density (ρ_s) and the density of the water (ρ_w) are known, the degree of saturation (Sr) can be calculated:

$$Sr = \frac{w \cdot \rho_b \cdot \rho_s}{\left[\rho_s \cdot [1+w] - \rho_b\right]} \frac{}{\rho_w} \quad \text{4-8}$$

In the calculations, a grain density (ρ_s) of 2780 kg/m^3 and a water density (ρ_w) of 1000 kg/m^3 have been used.

4.3.3 Sampling

A comprehensive sampling of the bentonite was made in conjunction with the dismantling to determine the water content and dry density distribution within the test volume. The sampling was done in eight cross-sections along the tunnel, see schematic drawing provided in Figure 4-5. In each of the cross-sections (A-H), samples were taken in four directions (0°, 90°, 180° and 270°) according to Figure 4-6. Thirty-three samples were thus taken from each of the eight cross-sections, which means that samples were taken at in total 264 positions.

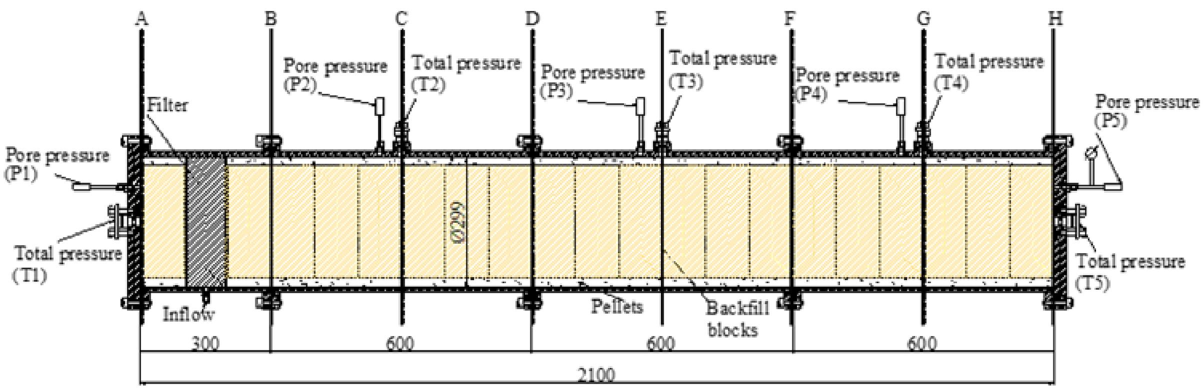


Figure 4-5. Planned sampling of the bentonite. The water content and density were determined at in total eight cross-sections, see detailed sampling in every cross-section in Figure 4-6.

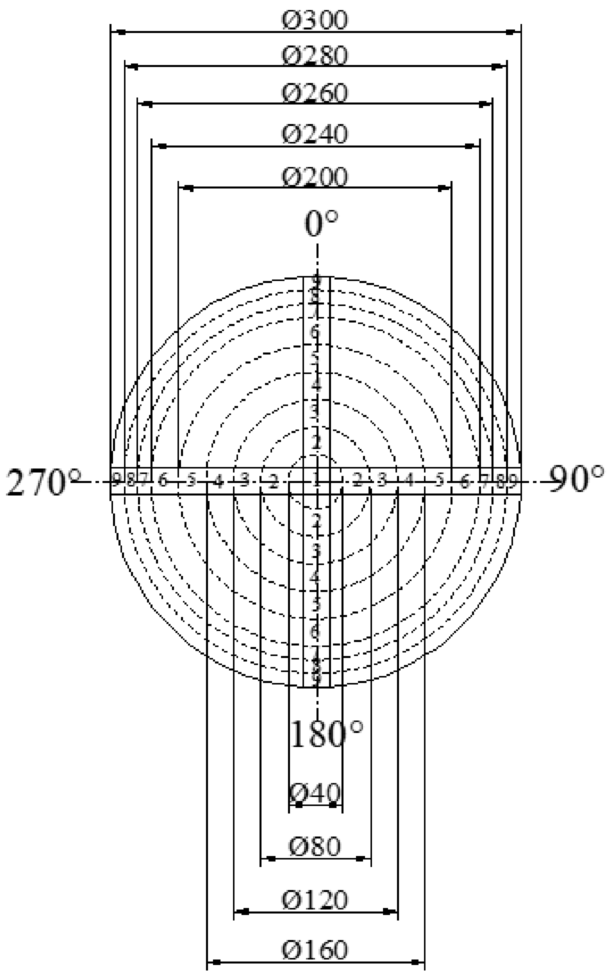


Figure 4-6. *Planned sampling of the bentonite. The water content and density were determined at in total thirty-three sampling positions in each of the eight sampled cross-sections.*

4.4 Results from sampling

The sampling sections positioned in the joints between the tube sections could easily be sampled after division, cross section A, B, D, F and H in Figure 4-7. For the sampling sections positioned in the middle of the tube sections (cross section C, E and G), a hydraulic piston was used to push out the bentonite from each of the tunnel sections after which the sampling could be done, see lower right photo in Figure 4-7.

In conjunction with dismantling, it was noticed that the bentonite had been wetted in an almost symmetrical way. The former pellet filled gap seemed to be completely saturated, see the two upper photos provided in Figure 4-7. It was also noticed that the parts with higher water content (dark sections) seemed to be larger at the top of the tunnel cross sections. The density of the central parts of the blocks was clearly higher than at the periphery, indicating that the homogenization had not proceeded far. The bentonite at both ends of the test (sampling section A and H) was clearly more wetted compared to the other sampling sections, see lower left photo in Figure 4-7.

Figure 4-7. *Photos taken in conjunction with the dismantling of Test 1. Upper left and right: These photos clearly show the wetting pattern that could be seen in all sampled cross-sections except the two outermost. Lower left: Photo from one of the outer cross-sections (H). The complete surface looked wet. Lower right: A hydraulic equipment was used to press out the bentonite from the test cell. The exposed surface has been sampled.*

The results from the sampling of each cross section (A to H) are provided in Figure 4-8 to Figure 4-15. Graphs are provided showing the water content, the dry density, and the degree of saturation in four directions for every sampled cross section.

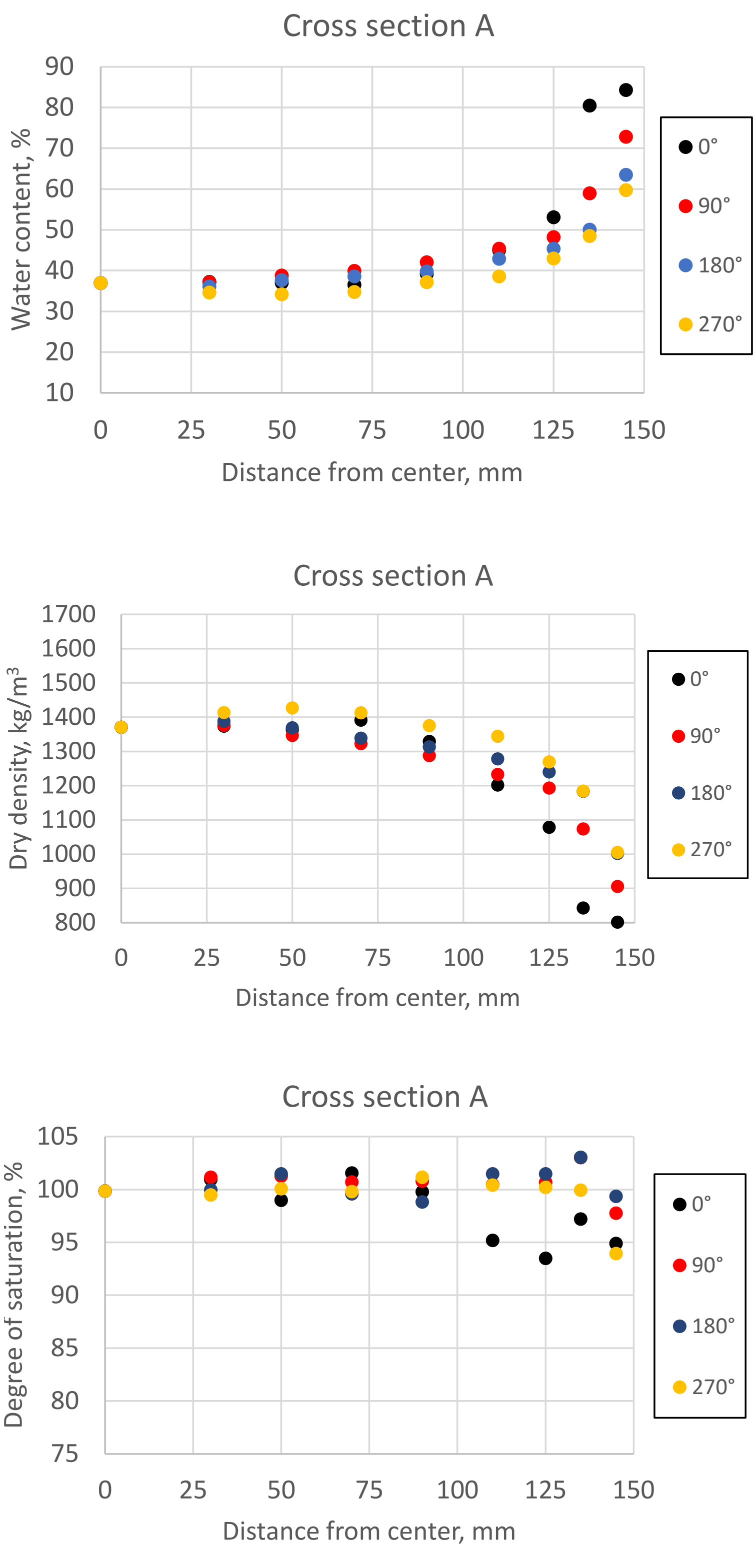
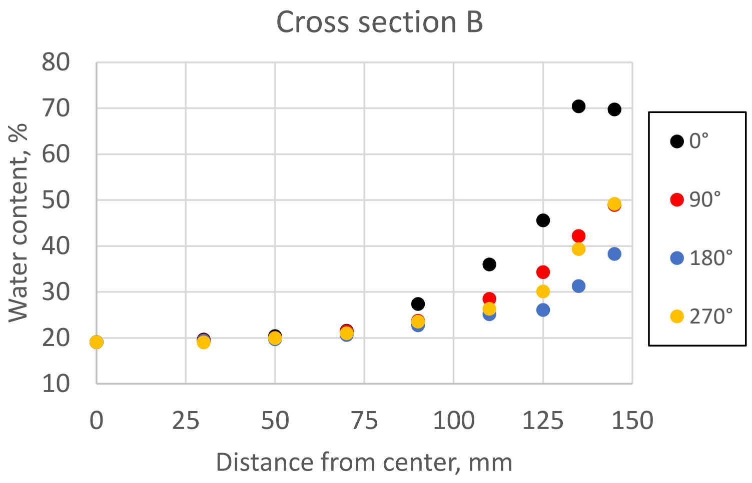
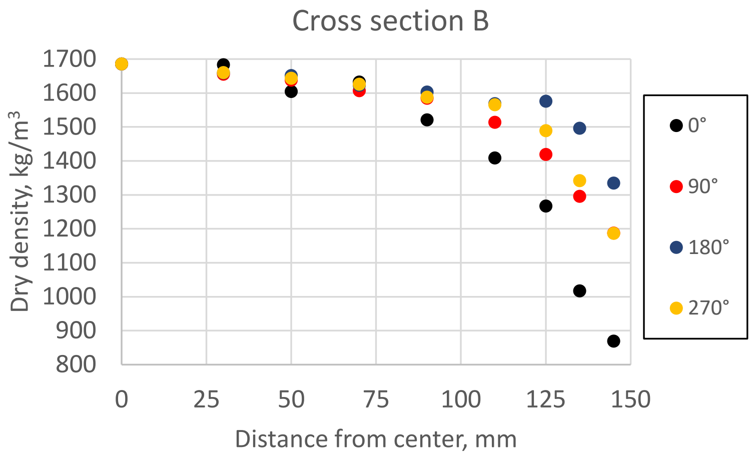


Figure 4-8. *Results from measurements in cross section A. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*





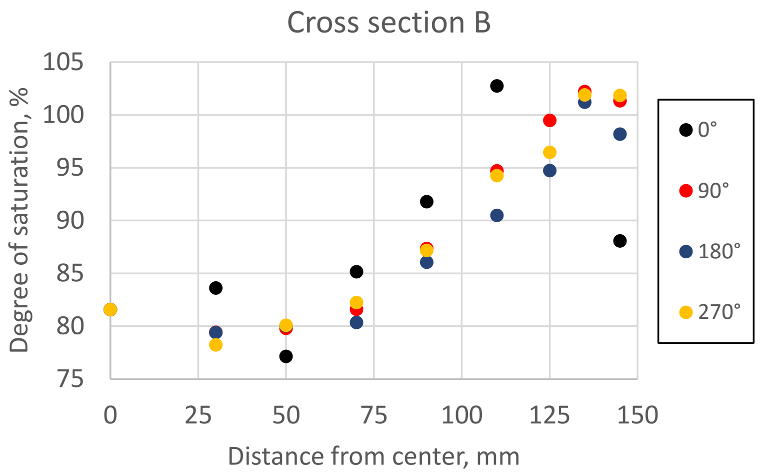


Figure 4-9. *Results from measurements in cross section B. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

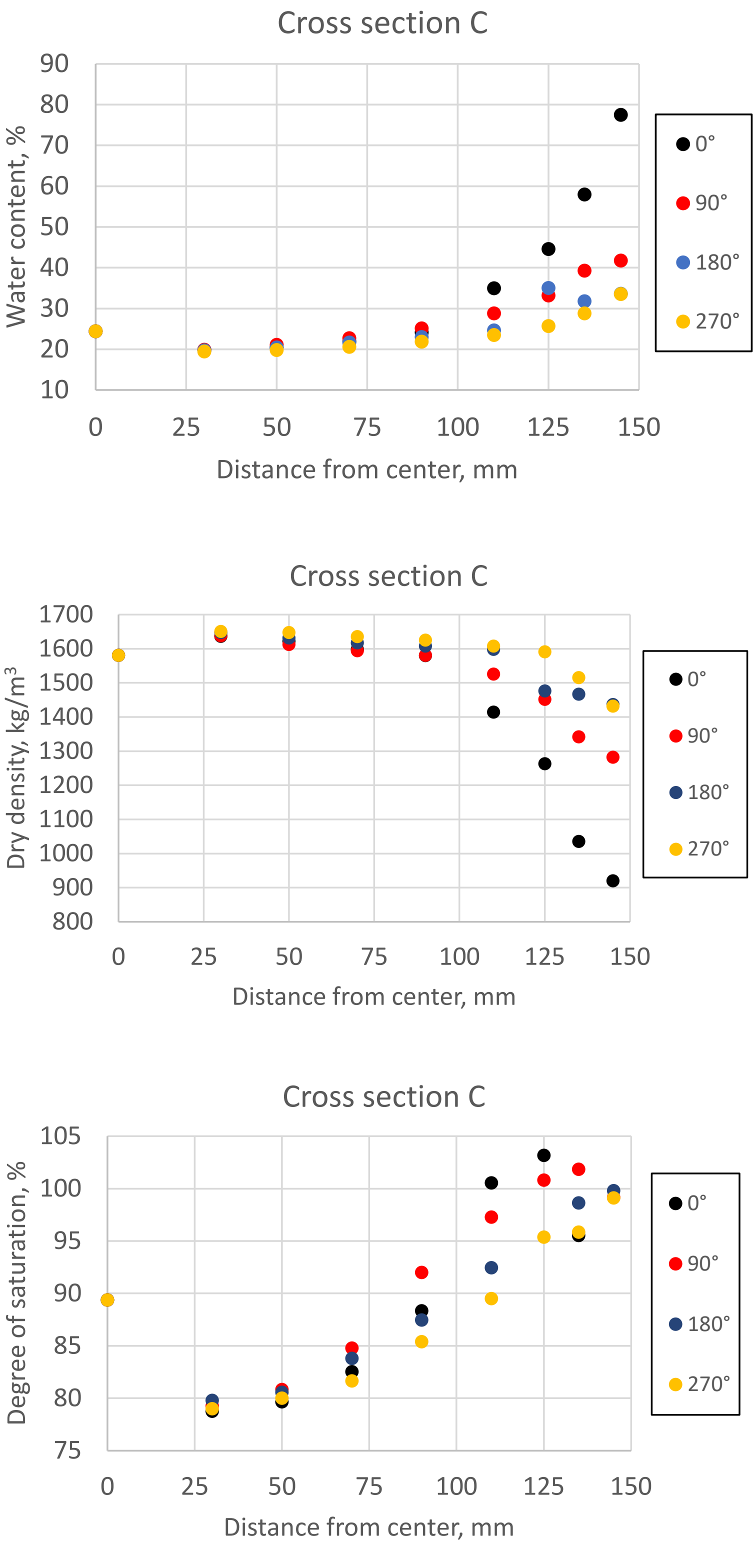
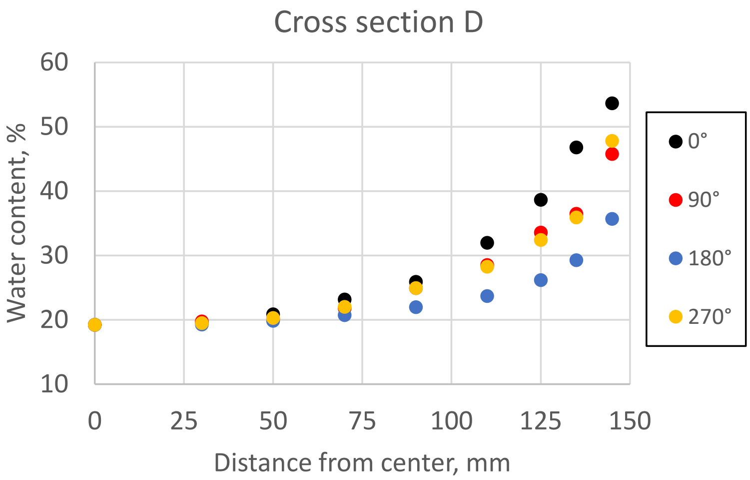
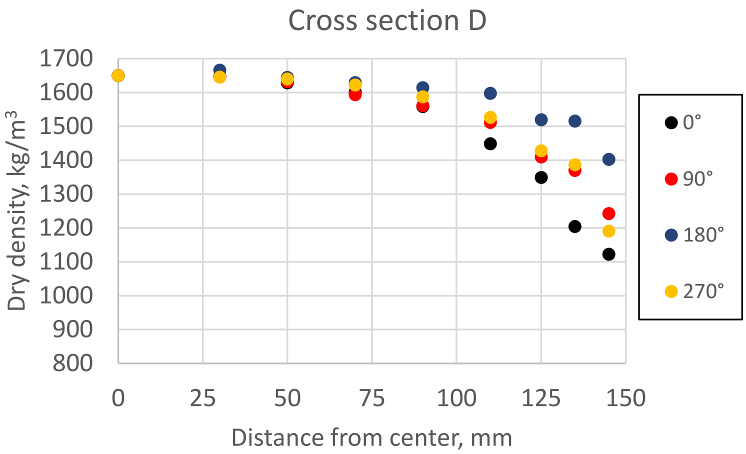


Figure 4-10. *Results from measurements in cross section C. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*





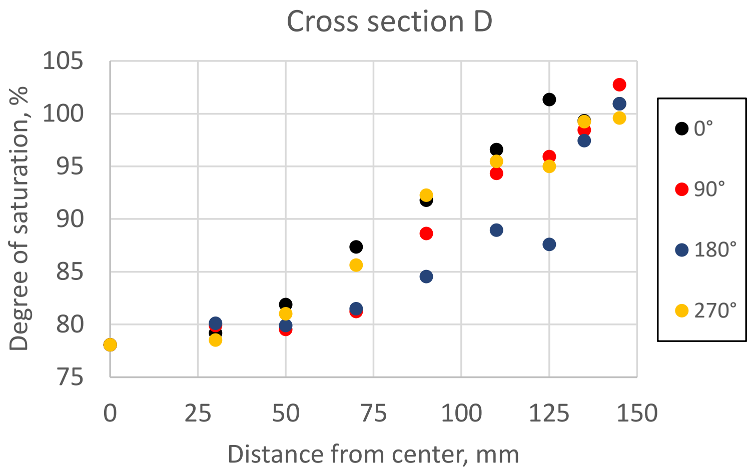


Figure 4-11. *Results from measurements in cross section D. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

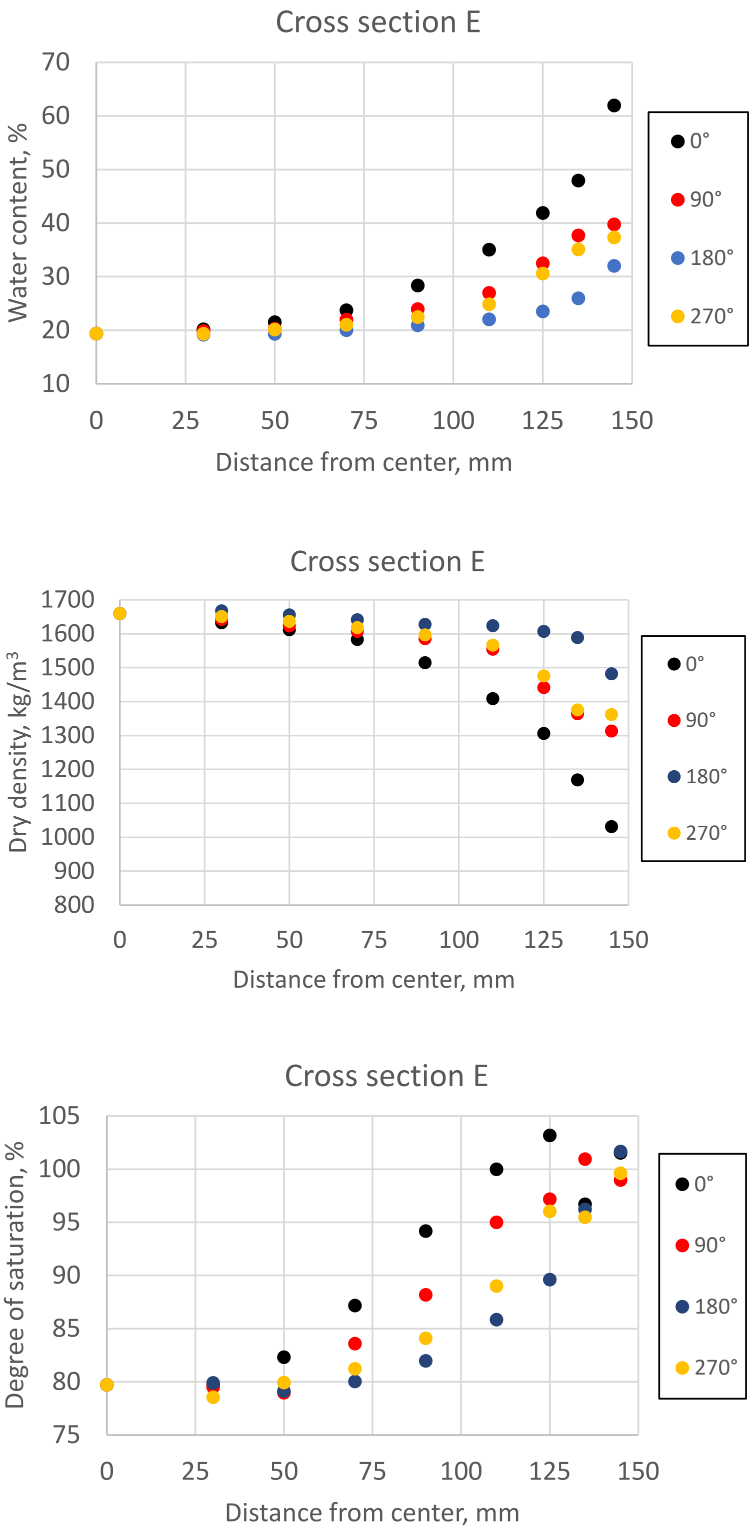
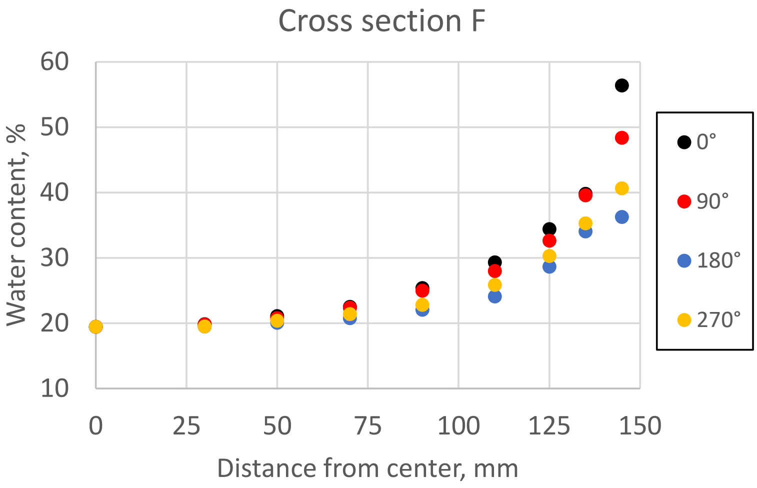
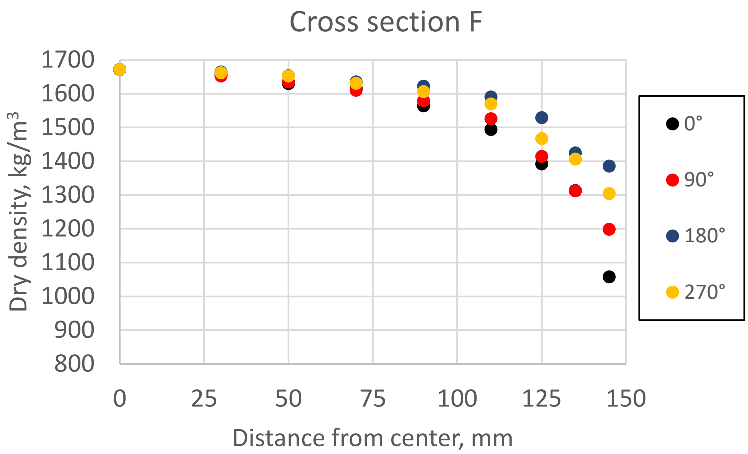


Figure 4-12. *Results from measurements in cross section E. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*





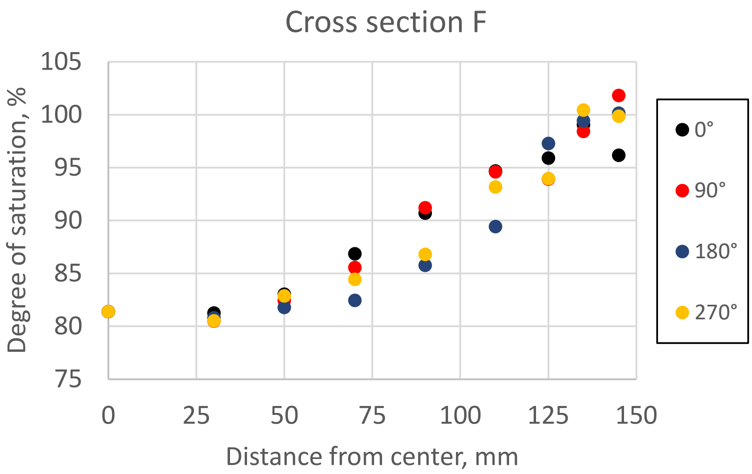


Figure 4-13. *Results from measurements in cross section F. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

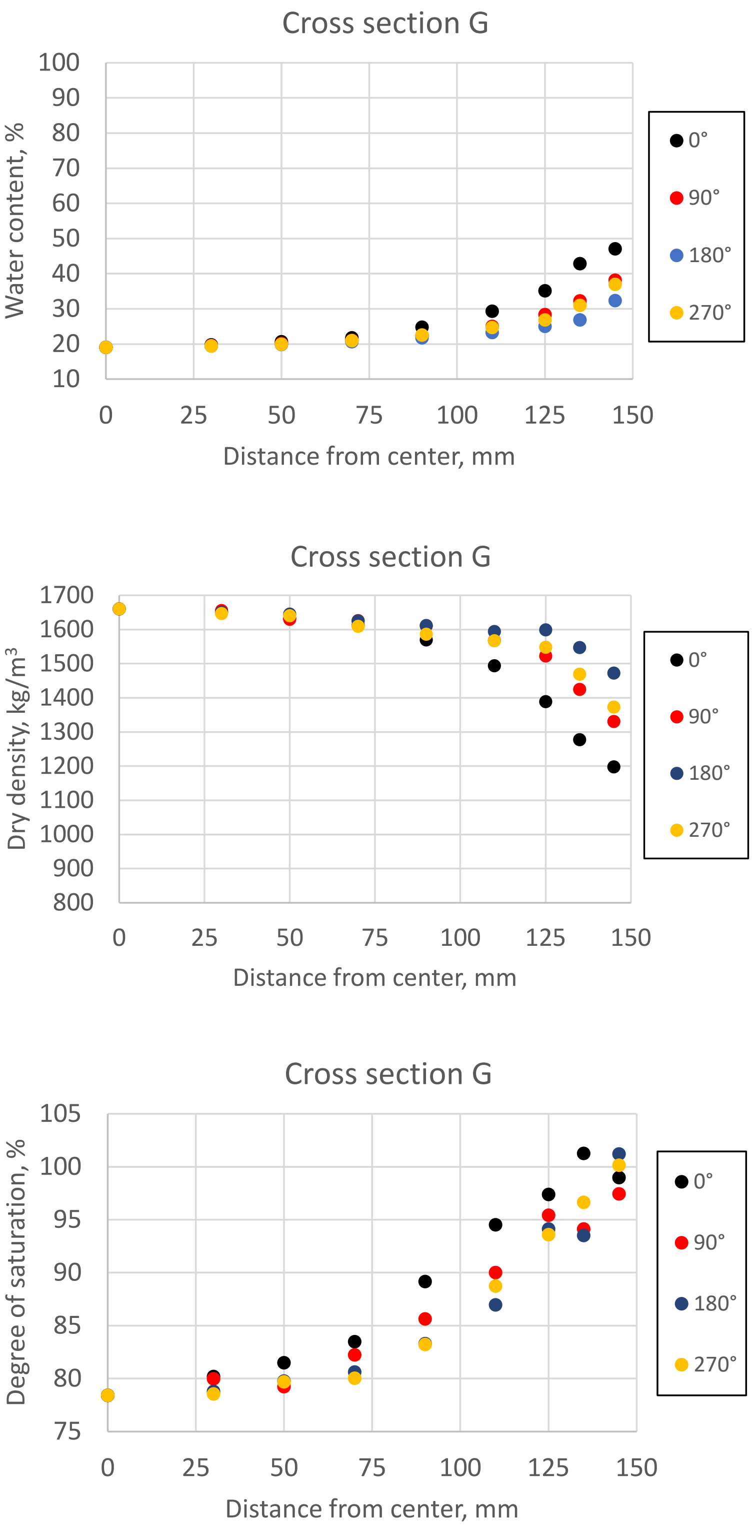


Figure 4-14. *Results from measurements in cross section G. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

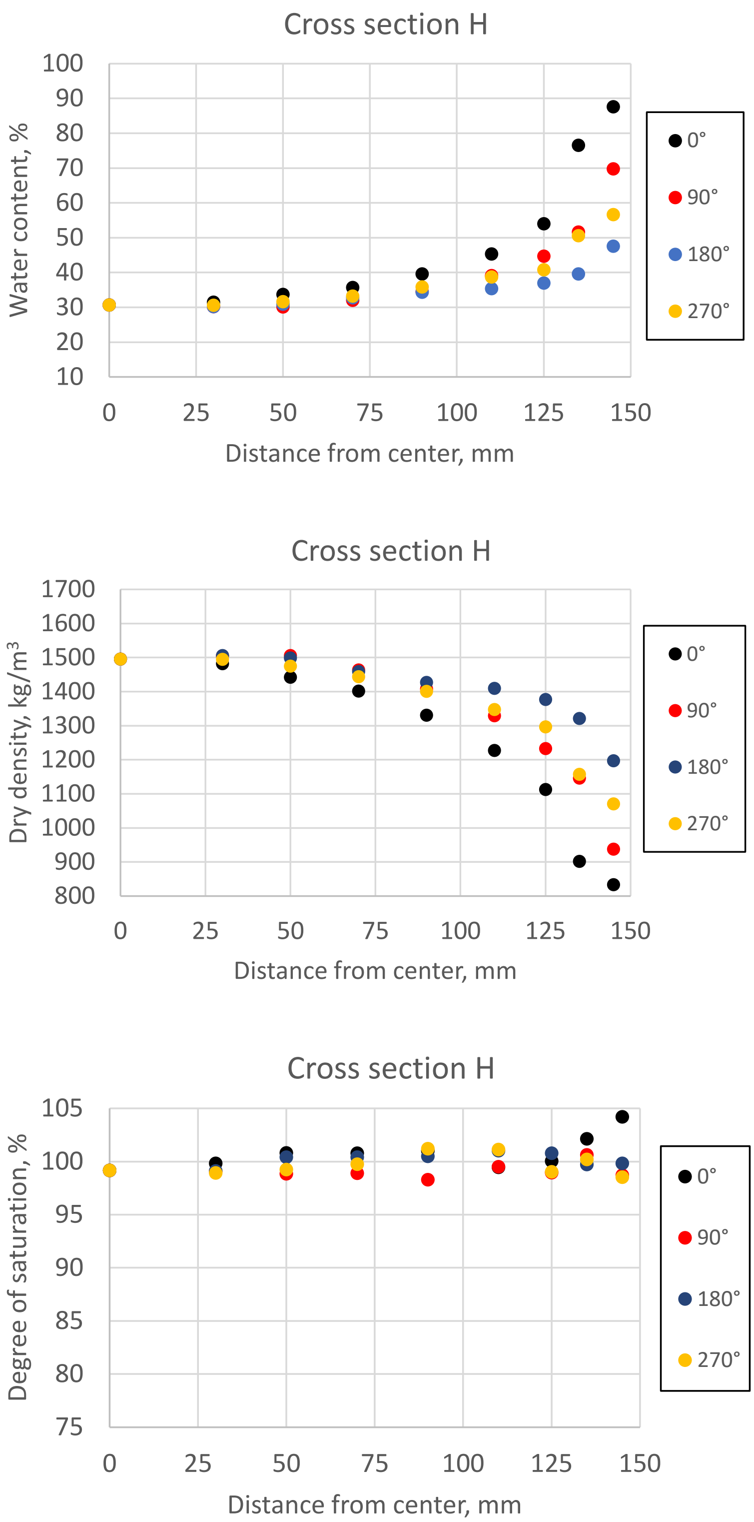


Figure 4-15. *Results from measurements in cross section H. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

4.5 Compilation of results

To give a good picture of the status of the bentonite in the test tunnel, contour plots were made using an interpolation program. The plots, see Figure 4-17, Figure 4-18, and Figure 4-19, are showing the water content, the dry density, and the degree of saturation distribution in two different cross sections:

1. A vertical cross section along the test tunnel axis in directions 0° to 180°.
2. A horizontal cross section along the test tunnel axis in directions 90° to 270°.

As shown in the contour plots, the bentonite has taken up water and swelled almost symmetrical along the test tunnel. The central parts where the blocks where positioned, have a lower water content (higher density) while the outer parts have higher water contents (lower density). The water content at the upper part of the tunnel (0°) was clearly higher, and the density lower, than at the other parts of the periphery. There was also a clear difference in water content and density distribution between the two outermost sampled cross sections, A and H, and the others. It was obvious that the end sections have had more access to water, probably due to the interface between the steel lids and the bentonite blocks. No similar behavior was found at the interfaces between the different blocks, see photos provided in Figure 4-16. The left photo shows an interface between two blocks in between cross section F and G, and the right photo shows cross section F, which was positioned in between two blocks (the surface at the middle was the compacted surface of a block).

At a test length of 600 mm there is a small "island" in the center of the test, see contour plots in Figure 4-17, Figure 4-18, and Figure 4-19. The sample at this position had a somewhat higher water content and a lower density than the surroundings. The reason for this is not known but may be due to mixing of samples.

Figure 4-16. *Photos taken in conjunction with the dismantling of Test 1. Left: Interface between two blocks in between cross section F and G (a shadow is covering the left block). Right: Cross section F.*

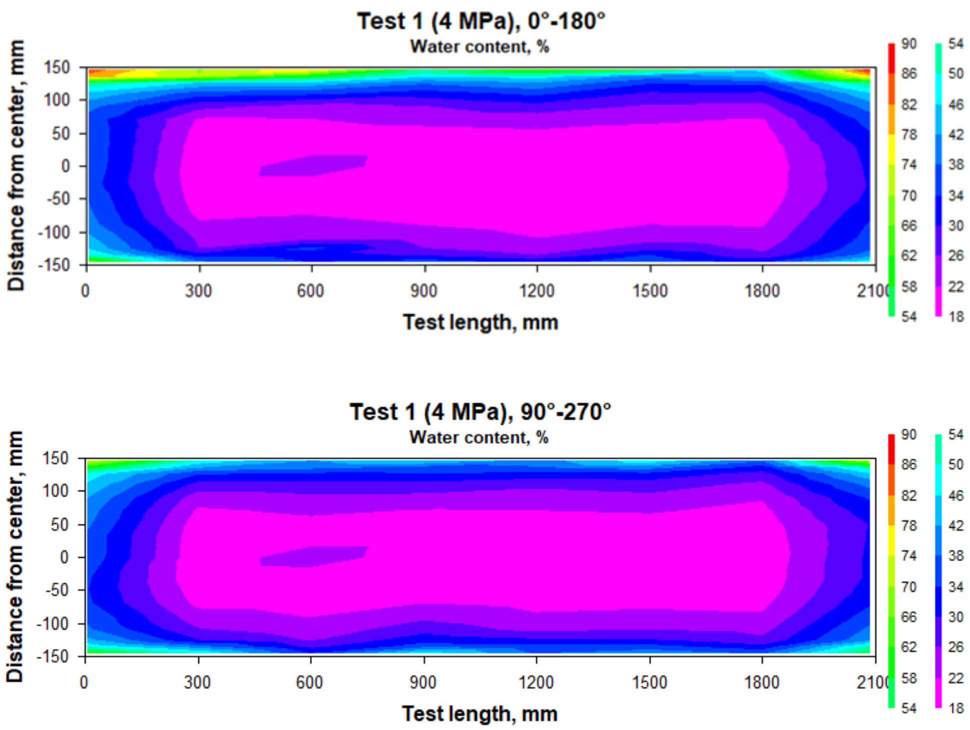


Figure 4-17. *Contour plots showing the water content distribution. The upper plot shows the distribution in a vertical cross section in directions 0° to 180°. The lower plot shows the distribution in a horizontal cross section in directions 90° to 270°.*

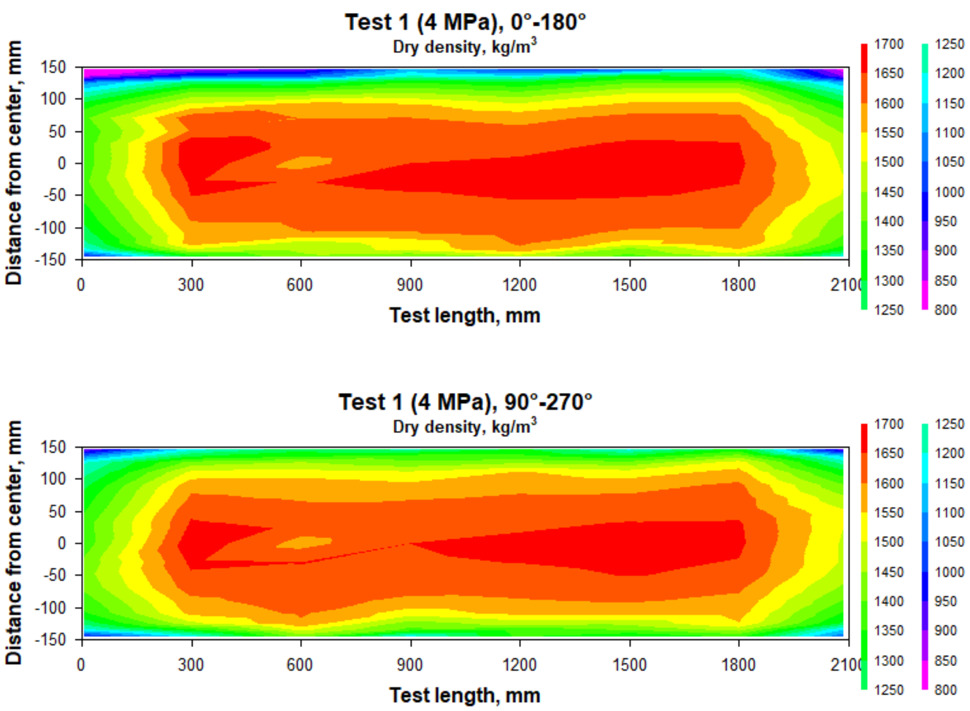


Figure 4-18. *Contour plots showing the dry density distribution. The upper plot shows the distribution in a vertical cross section in directions 0° to 180°. The lower plot shows the distribution in a horizontal cross section in directions 90° to 270°.*

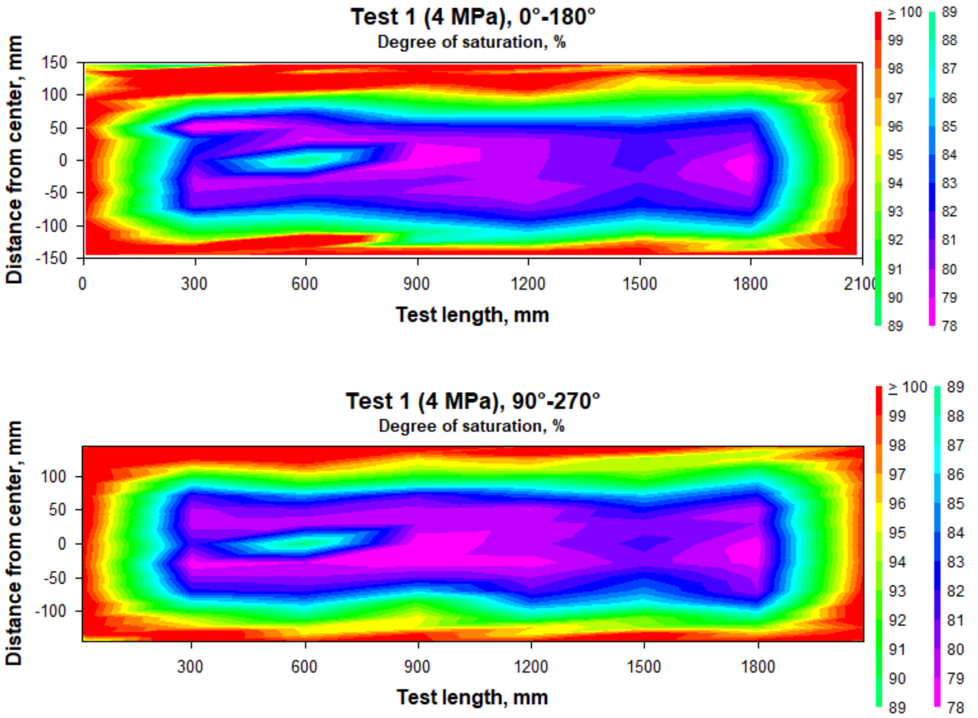


Figure 4-19. *Contour plots showing the degree of saturation distribution. The upper plot shows the distribution in a vertical cross section in directions 0° to 180°. The lower plot shows the distribution in a horizontal cross section in directions 90° to 270°.*

5 Test 2 (0.2 mL/min, 4 MPa)

5.1 Test preparation

5.1.1 Bentonite blocks

In total twenty-one blocks were used in this test plus a thin disc (thickness 19.5 mm). The thin disc was necessary to completely fill up the test cell with blocks (the length of the tunnel was 2100 mm, and the installed blocks had a height of between 98 to 99 mm). All blocks were measured and weighed before installation, see data provided in Appendix 2.

5.1.2 Bentonite pellets

Pellets were installed in the outer gap between the blocks and the tunnel walls. After installation of between one to three blocks, pellets were filled up in the outer gap. The weight of the installed pellets was determined, see data provided in Appendix 2. It should be noted that in the calculation of the achieved pellet density, the height of the pellet filling was set to the same as the block height since it was difficult to measure the actual height.

5.1.3 Assembly

The assembly of the test was made in the same way as for Test 1, see description in Section 4.1.3.

5.1.4 Installation data

Detailed data regarding the block dimensions, block weight, and pellets weight is provided in Appendix 2. A compilation of the most important data is provided below.

Blocks

The average bulk density of the blocks was 1967 kg/m^3. The bentonite had a water content of 17.4 % which means that the average dry density of the blocks was 1675 kg/m^3. The installed height of all blocks was calculated to 2092 mm which indicated that there was a total space between the blocks of 8 mm, probably rather evenly distributed along the test tunnel.

Pellets

The average bulk density of the installed pellet filling was 1159 kg/m^3. The pellets had a water content of 14.1 % which means that the average dry density of the pellet filling was 1016 kg/m^3.

Dry density in the test volume

The total test volume was 0.1475 m^3. In total 221.895 kg dry mass bentonite was installed in the test volume (blocks=185.378 kg and pellets=36.517 kg). This resulted in an installed average dry density in the test volume of 1505 kg/m^3.

Available pore volume

The determined bulk density, water content and dry density of the block filling and pellet filling respectively is provided in Table 5-1. The porosity (n) of the block filling and pellet filling was calculated according to the description provided in Section 4.1.4.

The available pore volume in the blocks was calculated to 0.01255 m^3 and in the pellets to 0.01767 m^3, see details in Table 5-1. The total available pore volume was thus 0.03022 m^3. To achieve a filling of available pore volume of 90 %, a water volume of 0.02720 m^3 should be injected.

Table 5-1. Installation data for Test 2 and the calculated available pore volume.

Test 2	
Test equipment	
V tunnel, m^3	0.14745
Installation	
Block	
w, %	17.4
Installed bulk mass, kg	217.634
Block volume (d=260 mm), m^3	0.11149
Bulk density, kg/m^3	1952
Dry mass, kg	185.378
Dry density, kg/m^3	1663
Density of solids, kg/m^3	2780
Void ratio	0.672
Sr, %	72.0
Porosity, %	0.402
Available pore volume, m^3	**0.01255**
Pellets	
w, %	14.1
Installed bulk mass, kg	41.666
Pellet volume, m^3	0.03596
Bulk density, kg/m^3	1159
Dry mass, kg	36.517
Dry density, kg/m^3	1016
Density of solids, kg/m^3	2780
Void ratio	1.737
Sr, %	22.6
Porosity, %	0.635
Available pore volume, m^3	**0.01767**
Water uptake	
Total available pore volume, m^3	0.03022
Desired part of pore volume to be filled, %	90
Water volume to inject, m^3	**0.02720**

5.2 Registered data during test time

5.2.1 Injected water volume and applied water pressure

The measured water uptake and water injection pressure for Test 2 are plotted versus time in Figure 5-1. The injected water volume did not reach the set maximum value corresponding to 90 % of the available pore volume within the maximum test duration (two hundred days). The test was thus stopped after two hundred days. At this time, a water volume of 18.49 liters had been injected into the test cell, corresponding to 61 % of the pore volume available at test start.

The injection pressure varied during the first 58 days. High pressures were occasionally built up which resulted in internal piping which in turn resulted in large pressure drops. When the water pressure had increased to 3.8 MPa, the pump settings were changed to instead apply a constant water pressure of 3.8 MPa. The water inflow rate, that earlier was set to a constant rate of 0.2 mL/min, clearly decreased when instead a constant water pressure was applied.

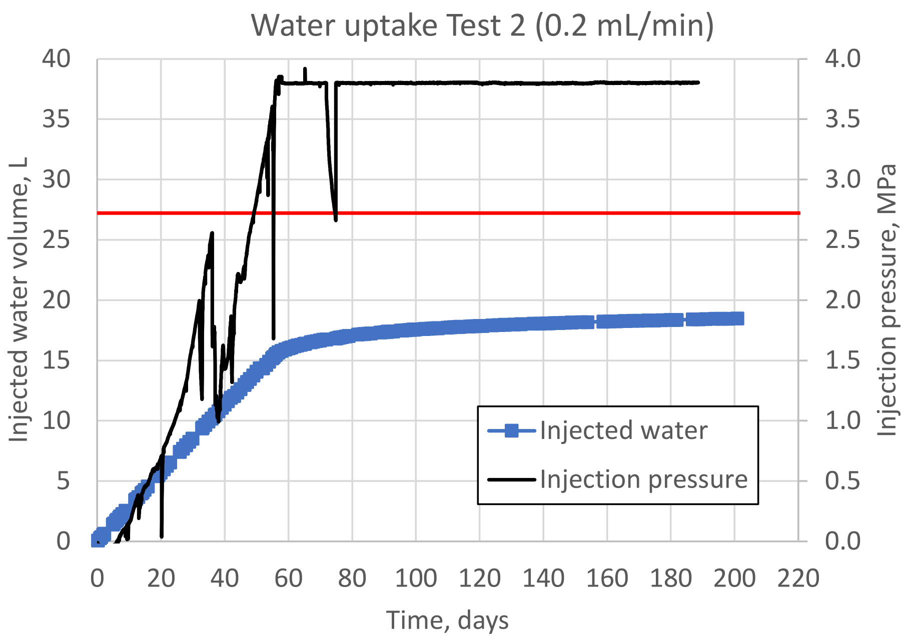


__Figure 5-1__ Injected water volume (blue) and water injection pressure (black) plotted versus time for Test 2. The red line indicates the volume needed to achieve a filling of the available pore volume of 90 %.

5.2.2 Registered total pressure and pore pressure

The graph provided in Figure 5-2 shows the registered water injection pressure (black line), the total pressure (full lines, different colors) and the pore pressure (dotted lines, different colors) in Test 2.

The two total pressure sensors positioned at the ends of the tunnel (Total pr. 1 and Total pr. 5) reacted early after having started the water inflow. However, the total pressure sensor at position 5, was probably registering a mechanical pressure from the blocks that were pushed forward during the early saturation of bentonite installed close to the inlet. After three weeks of test duration, both sensors at position 2 began to react and after 40 days the sensors at position 3 began to react.

A few problems occurred with the sensors during the test. The pore pressure sensor at position 2 stopped working after 155 days. The sensor was changed to another, but the sensor did not register the same pressure as earlier. The sensor registering the injection pressure stopped working after 188 days. No spare sensor was available, but the pressure was continuously checked on the pump equipment (GDS) the last days of the test.

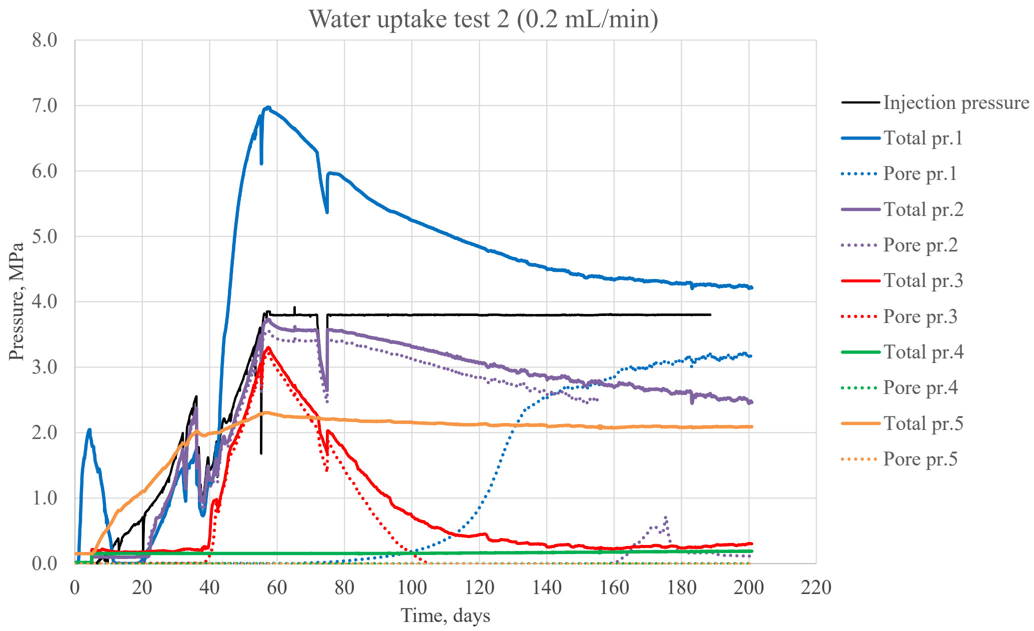


Figure 5-2 *Graph showing the registered water injection pressure (black line), the total pressure (full lines) and the pore pressure (dotted lines) in Test 2.*

5.3 Dismantling

5.3.1 General

After two hundred days test duration it was decided to stop the test and start the dismantling. The dismantling was made in the same way as for Test 1, see description in Section 4.3.

5.4 Results from sampling

The sampling sections positioned in the joints between the tube sections could easily be sampled after division. In this test, the sampling section G, positioned in the middle of the last tube section, was almost unaffected by the water inflow, and was therefore also easily sampled. For cross section C and E, also positioned in the middle of tube sections, a hydraulic piston was used to push out the bentonite from each of the tunnel sections whereafter the sampling could be done.

In conjunction with dismantling, it was noticed that the bentonite blocks and pellets in cross-section A to E were more or less affected by the inflowing water (the two upper photos and the lower left photo in Figure 5-3) while the bentonite in cross-sections F to H looked almost unaffected (see example in the lower right photo in Figure 5-3). In cross sections C to E, it was also noticed that the wetted parts seemed to be clearly larger at the top of the tunnel cross sections, see lower left photo in Figure 5-3.

Figure 5-3 *Photos taken in conjunction with the dismantling of Test 2. Upper left: Test section B before sampling. The bentonite was clearly wetted. Upper right: The photo shows a cross-section one block before sample section D, where the former pellet filling and parts of the block was wetted. Lower left: The photo shows the wetted upper part between cross-sections D (to the right) and E. Lower right: The photo shows the last cross-section (H) which looked unaffected by the inflowing water. The pellets in the gap also looked unaffected and was easily removed.*

The results from the sampling of each cross section (A to H) are provided in Figure 5-4 to Figure 5-11. Graphs are provided showing the water content, the dry density, and the degree of saturation in four directions for every sampled cross section.

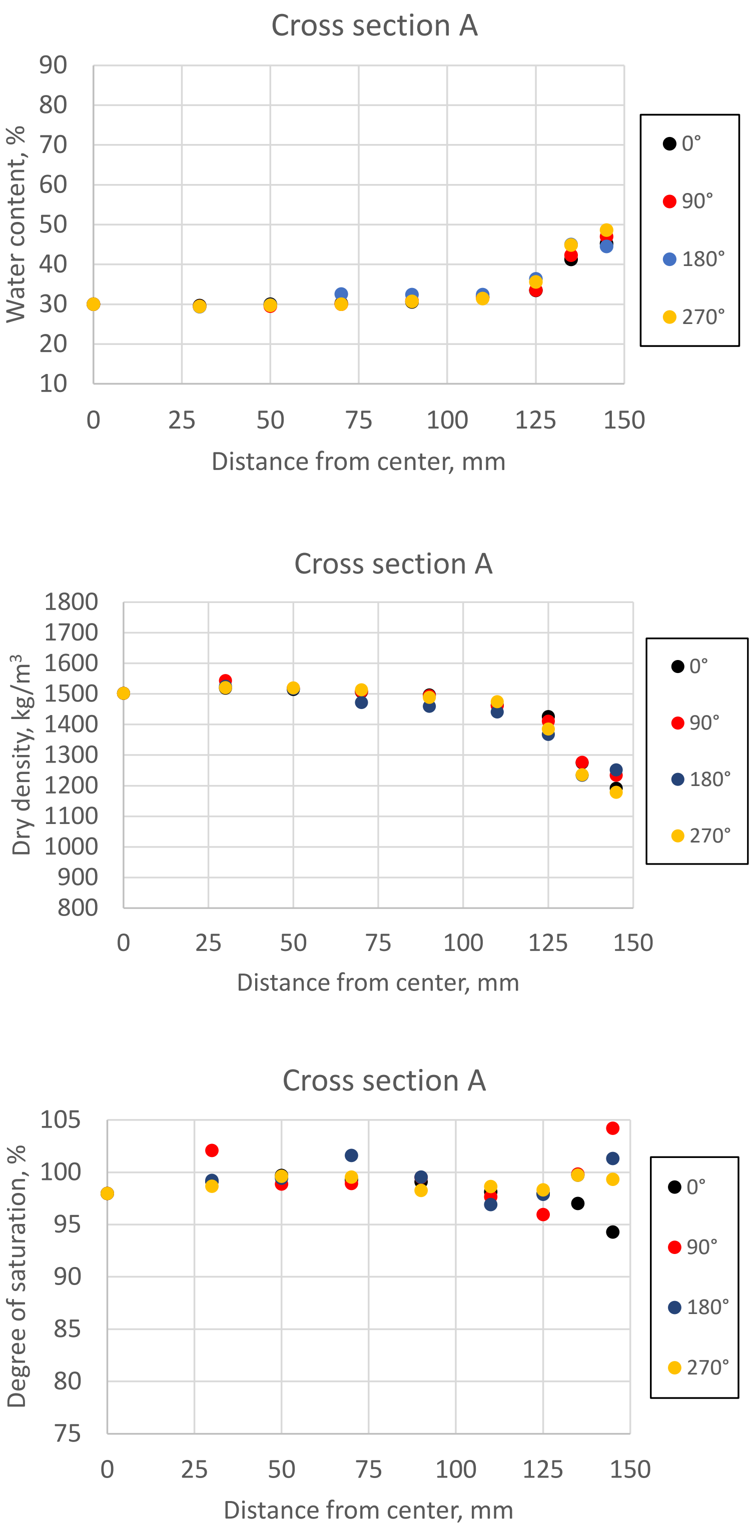


Figure 5-4 *Results from measurements in cross section A. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

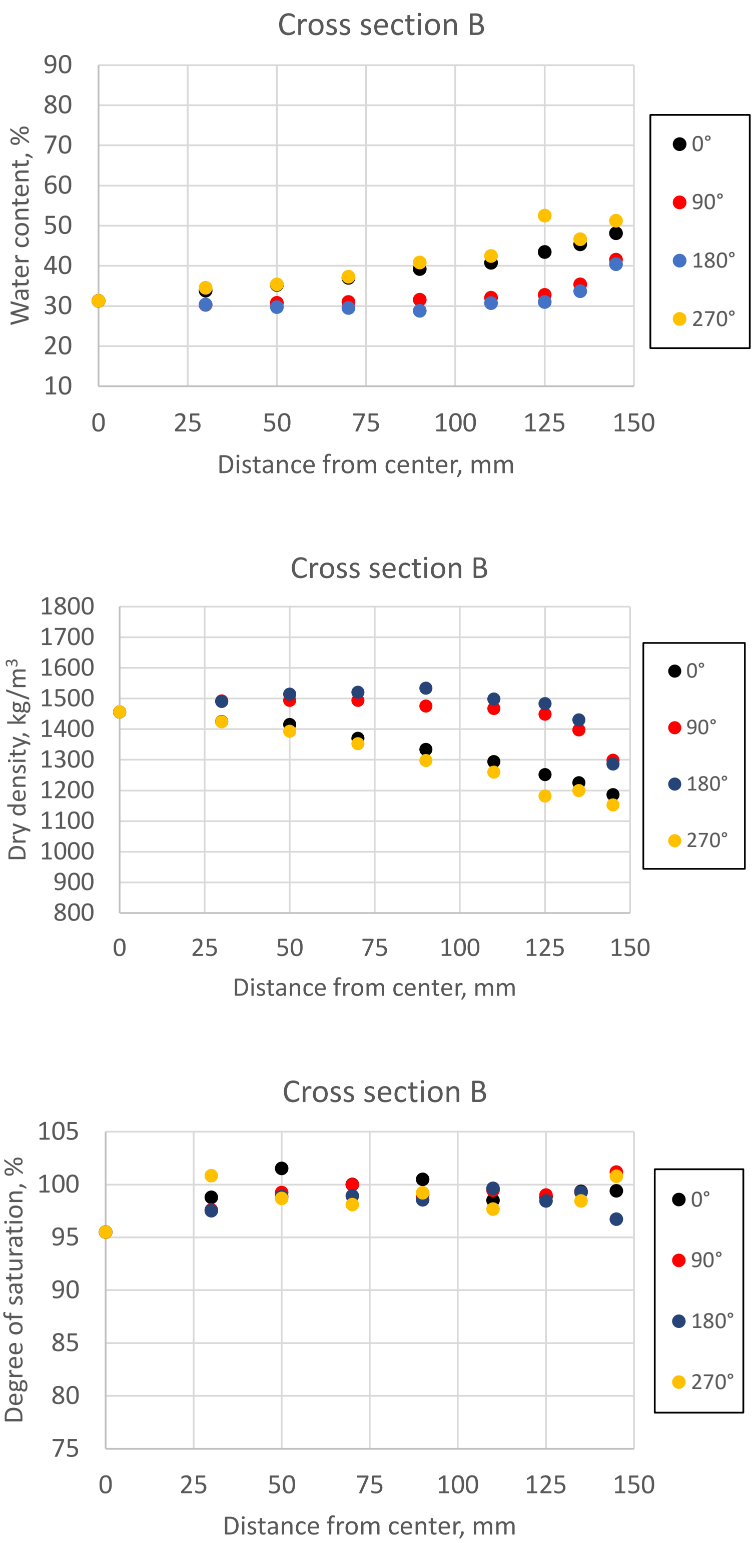


Figure 5-5 *Results from measurements in cross section B. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

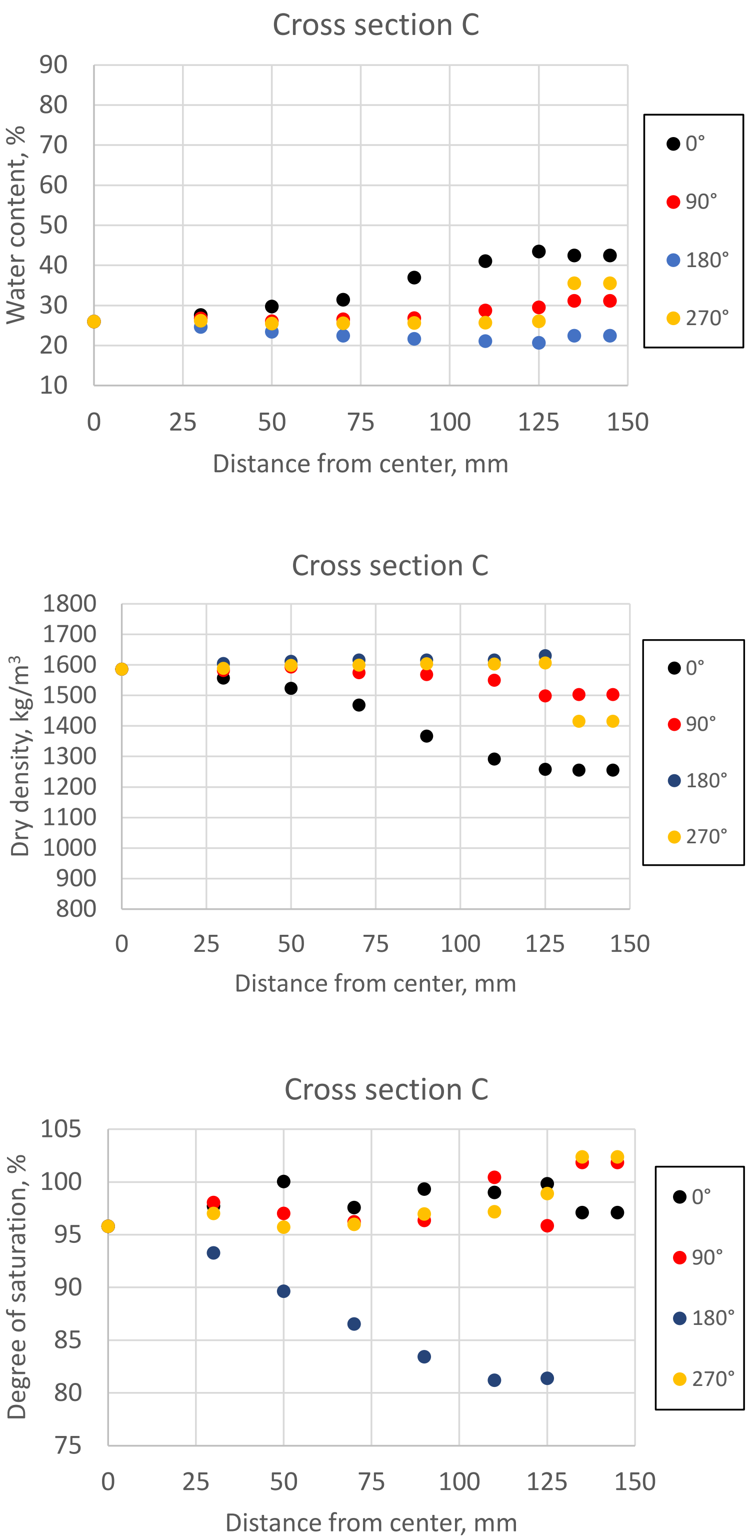


***Figure 5-6** Results from measurements in cross section C. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

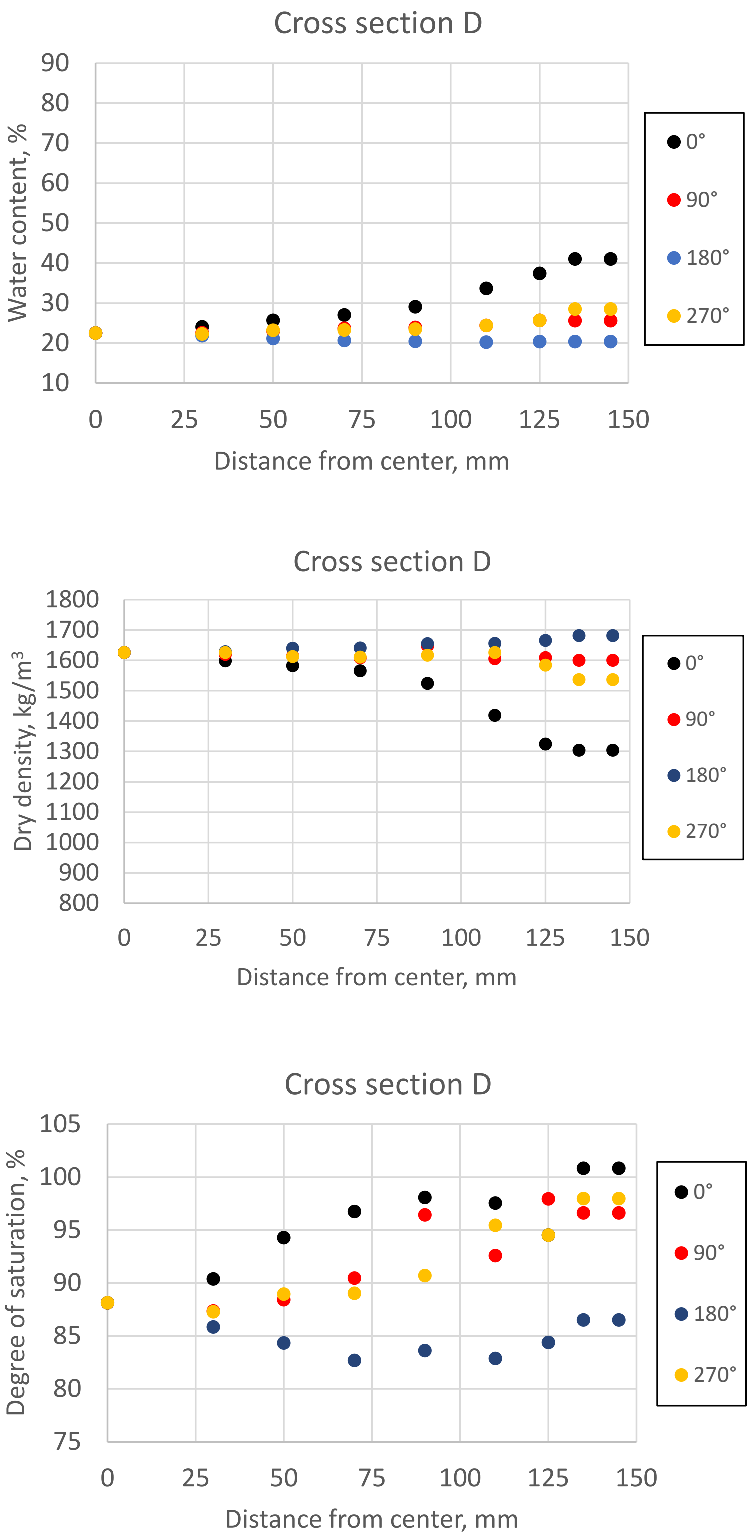


Figure 5-7 *Results from measurements in cross section D. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

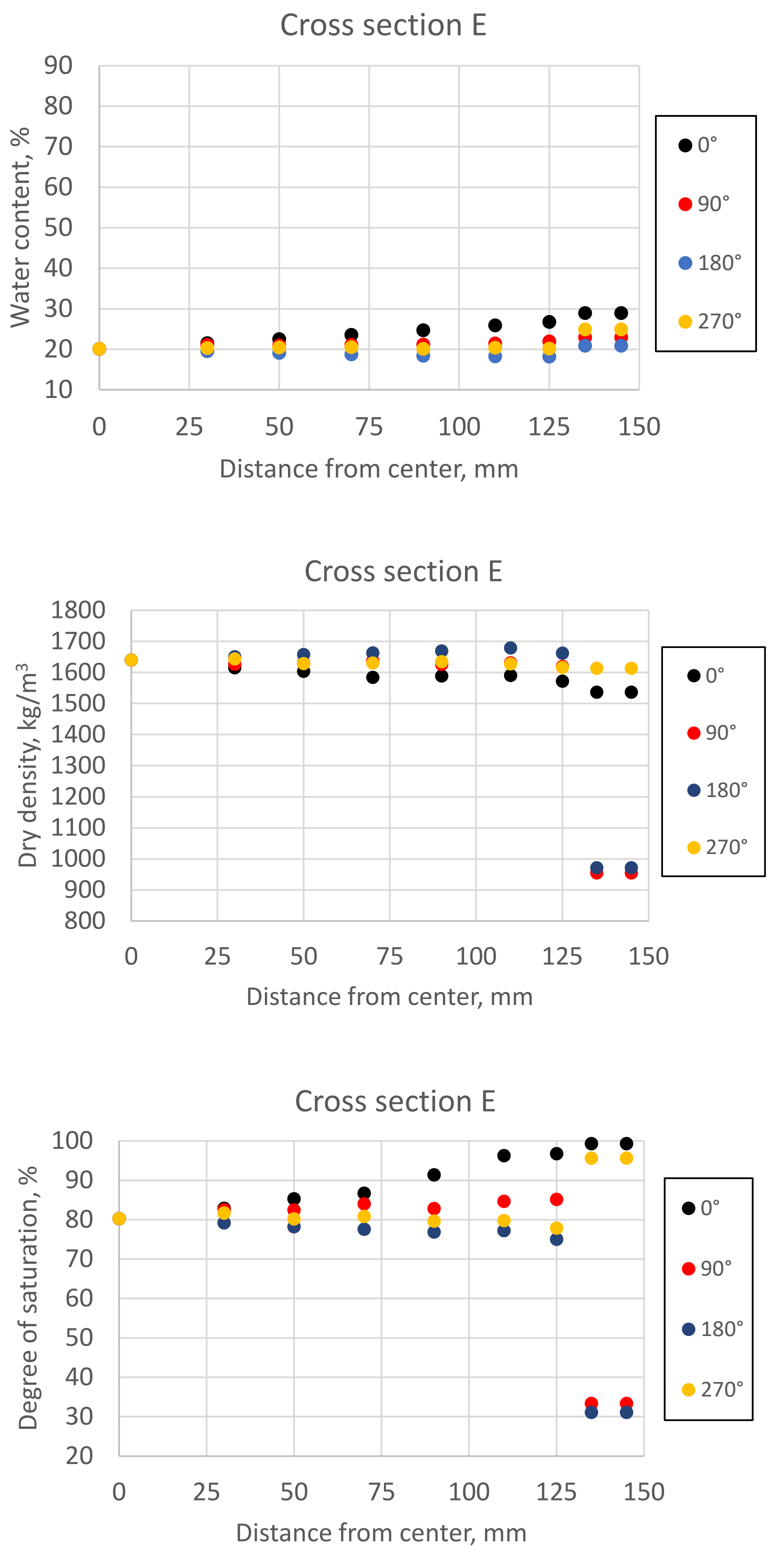


***Figure 5-8** Results from measurements in cross section E. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

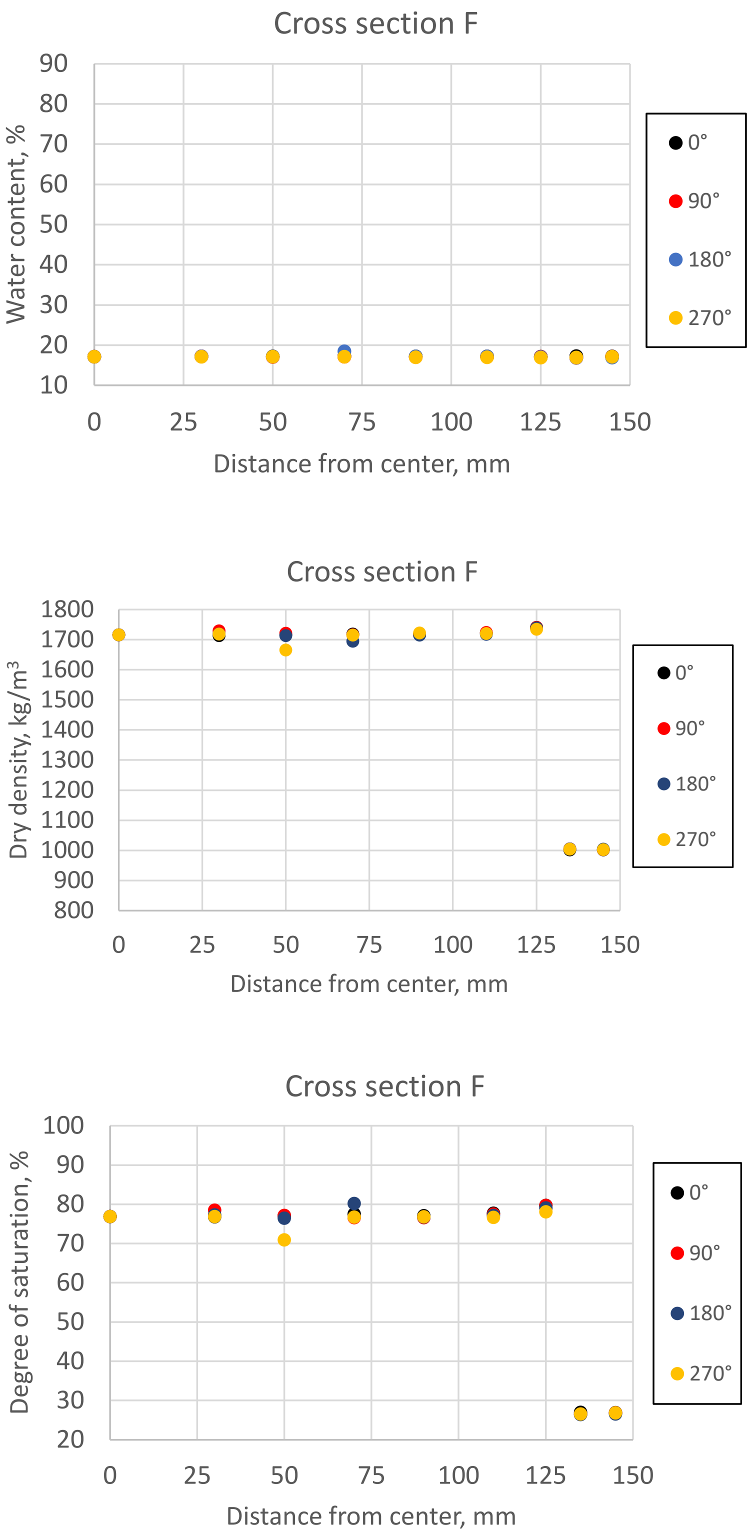


Figure 5-9 *Results from measurements in cross section F. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

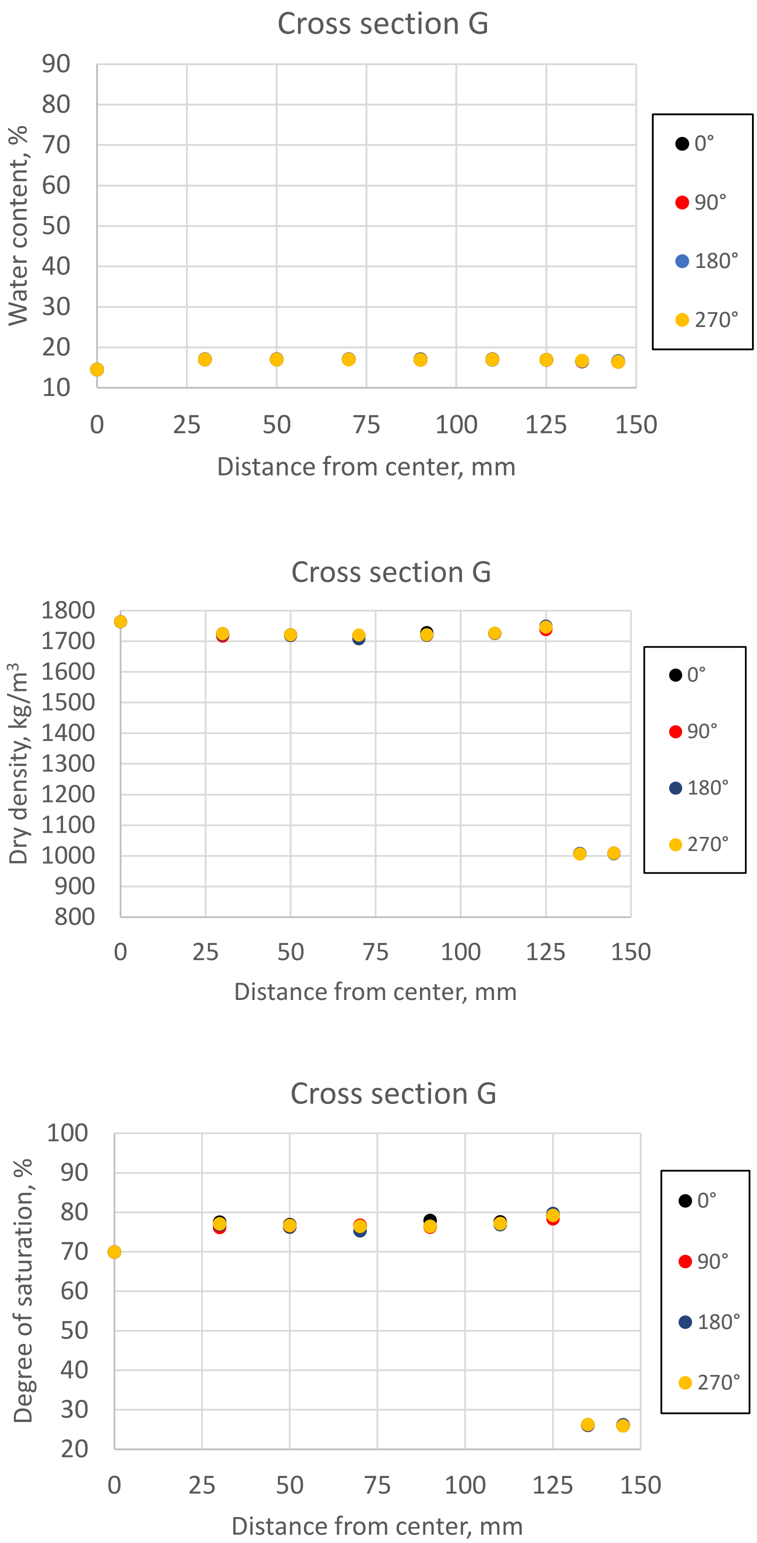


***Figure 5-10** Results from measurements in cross section G. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

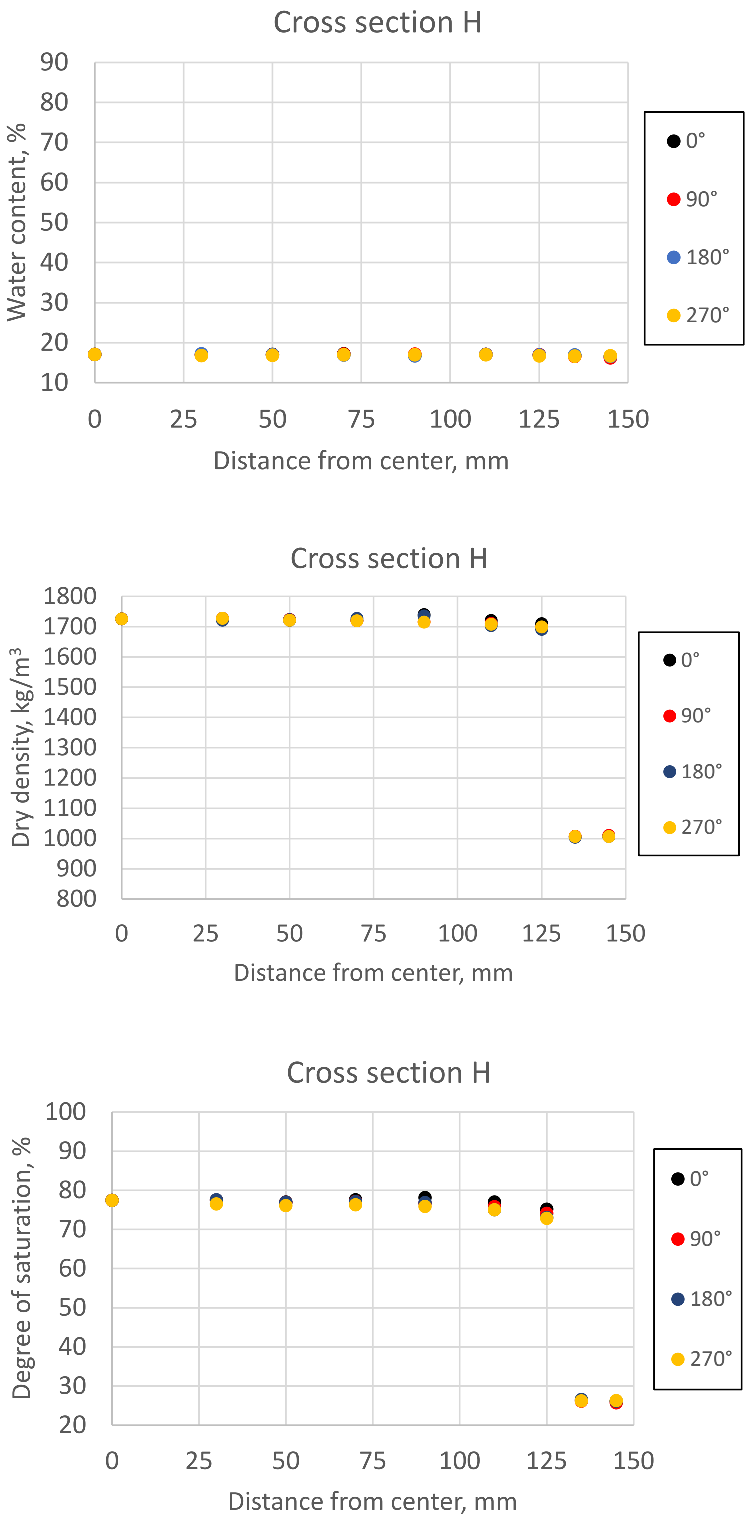


Figure 5-11 *Results from measurements in cross section H. Upper: Water content plotted versus distance from the center. Middle: Dry density plotted versus distance from the center. Lower: Degree of saturation plotted versus distance from the center.*

5.5 Compilation of results

To give a good picture of the status of the bentonite in the test tunnel, contour plots were made using an interpolation program. The plots, see Figure 5-13, Figure 5-14 and Figure 5-15, are showing the water content, the dry density, and the degree of saturation distribution in two different cross sections:

1. A vertical cross section along the test tunnel axis in directions 0° to 180°.
2. A horizontal cross section along the test tunnel axis in directions 90° to 270°.

As shown in the contour plots, the bentonite has taken up water and swelled the first 1300 mm of the test length, while the bentonite in the last 800 mm of the test cell was almost unaffected. The first 0–300 mm was symmetrically wetted but thereafter, approximately between 300 to 1300 mm, the upper part was clearly more wetted. The wetting at the top almost looked like an arrowhead, see photos in Figure 5-12. There was thus an almost clear line between the wetted bentonite and the bentonite that looked unaffected.

The contour plots also clearly show the difference between the different sampled directions. In direction 0°-180° (vertical), it was obvious that the wetting had proceeded farther at the top while in the contour plots showing the directions 90°–270° (horizontal), the wetting was almost symmetrical.

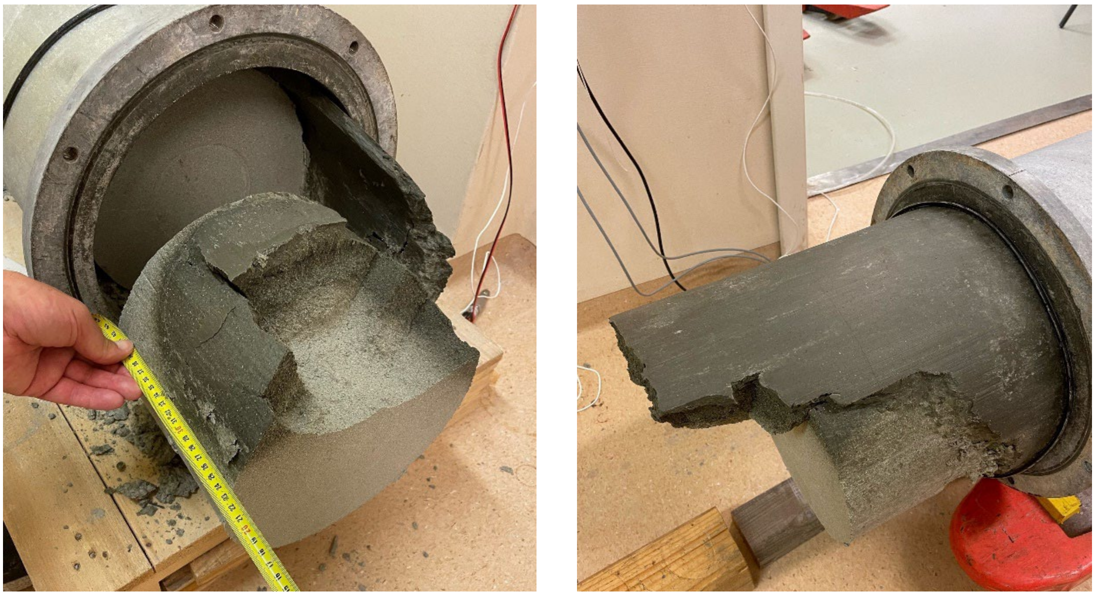


Figure 5-12 *Photos taken in conjunction with the dismantling of Test 2. Left: Photo showing the last part of the wetted bentonite at the top (100 mm after cross-section E). Right: The wetted part at the top. Cross-section D is positioned to the right at the steel tube.*

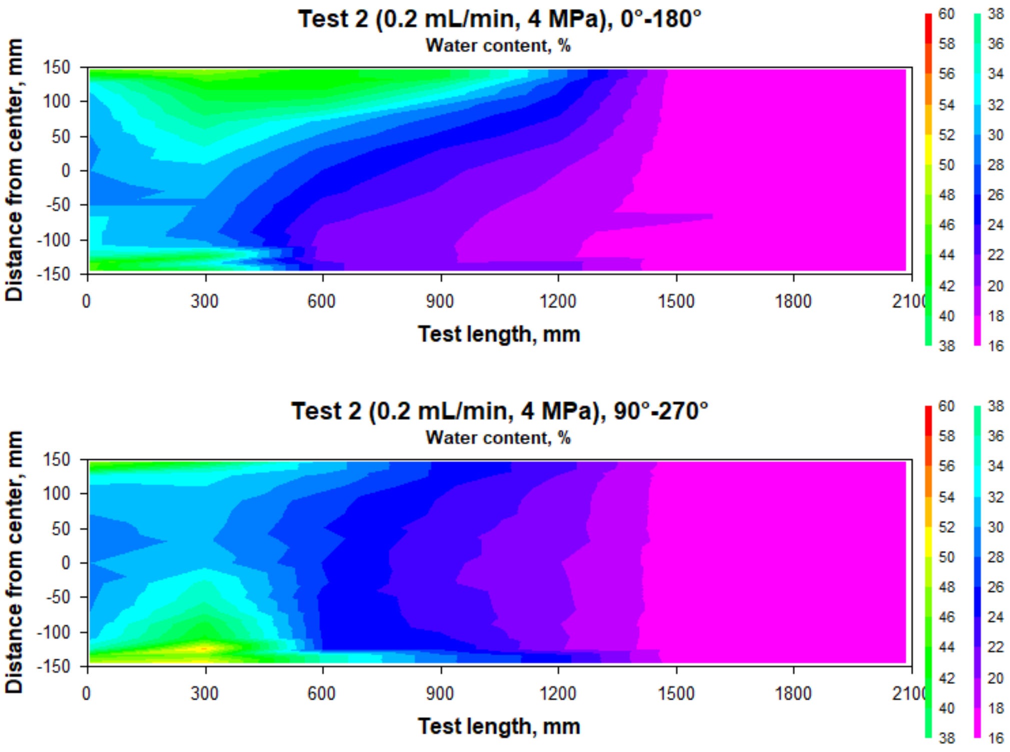


Figure 5-13 *Contour plots showing the water content distribution. The upper plot shows the distribution in a vertical cross section in directions 0° to 180°. The lower plot shows the distribution in a horizontal cross section in directions 90° to 270°.*

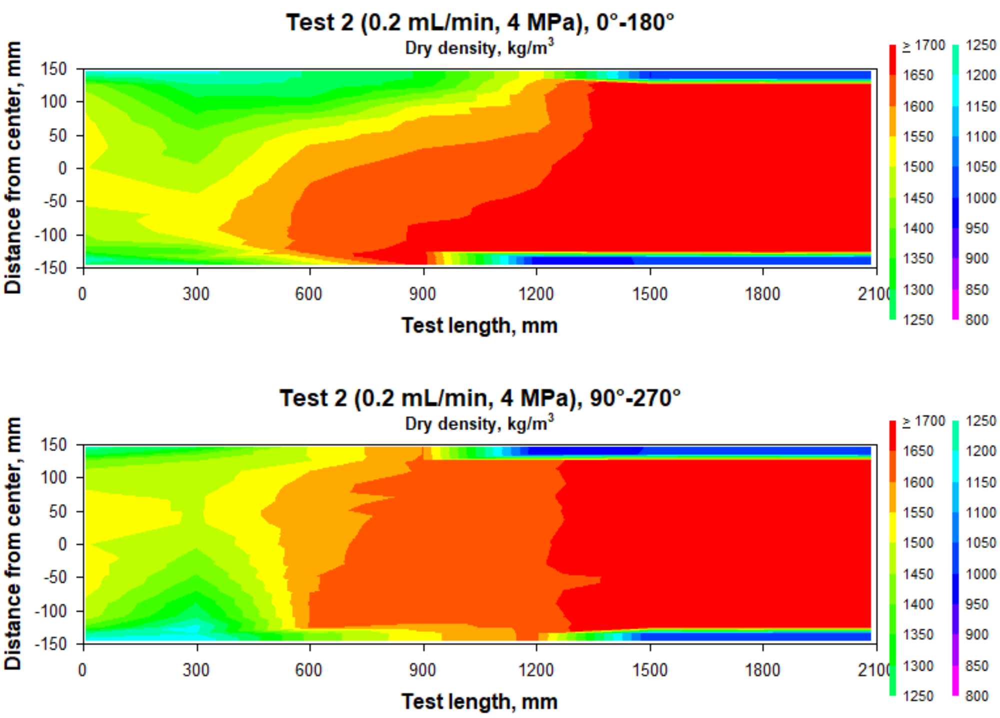


Figure 5-14 *Contour plots showing the dry density distribution. The upper plot shows the distribution in a vertical cross section in directions 0° to 180°. The lower plot shows the distribution in a horizontal cross section in directions 90° to 270°.*

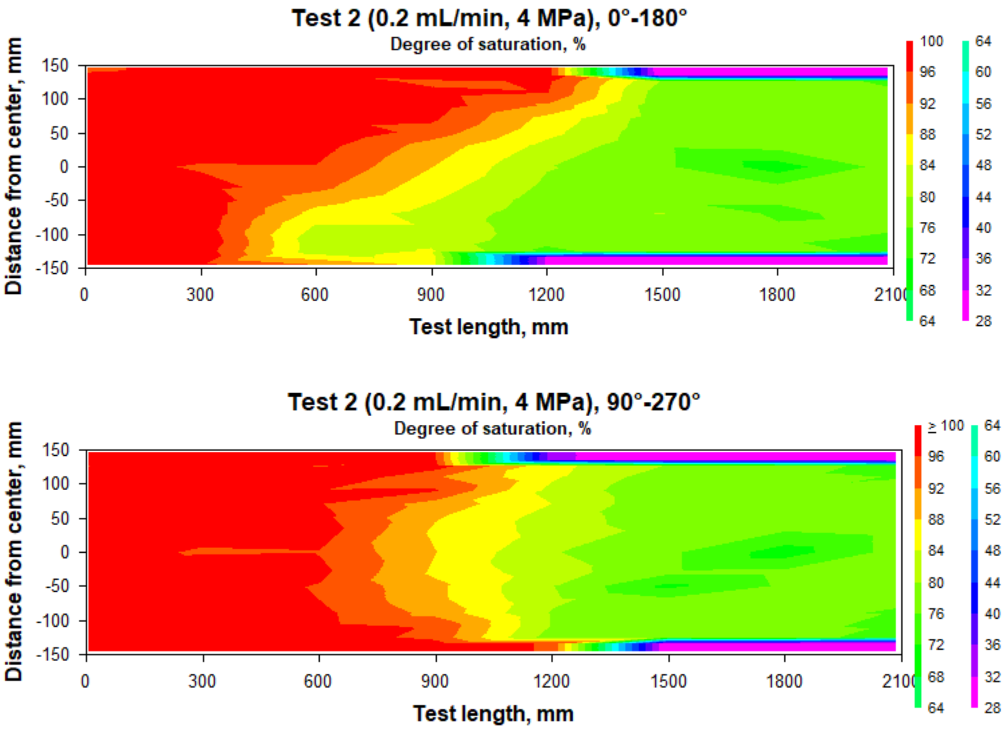


Figure 5-15 *Contour plots showing the degree of saturation distribution. The upper plot shows the distribution in a vertical cross section in directions 0° to 180°. The lower plot shows the distribution in a horizontal cross section in directions 90° to 270°.*

6 Comments and conclusions

6.1 General

In a final repository for spent nuclear fuel, inflowing water from fractures in the rock will with time saturate the bentonite. This report describes two laboratory experiments, where two quite different inflow scenarios have been investigated.

6.2 Test 1 (4 MPa)

In the first test, the inflow from the simulated fracture was set to have constant pressure of 4 MPa which means that the initial inflow rate was very high, and this resulted in that the available macro voids in the pellet filling were filled almost immediately, see graph provided in Figure 4-3. After this initial fast filling, the inflow rate decreased while the applied water pressure still was kept at a high pressure (3.5 to 4.3 MPa). After 33 days test duration, a water volume of 28.128 liters had been injected into the test cell (approximately 22.5 liters were injected in the initial phase with high inflow rate), corresponding to 91.3 % of the pore volume available at test start. At this time, the test was stopped and dismantled.

The results from the sampling showed that the bentonite had been wetted in a symmetrical way. The former pellet filled gap had in general a high degree of saturation while the innermost parts of the blocks still were dry. It was also noticed that the parts with high degree of saturation seemed to be somewhat larger at the top of the tunnel cross sections, see contour plots provided in Figure 4-17, Figure 4-18 and Figure 4-19. The density of the central parts of the blocks was clearly higher than at the periphery, indicating that the homogenization had not proceeded far. It was also noticed that the bentonite at both ends of the tunnel was more wetted compared to the buffer sections inside.

6.3 Test 2 (0.2 mL/min, 4 MPa)

In the second test, the water inflow was set to have a constant rate of 0.2 mL/min (0.288 L/24 h), Figure 5-1. The inflow rate was thus very low compared to the initial inflow rate in Test 1. This means that the wetted bentonite had time to absorb water and swell which resulted in the formation of local sealings in the pellet filling. The pressure of the inflowing water had to increase in order for the inflow rate to be kept at a specific value, which is likely to have caused local piping in the pellet filling. However, since no clear signs of piping channels were found, the piping probably only occurred at a small scale, which possibly was a consequence from the low inflow rate.

The maximum test duration was set to two hundred days, and after this time the test was stopped. A water volume of 18.49 liters had been injected into the test cell, corresponding to 61 % of the pore volume available at test start. The injection pressure varied during the first 58 days test duration. High pressures were occasionally built up which resulted in internal piping which in turn resulted in large pressure drops. When the water pressure had increased to 3.8 MPa, the pump settings were changed to instead apply a constant water pressure of 3.8 MPa. The water inflow rate, that earlier was set to a constant rate of 0.2 mL/min, clearly decreased when instead a constant water pressure was applied.

As shown in the contour plots (Figure 5-13, Figure 5-14, and Figure 5-15) the bentonite has taken up water and swelled approximately the first 0 to 1300 mm of the test length, while the bentonite in the last 800 mm of the test cell was almost unaffected. The first 0-300 mm were symmetrically wetted but thereafter, 300 to 1300 mm, the upper part was clearly more wetted. The wetting at the top almost looked like an arrowhead, see photos in Figure 5-12. There was thus an almost clear line between the wetted bentonite and the bentonite that looked unaffected.

The contour plots also clearly show the difference between the different sampled directions. In direction 0°-180° (vertical), it was clear that the wetting had proceeded farther at the top while in the contour plots showing the directions 90°-270° (horizontal), the wetting was almost symmetrical.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

Åkesson M, Goudarzi R, Börgesson L, 2020. EBS TF–THM modelling. Water transport in pellet-filled slots - laboratory tests and task descriptions. SKB P-19-06, Svensk Kärnbränslehantering AB.

Appendix 1 – Installation data Test 1

Data determined on the blocks after manufacturing, on the blocks after machining, and on the pellets installed.

No.	Manufactured blocks							Machined		Pellets installation						
	Dy mm	dy mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³	Dy mm	Mass kg	Dy mm	di mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³
1:1	280.3	276.3	99.6	11.820	1951	17.4	1662	260	9.965	299	260	99.6	1.922	1127	14.1	987
1:2	280.3	276.3	98.7	11.830	1970	17.4	1678	260	10.548	299	260	98.7	1.922	1137	14.1	996
1:3	280.3	276.3	98.5	11.802	1970	17.4	1678	260	10.370	299	260	98.5	1.853	1098	14.1	963
1:4	280.3	276.3	98.6	11.808	1969	17.4	1677	260	10.458	299	260	98.6	1.853	1097	14.1	962
1:5	280.3	276.3	98.5	11.810	1971	17.4	1679	260	10.213	299	260	98.5	1.897	1124	14.1	986
1:6	280.3	276.3	98.5	11.814	1972	17.4	1679	260	10.257	299	260	98.5	1.897	1124	14.1	986
1:7	280.3	276.3	98.4	11.774	1967	17.4	1676	260	10.258	299	260	98.4	2.007	1191	14.1	1044
1:8	280.3	276.3	98.9	11.810	1963	17.4	1672	260	10.106	299	260	98.9	2.007	1185	14.1	1038
1:9	280.3	276.3	98.4	11.817	1974	17.4	1682	260	10.436	299	260	98.4	1.757	1043	14.1	914
1:10	280.3	276.3	99.1	11.811	1959	17.4	1669	260	10.420	299	260	99.1	1.757	1035	14.1	907
1:11	280.3	276.3	98.4	11.808	1973	17.4	1680	260	10.425	299	260	98.4	1.900	1128	14.1	988
1:12	280.3	276.3	99.2	11.841	1962	17.4	1671	260	10.185	299	260	99.2	1.900	1119	14.1	980
1:13	280.3	276.3	99.0	11.822	1963	17.4	1672	260	10.157	299	260	99.0	2.009	1185	14.1	1038
1:14	280.3	276.3	98.4	11.808	1973	17.4	1680	260	10.180	299	260	98.4	2.009	1192	14.1	1045
1:15	280.3	276.3	98.7	11.817	1968	17.4	1677	260	10.342	299	260	98.7	1.813	1072	14.1	940
1:16	280.3	276.3	98.2	11.805	1976	17.4	1683	260	10.427	299	260	98.2	1.813	1078	14.1	945
1:17	280.3	276.3	98.2	11.802	1976	17.4	1683	260	10.313	299	260	98.2	1.793	1066	14.1	934
1:18	280.3	276.3	99.3	11.775	1949	17.4	1660	260	10.285	299	260	99.3	1.793	1054	14.1	924
1:19	280.3	276.3	98.8	11.809	1965	17.4	1674	260	10.460	299	260	98.8	1.858	1098	14.1	963
1:20	280.3	276.3	98.4	11.834	1977	17.4	1684	260	10.321	299	260	98.4	1.858	1103	14.1	966
1:21	280.3	276.3	98.6	11.830	1972	17.4	1680	260	10.243	299	260	98.6	1.920	1137	14.1	997
1:22	280.3	276.3	98.2	11.776	1971	17.4	1679	260	2.076	299	260	21.0	0.384	1068	15.1	928
Sum									218.445			2093.4	39.530			

Appendix 2 – Installation data Test 2

Data determined on the blocks after manufacturing, on the blocks after machining, and on the pellets installed.

No.	Manufactured blocks							Machined		Pellets installation						
	Dy mm	dy mm	Height mm	Mass kg	Bulk density kg/m^3	Water content %	Dry density kg/m^3	Dy mm	Mass kg	Dy mm	di mm	Height mm	Mass kg	Bulk density kg/m^3	Water content %	Dry density kg/m^3
2:1	280.3	276.3	98.8	11.813	1966	17.4	1674	260	10.256	299	260	98.8	2.0085	1187	14.1	1041
2:2	280.3	276.3	98.4	11.774	1967	17.4	1676	260	10.203	299	260	98.4	2.0085	1192	14.1	1045
2:3	280.3	276.3	98.5	11.817	1972	17.4	1680	260	10.342	299	260	98.5	1.977	1172	14.1	1027
2:4	280.3	276.3	99.2	11.811	1957	17.4	1667	260	10.310	299	260	99.2	1.977	1164	14.1	1020
2:5	280.3	276.3	98.4	11.786	1969	17.4	1677	260	10.273	299	260	98.4	1.984	1178	14.1	1032
2:6	280.3	276.3	98.3	11.783	1971	17.4	1678	260	10.263	299	260	98.3	1.984	1179	14.1	1033
2:7	280.3	276.3	98.4	11.808	1973	17.4	1680	260	10.227	299	260	98.4	2.04	1211	14.1	1061
2:8	280.3	276.3	98.9	11.833	1967	17.4	1675	260	10.282	299	260	98.9	2.04	1205	14.1	1056
2:9	280.3	276.3	99.4	11.821	1955	17.4	1665	260	10.302	299	260	99.4	1.98	1163	14.1	1020
2:10	280.3	276.3	98.9	11.837	1968	17.4	1676	260	10.309	299	260	98.9	1.98	1169	14.1	1025
2:11	280.3	276.3	98.9	11.826	1966	17.4	1674	260	10.239	299	260	98.9	2.003	1183	14.1	1037
2:12	280.3	276.3	98.5	11.842	1976	17.4	1683	260	10.235	299	260	98.5	2.003	1188	14.1	1041
2:13	280.3	276.3	98.4	11.805	1972	17.4	1680	260	10.264	299	260	98.4	1.981	1176	14.1	1030
2:14	280.3	276.3	99.2	11.795	1955	17.4	1665	260	10.250	299	260	99.2	1.981	1166	14.1	1022
2:15	280.3	276.3	98.4	11.806	1972	17.4	1680	260	10.260	299	260	98.4	2.069	1228	14.1	1076
2:16	280.3	276.3	99.0	11.795	1959	17.4	1668	260	10.299	299	260	99.0	2.069	1221	14.1	1070
2:17	280.3	276.3	98.3	11.777	1970	17.4	1678	260	10.357	299	260	98.3	1.8465	1097	14.1	961
2:18	280.3	276.3	98.5	11.810	1971	17.4	1679	260	10.290	299	260	98.5	1.8465	1095	14.1	960
2:19	280.3	276.3	98.5	11.820	1973	17.4	1680	260	10.175	299	260	98.5	1.95876	1161	14.1	1018
2:20	280.3	276.3	99.2	11.801	1956	17.4	1666	260	10.280	299	260	99.2	1.97268	1161	14.1	1018
2:21	280.3	276.3	98.4	11.796	1971	17.4	1679	260	10.310	299	260	98.4	1.95678	1161	14.1	1018
2:22	280.3	276.3	98.2	11.776	1971	17.4	1679	260	1.908	299	260	19.5	0.39	1161	15.1	1009
Sum									217.634			2092.0	41.666			