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Piping and erosion in buffer and backfill

Scale tests in laboratory

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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 fuel is encapsulated in copper canisters, which are placed in the deposition holes surrounded by highly compacted buffer blocks. The backfilling of the deposition tunnels above the deposition holes is planned to 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.

Inflowing water from fractures in the rock will affect the installed buffer and backfill and may result in piping and erosion of the bentonite material. A special case identified is if there is a certain water inflow to a deposition hole and at the same time, the deposition tunnel above is dry. The accessible pore volume in a backfilled deposition tunnel is significant which means that erosion from the buffer in a deposition hole, through which inflow occurs, can potentially be significant for such a case.

This report presents laboratory tests performed as scale tests (scale 1:10) and included both a deposition hole and a deposition tunnel section. The tests simulated an inflow to a deposition hole from which the water is led through piping, probably in the pellet filled gap, up into the backfill in the tunnel above. The deposition tunnel in the tests was equipped with outlets at one end, where the outflowing water was collected and the amount of eroded material determined.

Two tests were performed, one with a water inflow rate of 0.05 l/min and one with a water inflow rate of 0.02 l/min. The test duration was set to 10 and 5 weeks, respectively. During the test time, samples were taken to determine the bentonite erosion rate. In addition, the buffer mass loss was quantified during the dismantling of each test. By relating this loss to the total water volume, the mass loss from a full-scale deposition hole can be estimated, especially for the case when the deposition hole acts as the sole inflow point in a deposition tunnel.

Sammanfattning

KBS-3V 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 vilka 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.

Inflödande vatten från sprickor i berget kommer att påverka den installerade bufferten och återfyllningen och kan resultera i kanalbildning och erosion av bentonitmaterial. Ett speciellt fall är om det finns ett vatteninflöde till ett deponeringshål samtidigt som deponeringstunneln ovanför är torr. Eftersom den tillgängliga porvolymen i en återfylld tunnel är betydande, innebär detta att bufferterosionen från ett deponeringshål med ett sådant inflöde potentiellt också kan vara betydande.

I denna rapport presenteras laboratorieförsök som utförts som skalförsök (skala 1:10) och inkluderade både ett deponeringshål och en sektion av en deponeringstunnel. Försöken simulerade ett inflöde till ett deponeringshål som resulterar i kanalbildning, förmodligen i den pelletsfyllda spalten, upp till återfyllningen i tunneln ovanför. Deponeringstunneln i försöket var utrustad med utgångar i ena gaveln där det utflödande vattnet samlades upp och mängden eroderat material bestämdes.

Två tester har genomförts, en med ett vatteninflöde på 0.05 l/min och en med ett inflöde på 0.02 l/min. Försökstiden var 10 respektive 5 veckor. Under denna tid togs prover för att bestämma erosionshastigheten. Vid brytningen av varje test kvantifierades dessutom massförlusten av buffertmaterial. Genom att relatera denna massförlust med den totala vattenvolymen kan massförlusten från ett deponeringshål i full skala uppskattas, i synnerhet för det fall när deponeringshålet utgör den enda inflödespunkten i en deponeringstunnel.

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 surrounded by highly compacted buffer blocks. The backfilling of the deposition tunnels above the deposition holes is planned to 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.

Inflowing water from fractures in the rock will affect the installed buffer and backfill and may result in piping and erosion of the bentonite material. A special case identified is if there is a certain water inflow to the deposition hole and at the same time the deposition tunnel above is dry. The accessible pore volume in a backfilled deposition tunnel is significant, ~ 900 m^3 according to (Börgesson et al. 2015). This means that erosion from the buffer in a deposition hole, through which inflow occurs, can potentially be significant for such a case.

This report presents laboratory tests performed as scale tests (scale 1:10) and included both a deposition hole and a deposition tunnel section. The tests simulated an inflow to the bottom of a deposition hole from which the water was led through piping, probably in the pellet filled gap, up into the backfill in the tunnel above. The deposition tunnel in the tests was equipped with outlets at one end where the outflowing water was collected and the amount of eroded material was determined. Important results were to determine the mass loss of bentonite and how it relates to the total water volume and test duration. The buffer and backfill used in the tests were manufactured according to the present reference design.

Two tests were performed, one with a water inflow rate of 0.05 l/min and one with a water inflow rate of 0.02 l/min. The test duration was 10 and 5 weeks respectively.

In Chapter 2 the concepts of piping and erosion are defined. A detailed description of the test equipment is provided in Chapter 3. The bentonite material, blocks and pellets, used in the tests are described in Chapter 4. The test preparation, the registered data and the result from the sampling are provided in Chapter 5 (Test 1) and in Chapter 6 (Test 2). A discussion regarding the test results is presented in Chapter 7. Finally, some concluding remarks are given in Chapter 8.

2 Piping and erosion

2.1 Mechanical erosion and chemical erosion

It is important to distinguish between "mechanical erosion" and "chemical erosion". Chemical erosion is defined to occur at the release of bentonite colloidal suspension, which is produced when the material is exposed to very low salinity water. Mechanical erosion is defined to take place when the drag force on the clay particle from the water movement is higher than the sum of the friction and attraction forces between the particle and the clay structure. Such conditions are expected to occur when high hydraulic gradients are present.

In the tests described in this report it is thus mechanical erosion of the bentonite that have been investigated.

2.2 Piping

Piping is defined in Börgesson et al. (2015):

"If water inflow into a repository, deposition hole or deposition tunnel, is localised to fractures that carry more water than the swelling bentonite can absorb, there will be a water pressure in the fracture acting on the buffer. Since the swelling bentonite initially has a very low density (a gel), which increases with time as the water goes deeper into the bentonite, the gel may be too soft to stop the water inflow. The results from such a scenario, may be piping in the bentonite, formation of a channel and a continuing water flow and erosion of soft bentonite gel. There will be competition between the swelling rate of the bentonite and the flow and erosion rate of the buffer.

Piping will take place, and the pipes remain open if the following three conditions are fulfilled:

- The water pressure pwf in the fracture, when water flow is prevented, must be higher than the sum of the counteracting confining pressure from the clay and the shear resistance of the clay.
- The hydraulic conductivity of the clay must be so low that water flow into the clay is sufficiently retarded to keep the water pressure at pwf
- There is a downstream location available for the flowing water and the removal of eroded materials for the pipe to stay open

Piping probably only occurs before complete water saturation and homogenisation since the swelling pressure of the buffer material after homogenisation is high and the hydraulic gradient in the rock after re-establishment of original water pressure will be low. The consequence of piping will be a channel and outflow of water to dry or unfilled parts of the repository. Since the clay swells the channel will reduce in size with time but, on the other hand, erosion will counteract and abrade bentonite particles and thus increase the size of the channel. There is thus a competition between swelling clay and eroding clay. If the inflow is low and the increase in water pressure slow the pipe may seal before water pressure equilibrium has been reached".

Results from different investigations indicate influence of several factors on the piping process such as geometry, water inflow rate and rate of water pressure increase. The type of bentonite and the degree of water saturation will also have an impact on the occurrence of piping.

After water saturation of the repository and re-establishment of the hydraulic gradients, piping is not judged to be an issue.

In the tests described in this report, there is an inflow point positioned at the deposition hole wall, close to the bottom of the deposition hole, Figure 3-1. This means that inflowing water will enter the pellet filled gap between buffer blocks and rock. The water is then expected to flow upwards in the pellet filling until it reaches the backfill. The floor in the deposition tunnel is covered with a pellet layer on which a central block stack is positioned. The gaps between the block stack and the tunnel walls and the tunnel ceiling are also filled with pellets. The inflowing water is then expected to establish a piping channel in the pellet filling, first in the deposition hole and then in the deposition tunnel, before reaching the outflow points positioned at the ceiling of the tunnel end.

2.3 Mechanical erosion

Water flowing in a channel through bentonite after that piping had occurred, may result in that erosion of bentonite takes place. Erosion will take place if the drag force on the clay particle from the water movement is higher than the sum of the friction and attraction forces between the particle and the clay structure. The detached bentonite particles will follow the water flow either out from the repository area or to another place within the repository (internal erosion). It is very difficult for the bentonite to stop the water inflow before water pressure equilibrium has been reached and the swelling bentonite has sealed the pipe.

The erosion process is largely dependent on the water inflow rate, the number of inflow points, and the inflow rate to other parts of the repository. In order to limit the erosion, it is therefore essential to establish a tight tunnel end plug since this will decrease the hydraulic gradients within the tunnel once the accessible pore volume in this have been water-filled. Still, this pore volume, ~900 m^3 (Börgesson et al. 2015) may lead to an extensive erosion if it would be filled from a single inflow point in a deposition hole. Other important parameters influencing the erosion process are e.g. the bentonite properties and the water chemistry.

3 Test description

3.1 Objectives

This report describes laboratory experiments performed with the aim of investigating piping and erosion in an integrated buffer and backfill system. A special case has been identified, which includes that there is a certain water inflow to the deposition hole and at the same time the deposition tunnel above is dry. The accessible pore volume in a backfilled deposition tunnel is significant, ~ 900 m^3 according to (Börgesson et al. 2015). This means that erosion from the buffer in a deposition hole, through which inflow occurs, can potentially be significant. Earlier tests (e.g. those presented by Börgesson et al. 2015) have been focussed on single components and the purpose with the tests presented in this report was to investigate the integrated performance.

The main objective of the tests was to simulate an inflow to a deposition hole from which water is led through piping, probably in the pellet filled gap, up into the backfill in the tunnel above. The inflowing water will fill up the gas-filled pore volume, especially the rather large macro voids in the pellet filling, which will result in bentonite swelling, and an increased water pressure with following piping and erosion of bentonite. The deposition tunnel in the tests was equipped with outlets at one end where the outflowing water was collected and the amount of eroded material determined. These outlets represented the remaining accessible pore volume of a backfilled deposition tunnel (not a leaking tunnel plug).

3.2 Test design

3.2.1 General

The tests were performed as scale tests, scale 1:10, including one deposition hole and a tunnel section with a length corresponding to two c/c distances between deposition holes, see schematic drawing of the deposition tunnel and the deposition hole in Figure 3-1. The deposition hole was equipped with a water inlet (d=4 mm) close to the bottom and the tunnel section was equipped with three water outlets (d=10 mm) positioned close to the ceiling at the tunnel end which means that the distance to the deposition hole was as long as possible.

To facilitate the installation, the tunnel roof could be removed. The tunnel roof also included four large openings on the top which were used in conjunction with the installation to fill up the tunnel completely with pellets. The removable roof did also facilitate the dismantling of the tests.

A schematic showing the test setup is provided in Figure 3-2 and a photo showing the arrangement in laboratory is provided in Figure 3-3. Water with a defined salinity was mixed in a large water reservoir (450 litres). A dose pump was used to inject the water into the bottom of the deposition hole at a constant flow rate. The water flowing out from the deposition tunnel was collected in special sedimentation vessels in three steps, see Figure 3-2.

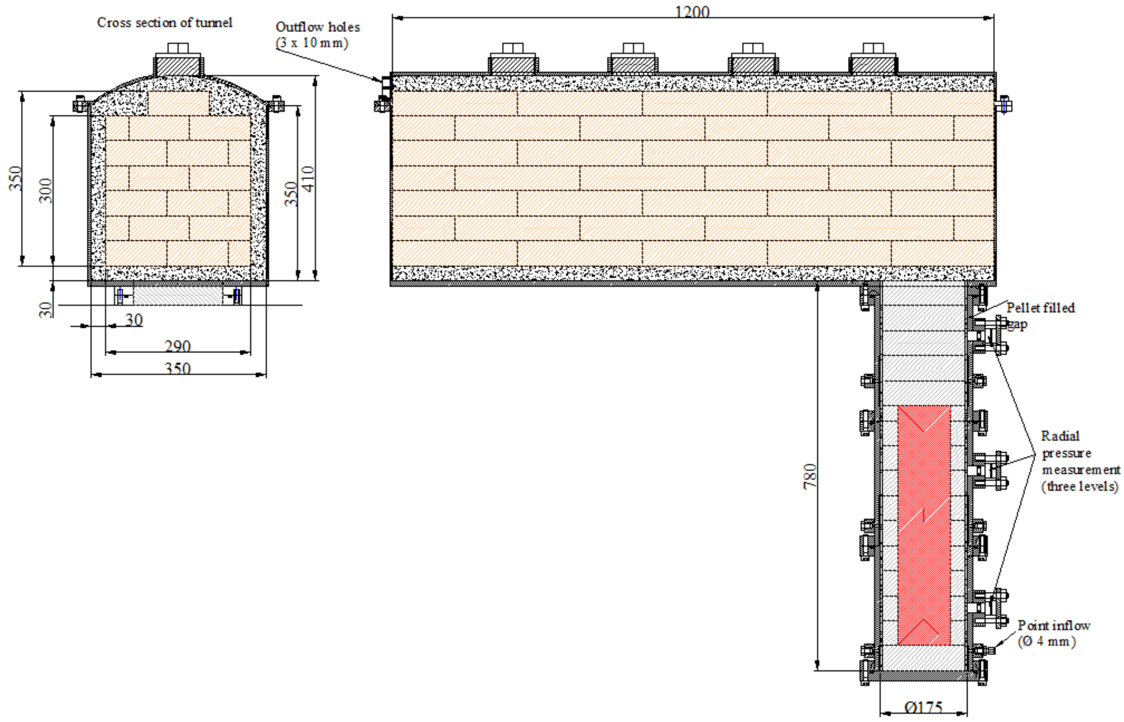


Figure 3-1. *Schematic overview showing the design of the test equipment. The drawing up to the left shows a cross section of the deposition tunnel and shows also the backfill block stacking pattern.*

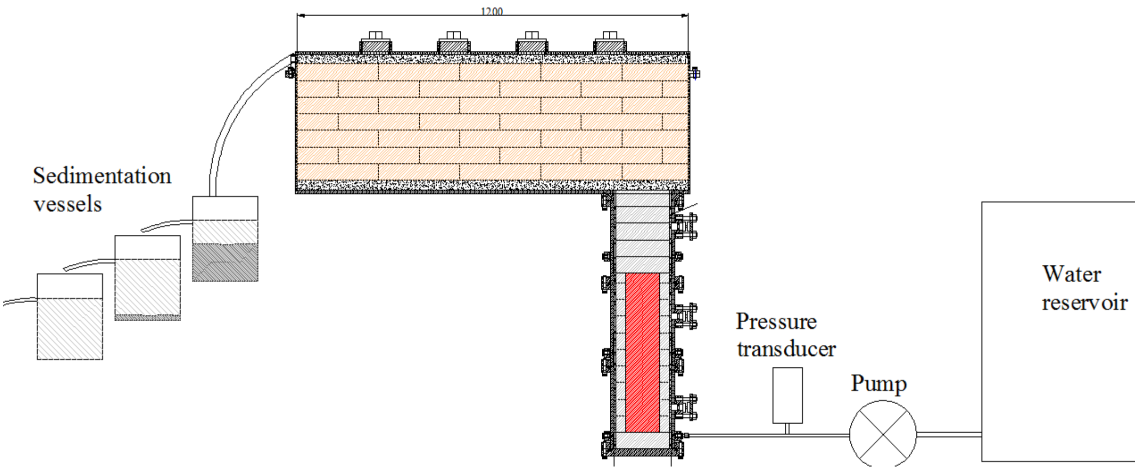


Figure 3-2. *Schematic showing the test setup.*

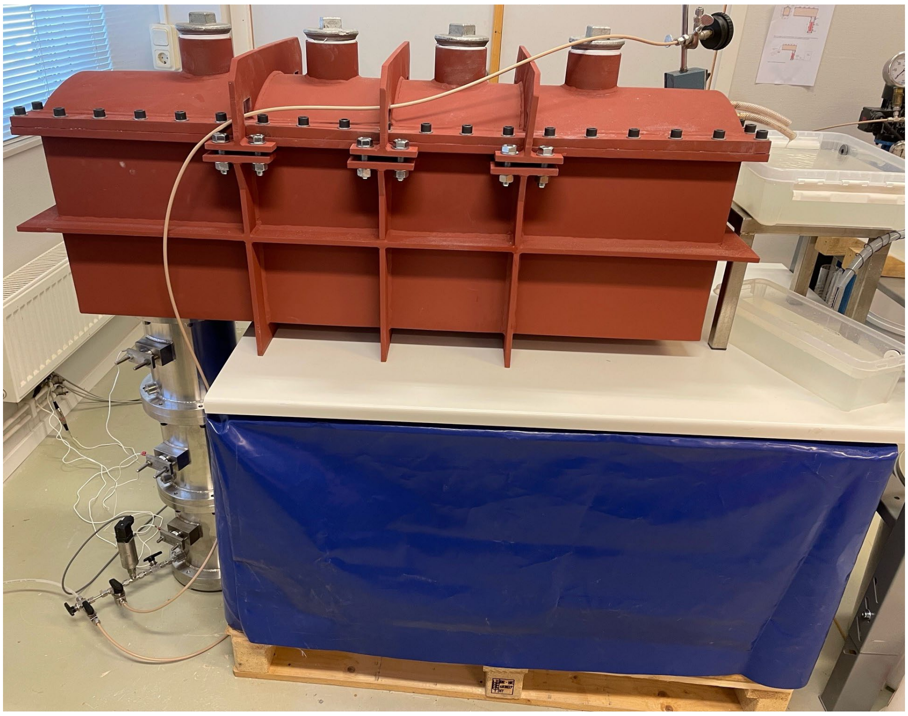


Figure 3-3. Photo showing the test arrangement. The deposition tunnel was placed on a bench and the deposition hole was standing on the floor below (to the left in the photo). The sedimentation vessels can be seen to the right in the photo.

3.2.2 Deposition hole

The deposition hole consisted of three individual tube sections, Figure 3-1. This design facilitated both the assembly and the later dismantling of the tests. All parts of the deposition hole were manufactured of stainless steel. The deposition hole had an inner diameter of 175 mm and a height of 780 mm. The radial total pressure was measured at three levels in the deposition hole, 150 mm, 400 mm and 650 mm from the bottom.

The equipment had been used in an earlier test where filters were countersunk into the hole periphery at some levels. The filters had a thickness of two mm. In the tests described in this report, rubber mats were placed in these grooves to achieve the correct diameter (three rubber mats, one with a height of 50 mm and two with a height of 100 mm).

3.2.3 Canister

The simulated canister was made of stainless steel and had a length of 483.5 mm and a diameter of 105 mm. The weight of the canister was approximately 16 kg.

3.2.4 Deposition tunnel

The deposition tunnel consisted of two main parts, a rectangular box (tunnel floor and walls) and a roof that was bolted to the box. The design is shown in Figure 3-1 and in the photo in Figure 3-3. On the roof there were four large openings that were used for installation of the pellets at the top of the block stack. The tunnel had a length of 1200 mm, a width of 350 mm and a height of 410 mm (at the midpoint). To withstand the swelling pressure from the backfill, the tunnel was reinforced with several steel beams positioned on both floor, walls and on the roof. The deposition tunnel was manufactured of carbon steel which was protected with anti-rust paint. A special adapter was placed at one tunnel end for the connection of the deposition hole.

3.3 Instrumentation

The tests included only a few sensors. The radial total pressure was measured at three positions along the deposition hole, see drawing provided in Figure 3-1. The total pressure was measured using pistons, d=20 mm, which were transferring the pressure in the deposition hole to an external loadcell.

In addition, the applied water pressure was registered. The injected water volume was manually registered, see description in Section 3.6.

3.4 Buffer and backfill materials

3.4.1 Deposition hole

The buffer consisted of compacted blocks, see detailed description in Section 4.1. Solid blocks were positioned below and above the canister and ring-shaped blocks were positioned along the canister, Figure 3-1. The gap between the blocks and the deposition hole walls was filled with pellets, see description in Section 4.3, specially designed to fill up the rather narrow gap with a width of 5 mm.

3.4.2 Deposition tunnel

The backfill consisted of both compacted blocks, see description in Section 4.2, stacked in a predetermined pattern, Figure 3-1, but also of bentonite pellets filling up the gaps between the block stack and the tunnel walls and ceiling, see description in Section 4.4.

3.5 Water and pump equipment

3.5.1 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. The molar concentration of NaCl was thus 86 mM, while the corresponding concentration of $CaCl_2$ was 45 mM. Water with the defined salinity was mixed and stored in a large water reservoir (450 litres), Figure 3-4 (left). This type of water has been used in several earlier tests in which the piping/erosion processes were investigated, e.g. Börgesson et al. 2015.

3.5.2 Pump equipment

Two different pumps were used in these tests.

1. A dose pump was used to inject the water into the test cell at a constant flow rate. A photo showing the water reservoir, and the dose pump is provided in Figure 3-4 (left). The maximum injection pressure from the dose pump was 1 MPa. This pump gave a rather constant flow rate independent of the resistance pressure.
2. Since the water pressure needed to establish a piping channel through the buffer and backfill, and also to keep it open, wasn't known, it was necessary to also have access to a special ”High Pressure Pump”. The pump was lifting water from the same vessel as was used by the dose pump. The maximum pressure could be adjusted by use of a pressure relief valve that opened and let the water out back to the vessel when the set maximum pressure value was reached. A photo of the pump is provided in Figure 3-4 (right).

The water reservoir had to be refilled several times during each test (see below).

3.6 Test matrix

Two tests were performed in this test series:

1. Test 1: Water inflow rate of 0.05 litre/min. The test duration was set to 10 weeks which means that the total amount of inflowing water was approximately 5000 litres.
2. Test 2: Water inflow rate of 0.02 litre/min. Test duration was set to 5 weeks, and the total amount of inflowing water was approximately 1000 litres.

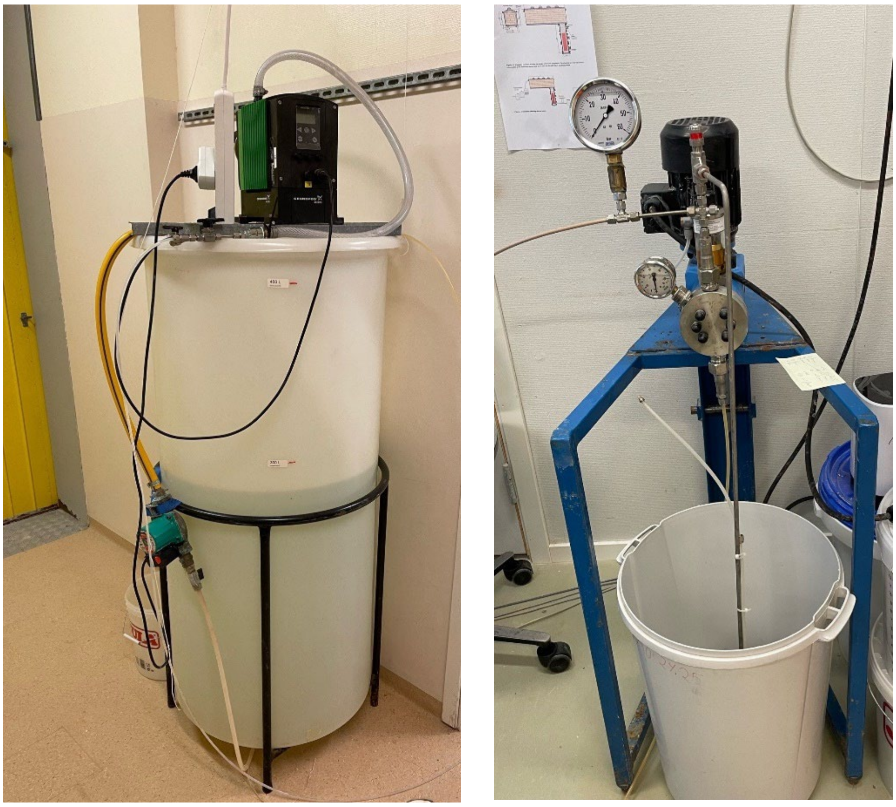


***Figure 3-4.** Left: Photo showing the dose pump positioned above the vessel with water. Right: Photo showing the high-pressure pump.*

3.7 Erosion measurements

During test time, the following variables were registered/measured:

Inflowing water

- Water flow rate. The desired flow rate was set on the dose pump. Before starting the test, a check of the achieved flow rate was done. In addition, the amount of mixed water added to the vessel during the test period was noted.
- Water injection pressure. The injection pressure was registered.
- Water salinity. Samples were taken from the reservoir to check the water salinity. A circulation pump was used to continuously mix the water.

Outflowing water

- Water flow rate. Manual measurement of water flow from the last sedimentation vessel during a decided time.
- Eroded material. Manual measurement by collecting and drying material from the three sedimentation vessels.

An important and quite labour-intensive measurement was the quantification of the erosion rate. This was performed by collecting all sedimented material from the sedimentation vessels. The accumulated sediment was collected and dried (between 3 to 5 times a week). In the calculations of the amount of eroded material, compensation was made for salt present in the water that was evaporated during drying. A photo showing the arrangement of sedimentation vessels is provided in Figure 3-5.

Figure 3-5. *Photo showing the arrangement of sedimentation vessels.*

4 Material

4.1 Buffer blocks

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 tap water in an Eirich-mixer, to achieve a target water content of 17 % (the final water content was determined to 17.7 %).

The block manufacturing was made in Clay Technology´s laboratory, see photo to the left in Figure 4-1. Both solid and ring-shaped blocks were manufactured. The blocks had an outer diameter of 175/173 mm (somewhat conical), and a height of 50 mm. The ring-shaped blocks had an inner diameter of 106 mm. The blocks were after manufacturing machined to a target outer diameter of 165 mm in a lathe. The target dry density for the compacted blocks was 1652 kg/m^3 (solid blocks) and 1747 kg/m^3 (ring-shaped blocks). The compaction pressure was about 29 MPa for the solid blocks and 52 MPa for the ring-shaped blocks.

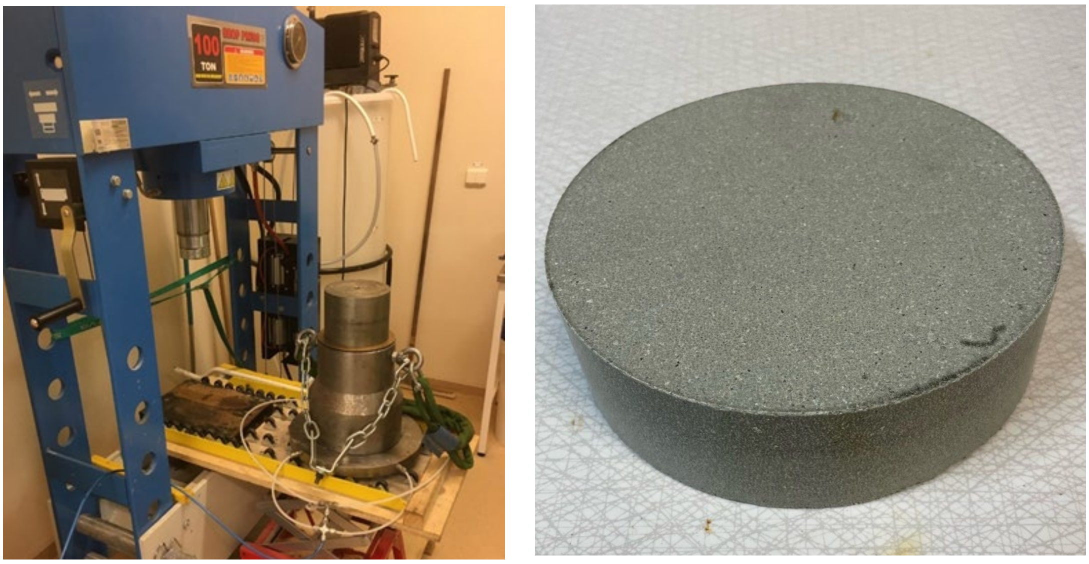


Figure 4-1 *Left: Manufacturing of blocks with an outer diameter of 175/173 mm using the 100-ton press at Clay Technology, Lund. Right: Photo showing a manufactured block.*

4.2 Backfill blocks

The backfill blocks were manufactured of the same material as the buffer blocks. The manufacturing was made at Höganäs Borgestad in Bjuv, Sweden. The blocks used in these tests were spare blocks, stored by SKB, originally manufactured to be used in a large-scale test at Äspö HRL.

The block dimensions were 50 mm x 122 mm x 250 mm, Figure 4-2. The blocks had a water content of 15.8 % and a dry density of 1770 kg/m^3. About one third of the blocks were cut, using a band saw, to achieve a width of 46 mm. This was made to make it possible to achieve the desired block stack pattern, see description in Section 2.3 and Figure 3-1.

Figure 4-2. Photo showing one of the backfill blocks used in the tests.

4.3 Pellets in deposition hole

These pellets were manufactured of Bara-Kade bentonite from Wyoming, USA. The pellets were taken from a storage at SKB and originated from an old batch used for different large-scale tests. The individual pellets were shaped as small pillows with the approximately dimensions 16 x 16 x 8 mm, see photo provided in Figure 4-3 (left photo).

The gap between buffer blocks and deposition hole walls was in this scale test 5 mm. To fill up the gap like in the full scale, it was necessary to crush the pellets. The pellets were crushed using a so-called jaw-crusher and was afterwards sieved to achieve a fraction with a size between 2 and 4 mm, Figure 4-3 (right photo). The crushed pellets had a water content of 12.4 %.

Figure 4-3. Left: Photo showing compacted pellets. Right: Photo showing the compacted pellets after crushing.

4.4 Pellets in deposition tunnel

The pellets used in the deposition tunnel were manufactured using the same material as was used for the pellets in the deposition hole and were also taken from a storage at SKB. The pellets were manufactured by extrusion. With this method, bentonite material is squeezed through a hole-matrix, which results in pellets shaped as rods with varying length, Figure 4-4 (right photo). 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 15.2 %.

Figure 4-4. *Photo showing pellets manufactured by extrusion.*

5 Test 1 (0.05 l/min)

5.1 Preparation of the deposition hole

The assembling started from the bottom of the deposition hole. All buffer blocks were weighed and measured in conjunction with the installation. Pellets were installed, and weighed, in parallel after installation of one or two buffer blocks, Figure 5-1.

The installation was made according to the following:

1. Mounting of the bottom lid on the first section of the deposition hole.
2. Positioning of the bottom block. Installation of pellets in the gap between block and deposition hole wall.
3. Positioning the first ring-shaped block including pellets.
4. Installation of the canister.
5. Ring-shaped blocks were then threaded around the canister one by one. Pellets were installed in parallel for every second block. The next deposition hole section was mounted when the one below was filled with block and pellets.
6. The height of the uppermost ring-shaped block was adjusted so that the top surface of the block was at the same level as the top of the canister.
7. Installation of blocks above canister. Pellets were installed in parallel for every second block.
8. After installation of all blocks above the canister but one, the deposition hole was placed below the deposition tunnel, which was standing on a bench. The deposition hole was then bolted to the tunnel, see photo provided in Figure 3-3.
9. The height of the last buffer block was adjusted before installation so that the height of the top surface was at the same level as the tunnel floor, see right photo in Figure 5-1.

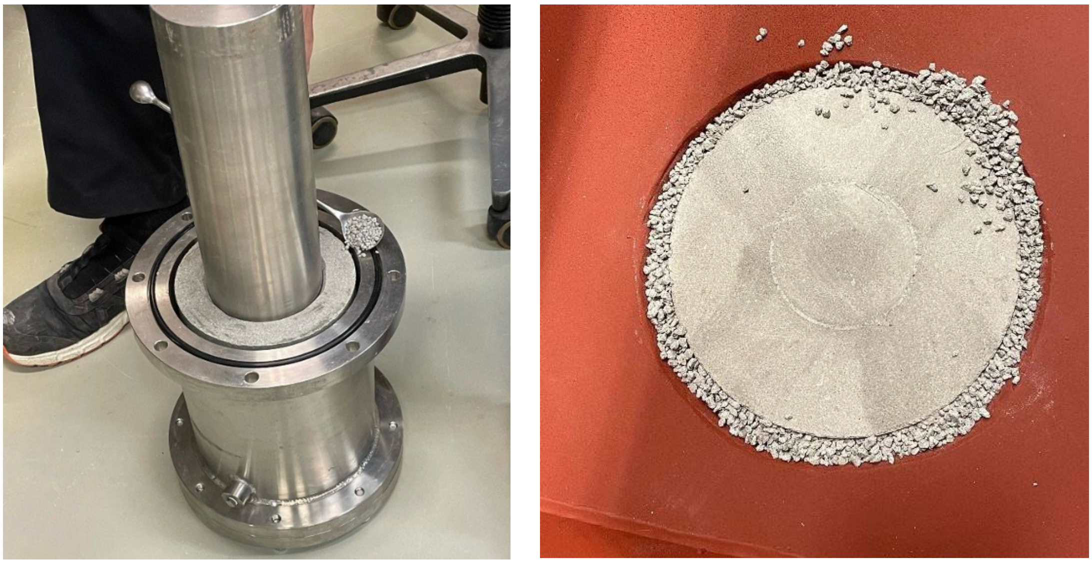


Figure 5-1. *Photos taken in conjunction with the preparation of the deposition hole. Left: Installation of pellets around a ring-shaped block. Right: The deposition hole has been attached to the tunnel floor and the last buffer block has been installed together with the pellets.*

5.2 Preparation of the deposition tunnel

The mass of all backfill blocks and pellets were determined in conjunction with the installation. The installation was made according to the following (see also photos provided in Figure 5-2):

1. The bottom layer consisting of a pellet layer with a thickness of 30 mm was installed.
2. The blocks were positioned according to the stacking pattern shown in Figure 3-1 i.e., as a masonry. The lengths of the last blocks were adjusted to the length of the deposition tunnel. After positioning of one block layer, the gap between the block stack and the walls was filled with pellets.
3. After installation of the first six block layers and installation of pellets in the gaps, the last block layer, with one block width, was installed. Parts of the last pellets layer were installed at the top where it was possible without flowing over the tunnel walls.
4. After mounting of the roof, the last pellets at the top of the block stack, were installed through the four openings in the roof. After installation of plugs in the four openings the installation of backfill was complete. A photo of the complete deposition tunnel with roof is provided in Figure 3-3.

Figure 5-2. *Photos taken in conjunction with the backfill installation. Upper left: The bottom pellet layer has been installed together with the first blocks. Upper right: The third block layer has been installed. Lower left: The sixth block layer have been completed. Lower right: The seventh block layer has been installed.*

5.3 Installation data

Detailed data regarding the blocks and pellets in the deposition hole and the deposition tunnel is provided in Appendix 1 and 2. A compilation of the most important data is provided below.

5.3.1 Deposition hole

The dry density of the ring-shaped blocks varied between 1721 to 1747 kg/m^3 and between 1642 and 1674 kg/m^3 for the solid blocks. The dry density of the pellet filling was 907 kg/m^3.

The average dry density of the buffer in the deposition hole was 1564 kg/m^3 (1558 kg/m^3 for the section with ring-shaped blocks and 1571 kg/m^3 for the sections with solid blocks). This is somewhat lower than the target dry density, which was 1580 kg/m^3.

5.3.2 Deposition tunnel

The total dry mass of the installed backfill blocks was 193.29 kg. The total dry mass of the pellets was 51.8 kg. The backfill block stack had a dry density of 1730 kg/m^3 and the pellet filling had a dry density of 995 kg/m^3. The block filling degree in the tunnel was 68.2 % and the average dry density of the backfill in the deposition tunnel was 1496 kg/m^3.

5.4 Registered data

5.4.1 Test start and regular control of test parameters

Test start

After having started the test, it took about seven hours until the first water outflow from the deposition tunnel was noticed. This means that approximately twenty-one litres were injected before any outflow occurred. This volume was slightly lower than the available (air-filled) void space of the pellets-filled slots, which were 1 litre in the buffer and 26 litres in the backfill. The corresponding volumes for the blocks were 1 litre in the buffer and 12 litres in the backfill.

Water flow rate

The flow rate out from the deposition tunnel was checked regularly. Before emptying the sedimentation vessels to determine the amount of eroded material, the outflowing water from the last sedimentation vessel was collected during a defined time (15 minutes). The amount of water flowing out during this test time was weighed and then the flow rate could be calculated. These measurements were made to ensure that the intended flow rate was kept at the right level.

Results from the water flow measurements are presented in Figure 5-3. As shown in the graph there were some deviations from the set value during the first week. The reason for this was that it at some periods was necessary to use the High Pressure Pump since the resistance pressure increased. With this pump it was more difficult to keep the inflow rate at a constant rate (see also pump description in Section 2.6.2). The deviations from the set value on the dose pump were, however, small (from day 8 and forward).

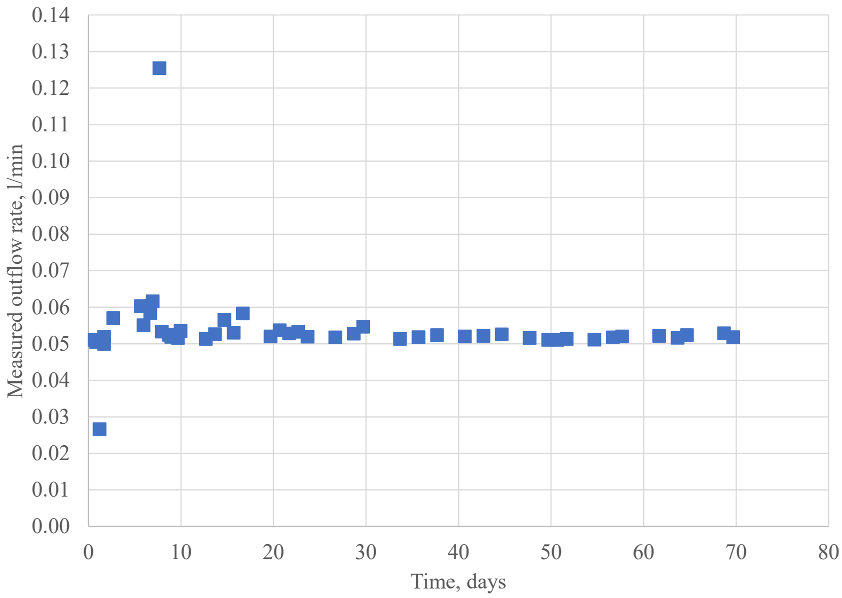


***Figure 5-3.** The measured outflow rate plotted versus time for Test 1. The inflow rate was set to 0.05 l/min.*

Salinity of water

The salt content in the water is believed to be an important parameter influencing the erosion properties of bentonite. In conjunction with the determinations of the water flow rate, see above, one sample was taken from the reservoir with mixed water. The sample, approximately 0.8 litres, was weighed and dried in an oven and the amount of salt left determined.

The results from the measurements are presented in Figure 5-4. The results are quite consistent with the intended target although there were small deviations, especially during the first five weeks.

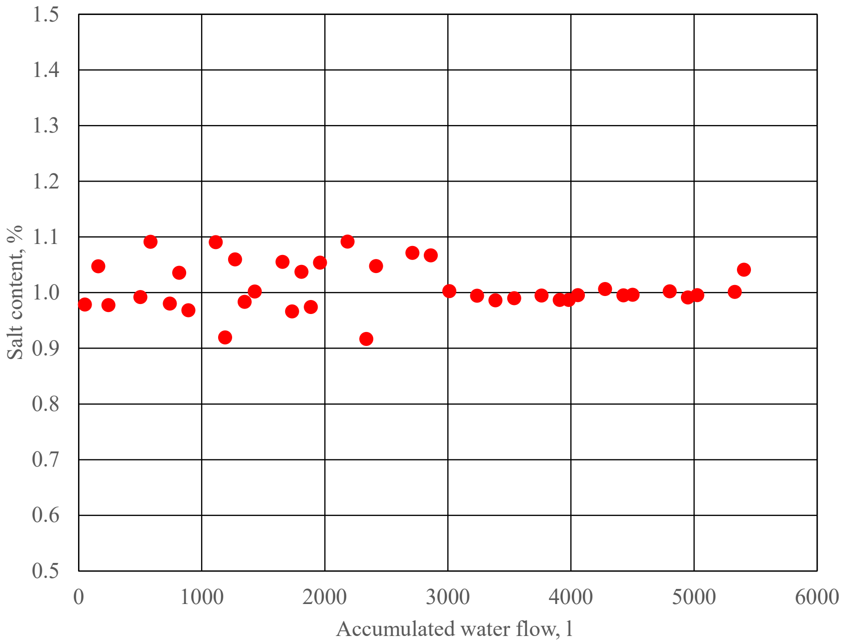


***Figure 5-4.** Results from measurements of the salt content plotted versus the accumulated water flow in Test 1.*

5.4.2 Erosion measurements

The erosion rate was determined by collecting all sedimented material from the three sedimentation vessels at decided intervals, normally between three to five times a week. The accumulated amount of sedimented material during a known period was collected and decanted. The bentonite solution was put in aluminium vessels with a determined weight. The vessels, including the solution of bentonite and water, were weighed and thereafter put in an oven at a temperature of 105°C. After drying, which took about 48 hours, the vessels including the dry mass were weighed again and the amount of dry bentonite could be calculated. In the calculations it was compensated for the mass of salt present in the evaporated water.

The results from the erosion measurements are provided in Figure 5-5 and Figure 5-6. In Figure 5-5 the results are presented as the accumulated amount of eroded material plotted versus the accumulated amount of water outflow (upper figure shows the result in a lin-lin graph and the lower in a log-log graph). The erosion rate seemed to decrease somewhat after an accumulated outflow of approximately 3000 litres, but the tendency was not clear.

The graph provided in Figure 5-6 shows the results as the bentonite concentration in the outflowing water plotted versus the accumulated amount of water outflow. The bentonite concentration in the outflowing water varied between 0.2 and 2.7 g/l during the test.

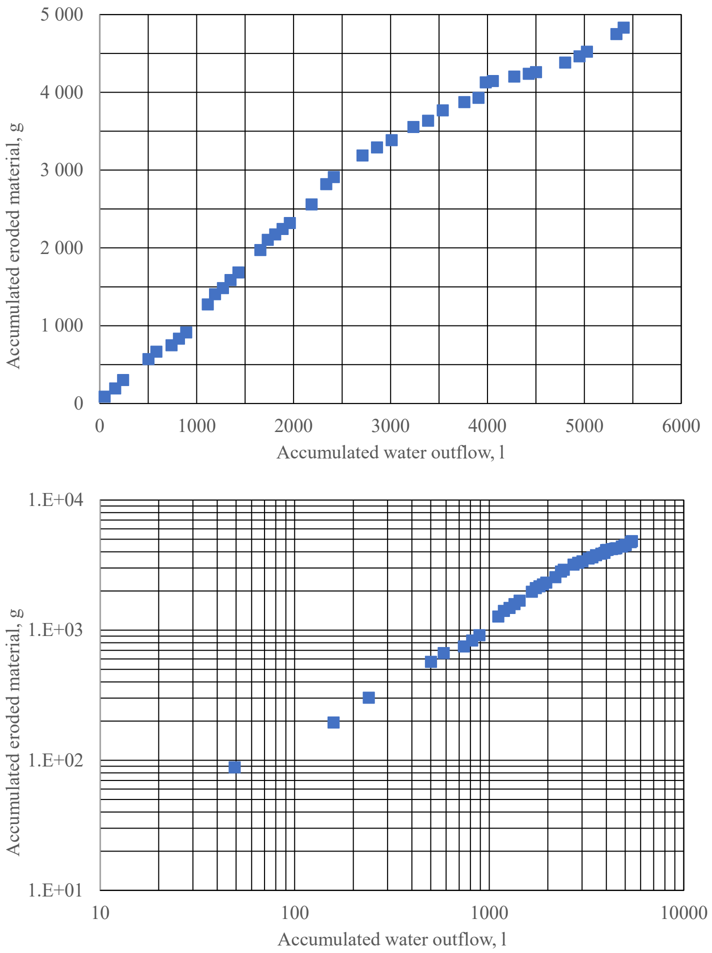


Figure 5-5. *The accumulated eroded material plotted versus the accumulated water outflow for Test 1. Upper: The results presented in a lin-lin graph. Lower: The results presented in a log-log graph.*

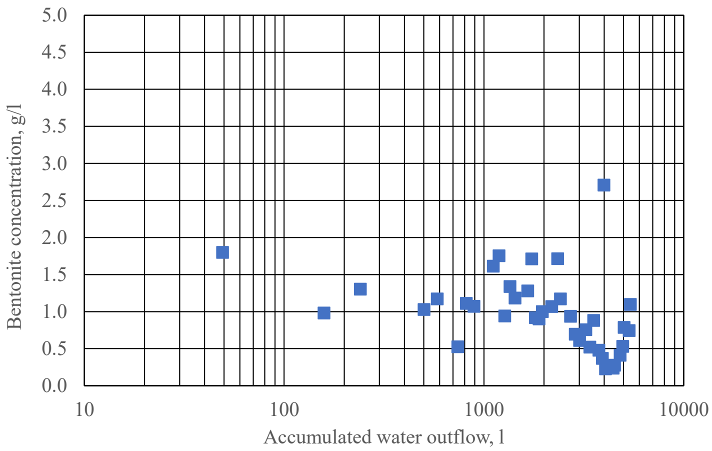


Figure 5-6. *The bentonite concentration plotted versus the accumulated water outflow for Test 1.*

5.4.3 Water injection pressure

A pump, either a dose pump or a High-Pressure Pump, was used to achieve a constant water inflow rate to the test. Keeping the inflow at a constant level caused the water pressure to increase if the flow resistance in the test cell increased e.g. depending on the swelling bentonite.

The water injection pressure on the inflowing water was registered continuously during the test time, see the schematic test setup in Figure 3-2. The results from the water injection pressure measurements are presented in Figure 5-7 (blue line) together with the measurements of the radial total pressure in the deposition hole. As shown in the graph, the water injection pressure varied a lot during the first eight days, mainly between 0.1 to 0.5 MPa, but several pressure peak values occurred during this time, maximum up to more than 1.7 MPa. After eight days of test duration, the water injection pressure dropped to almost zero which implied that a stable channel had been created through the buffer and the backfill.

5.4.4 Radial total pressure in deposition hole

The radial total pressure was measured at three positions along the deposition hole, see description in Section 3.3.2. The results from the measurements are presented in Figure 5-7.

All three sensors reacted almost immediately after the test started and registered after about 24 h a pressure of 0.4 MPa. After that, the lower sensor continued to register increasing pressure for another two days before decreasing to 0.2 MPa. The middle sensor instead showed a decreasing pressure, and the upper sensor registered an almost constant pressure. However, after approximately 10 days of test duration all three pressure sensors have registered an increasing pressure. After about 50 days of test duration all three sensors registered a decrease in pressure of approximately 0.15 MPa. The reason for this decrease is not known but it is considered likely that some kind of movement of the buffer has occurred in the deposition hole. After the pressure drop, the lower sensor continued to register a decreasing pressure while the other two sensors registered a slowly increasing pressure.

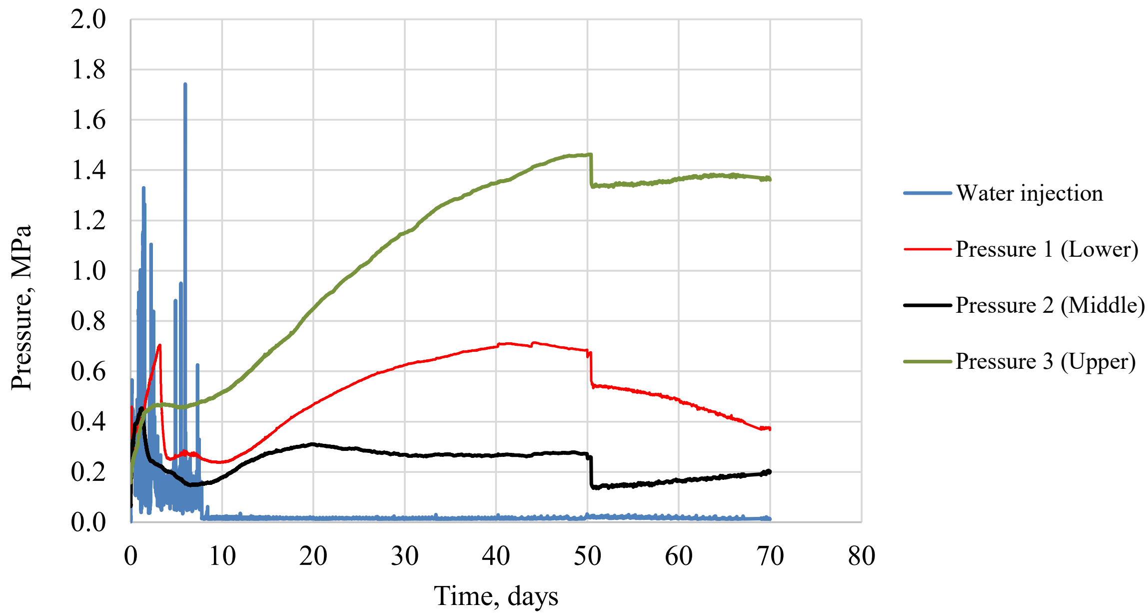


Figure 5-7. *Applied water injection pressure (blue line) and radial total pressure for Test 1, registered at three levels in the deposition hole (red, black and green lines) plotted versus time.*

5.5 Dismantling

Sampling

After ten weeks test duration the test was stopped and the dismantling started. An extensive sampling was conducted to determine the water content and the dry density distribution in the backfill and in the buffer.

The water content and bulk density were determined in the backfill at 195 positions and in the buffer at 180 positions. This data was then used to calculate the dry density and the degree of saturation, see description below.

Sampling of the backfill

The sampling was done in five cross-sections, S1 to S5, along the deposition tunnel, see schematic drawing provided in Figure 5-8. In each of the cross-sections, 39 samples were taken in four directions (A, B, C and D) according to Figure 5-9. Samples were taken from a total of 195 positions in the backfill.

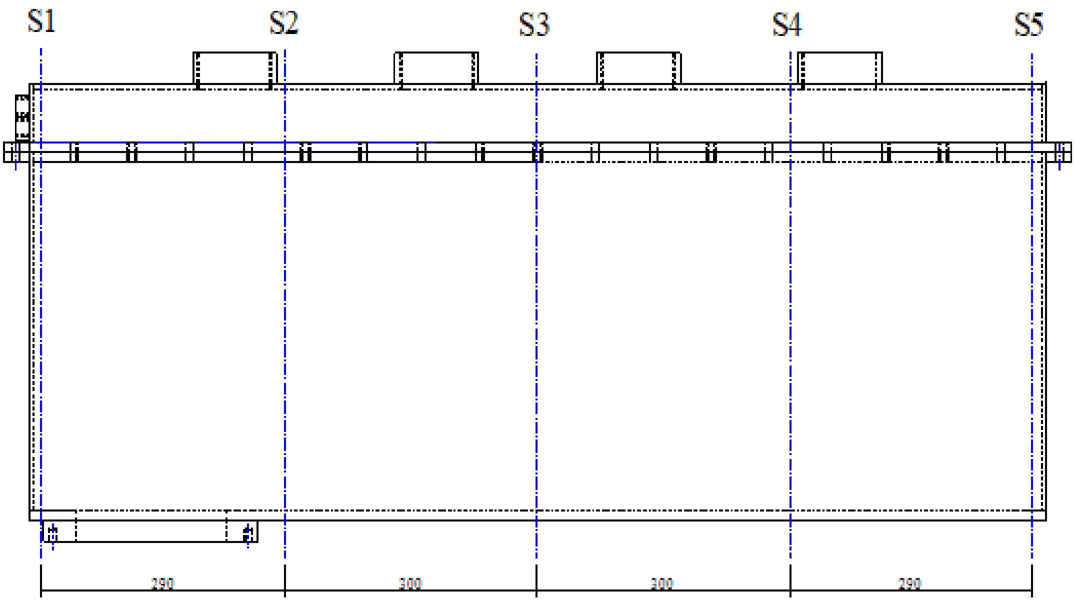


Figure 5-8. Planned sampling of the backfill. The sampling was made in five cross-sections, S1 to S5.

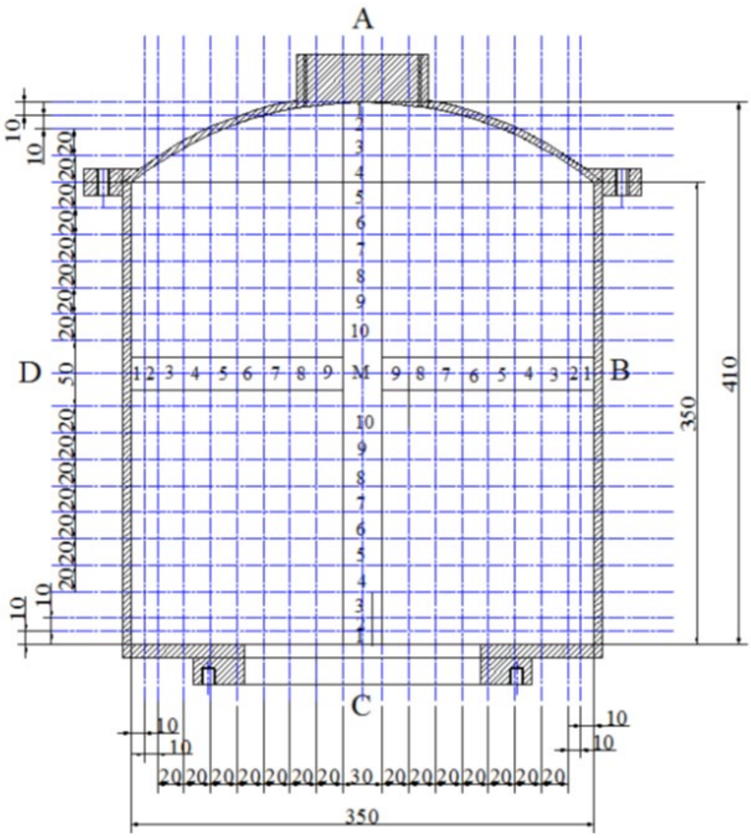


Figure 5-9. Planned sampling of the backfill. The picture shows the planned sampling in each of the cross-sections.

Sampling of the buffer

The sampling was done in nine horizontal cross-sections, L1 to L9, in the deposition hole, see schematic drawing provided in Figure 5-10 (left). In each of the cross-sections, samples were taken in four directions (A, B, C and D) according to Figure 5-10 (right). Samples were taken from in total 180 positions in the buffer.

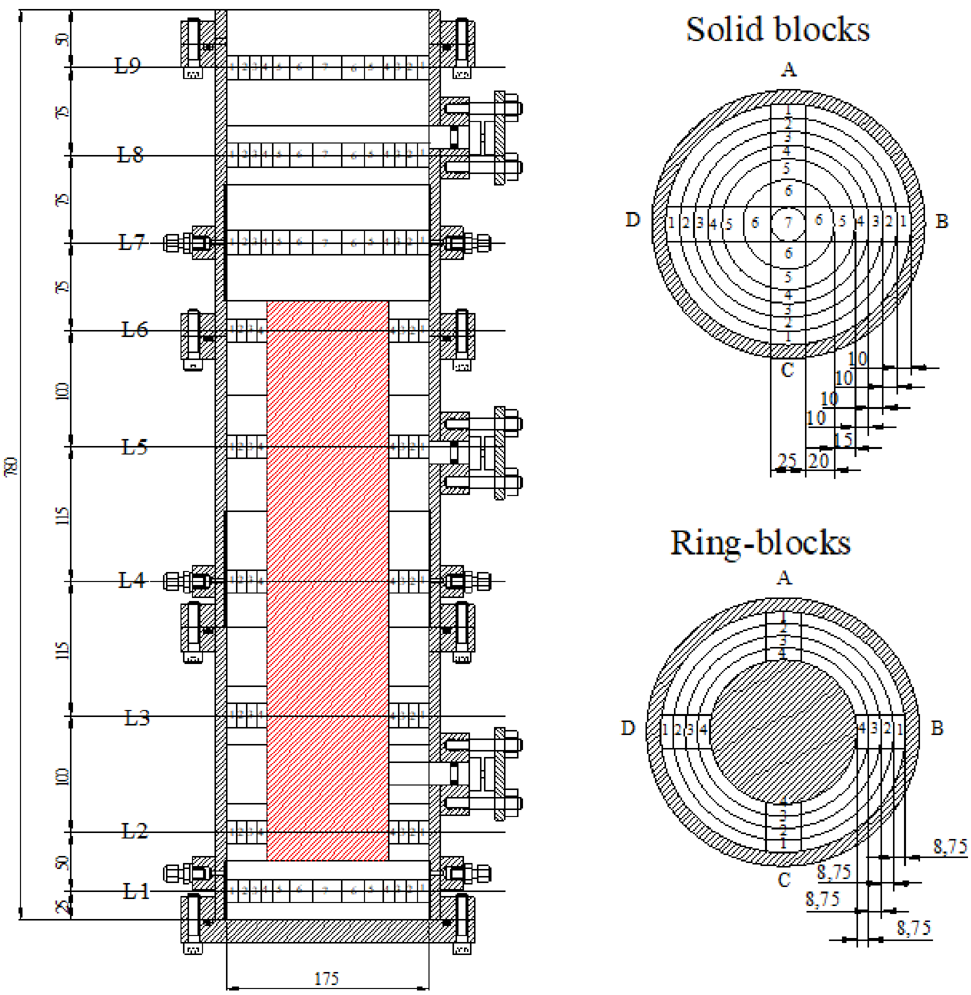


Figure 5-10. *Planned sampling of the buffer.*

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 aluminium 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:

$$m_w = m_b - m_s \qquad \text{4-1}$$

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

$$w = \frac{m_w}{m_s} \qquad \text{4-2}$$

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:

$$V = \frac{(m_b - m_{bp})}{\rho_p} \qquad 4\text{-}3$$

where ρ_b is the paraffin oil density. The bulk density of the sample was then calculated:

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

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

$$\rho_d = \frac{\rho_b}{1 + w} \qquad 4\text{-}5$$

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

$$Sr = \frac{w \cdot \rho_b \cdot \rho_s}{[\rho_s \cdot [1 + w] - \rho_b]\,\rho_w} \qquad 4\text{-}6$$

In the calculations, a grain density (ρ_s) of 2780 kg/m^3 have been used. The dissolved salt in the injected water was expected to have a negligible effect on the evaluated quantities and was therefore not considered.

5.6 Results from sampling

In addition to the sampling to determine the water content and dry density distribution, it was important to identify how the water has been flowing and if there were any clear erosion channels within the buffer and backfill.

5.6.1 Erosion channels in backfill

In conjunction with the removal of the tunnel ceiling, a large amount of bentonite was also removed, see upper photo in Figure 5-11. Parts of an erosion channel could be observed along the edge between tunnel walls and ceiling (see upper part of the photos).

After having finished the sampling of the bentonite stuck on the ceiling, the rest of the bentonite was removed. As shown in the lower photo in Figure 5-11, the erosion channel could be seen very clearly on the ceiling surface. The channel started in one of the tunnel corners close to the deposition hole, see red arrow in photo, and followed partly the edge between wall and ceiling and partly it did some loops into the top of the tunnel ceiling, before entering the outflow point.

The left photo in Figure 5-12 shows the position were water flowing from the deposition hole have reached the upper corner of the tunnel (see corresponding photo of the tunnel ceiling in the photos provided in Figure 5-11). The right photo in Figure 5-12 shows the exposed top surface of the deposition hole. The four red arrows (A, B, C, and D) show the sampling directions where A was close to the inflow point in the bottom of the deposition hole. A few extra samples were taken from the upper surface of the deposition hole after having removed the backfill (right photo in Figure 5-12). The water content varied between 25 % at the driest parts and 70 % at the wettest part. The wettest part was in direction D where water seemed to have entered the tunnel, see also Section 5.6.4.

Figure 5-11. *Upper: Photo showing the tunnel ceiling after removal of the steel lid in Test 1. Parts of the pellet filling was left on the top of the block stack, see also photos provided in Figure 5-13. Lower: All bentonite has been removed and the erosion channel along the tunnel ceiling can clearly be seen. The photo shows clearly the point where the vertical flow from the deposition hole has reached the ceiling (red arrow). The water then flowed along the ceiling, with some curves against the mid, and has finally reached the outflow point (red/orange flow path).*

Figure 5-12. *Left: Photo showing the corner were water flowing from the deposition hole have reached the upper corner of the tunnel in Test 1 (see corresponding photo of the tunnel ceiling in the photo above). Right: After removal of all the backfill, the upper part of the buffer in the deposition hole was exposed. The red arrows show the sampling directions of the buffer (direction A is almost at the same direction as the inflow point and also close to the pressure measurements).*

5.6.2 Dismantling and sampling of the deposition tunnel.

Dismantling

After having finished the first sampling of the backfill stuck on the ceiling, see Section 5.6.1, the sampling of the tunnel continued, see photos provided in Figure 5-13. The pellet filled gaps between the block stack and the walls had clearly been wetted. Water also seemed to partly have entered the small gaps between the blocks and by that "glued" them together.

The sampling of the softer material in the pellet filled gap was done using sharp tools. The backfill blocks were removed using hammer and sharp tools. Most of them could be loosened one by one (some of them fractured), and the following sampling was made using a bandsaw.

The lower right photo in Figure 5-13 shows the bottom layer after having removed one block and by that exposing the pellet layer on the tunnel floor. The pellets here were "glued" to each other which indicated that water had entered, but the pellet filling was clearly not saturated.

Figure 5-13. *Test 1. Upper left: The top lid has been removed. Upper right: The first block layer has been removed. Lower left: The second block layer has been removed. Lower right: The bottom block layer. One block has been removed exposing the bottom pellet layer.*

Water content and dry density distribution

The results from the sampling of the backfill are shown in the graphs provided in Figure 5-14 (sampling along five central vertical lines with sampling direction A upwards) and in Figure 5-15 (sampling along five central horizontal lines of the tunnel with sampling direction B upwards), see also sampling plans provided in Figure 5-8 and Figure 5-9. The graphs show the water content (upper graph), the dry density (middle graph), and the degree of saturation (lower graph) plotted versus the tunnel height and the tunnel width respectively.

The graphs show that the water content had increased in most positions in the backfill, but mostly in the pellet filled gaps on the long side walls and in the pellet-filling positioned at the top of the block stack. The influence of the flowing water on the pellet filling on the floor was more limited. The water content had mainly increased in the pellet filling on the floor close to the deposition hole.

The wetting of the backfill had also resulted in an increase of the density in the pellet fillings and a certain decrease of the density in the block stack. Since the test duration was limited, the homogenization process of the backfill had only started.

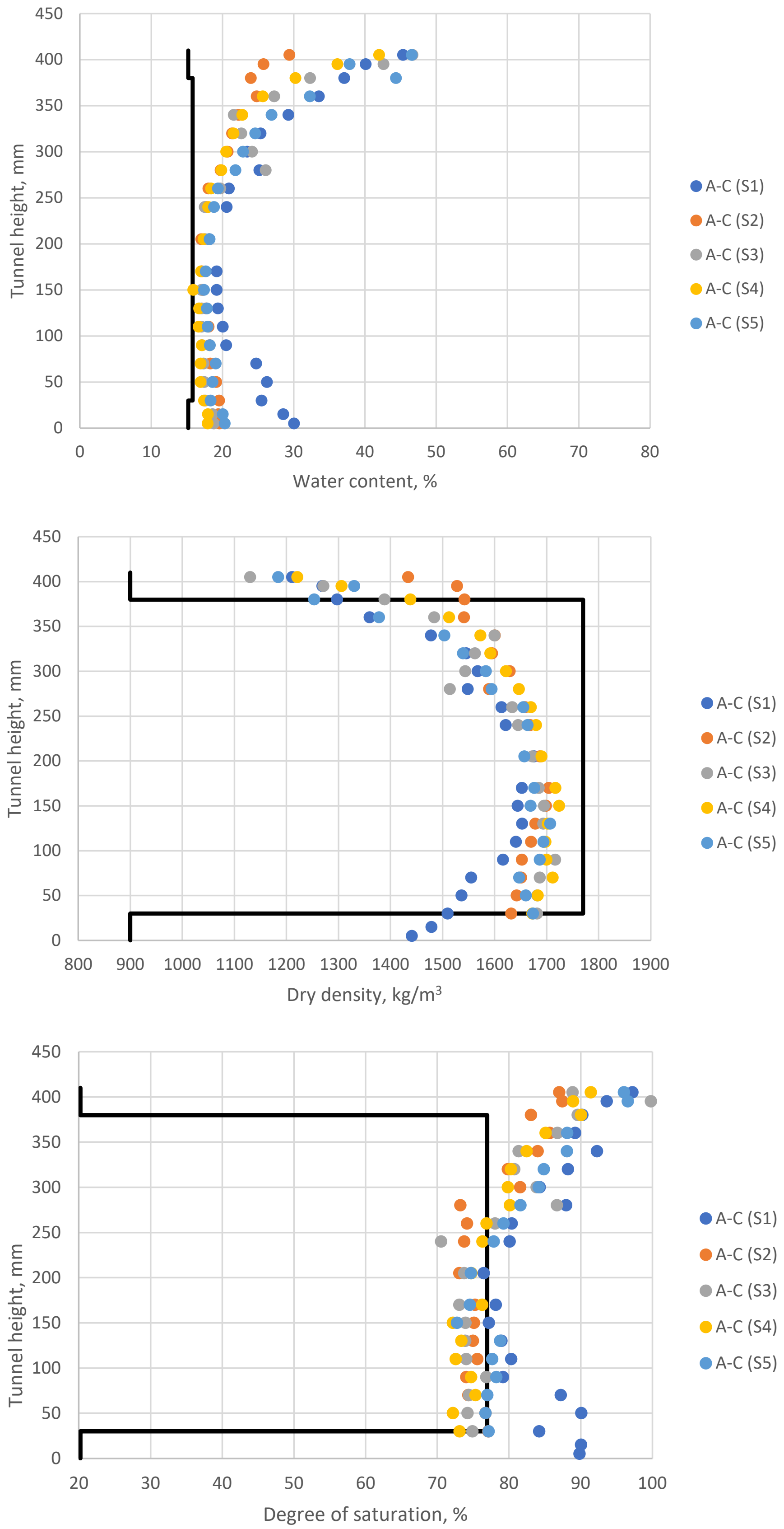


Figure 5-14. *Water content (upper), dry density (middle), and degree of saturation (lower) along central vertical lines at five different sections in Test 1, see Figure 5-8 and Figure 5-9. The black lines indicate the initial values. Sampling direction A upwards.*

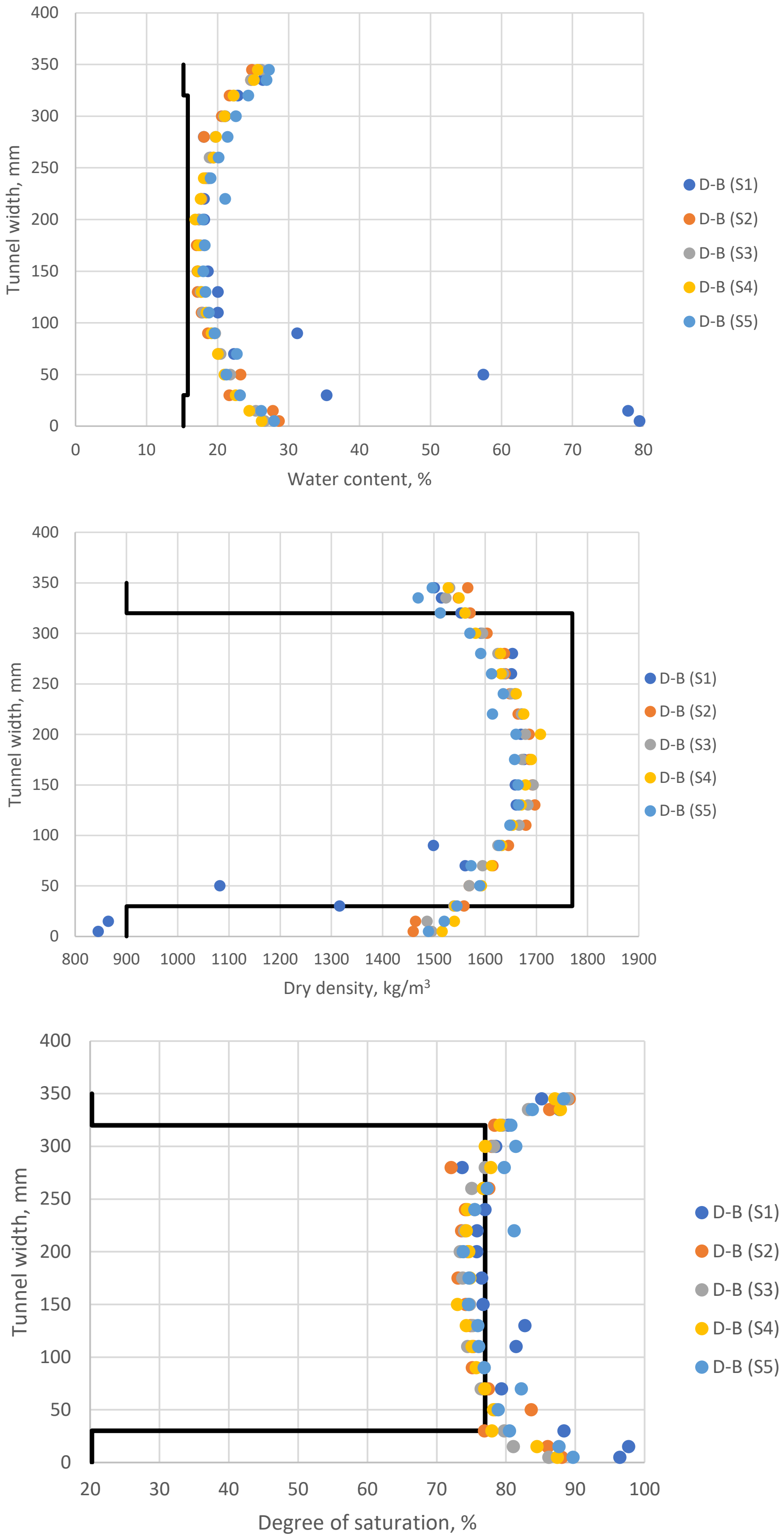


Figure 5-15. *Water content (upper), dry density (middle), and degree of saturation (lower) along a horizontal line, positioned at the mid-height of the tunnel, at five different sections in Test 1, see Figure 5-8 and Figure 5-9. The black lines indicate the initial values. Sampling direction B upwards.*

5.6.3 Erosion channels in buffer

The sampling directions of the buffer are shown in the right photo in Figure 5-12. The inflow point in the bottom of the deposition hole corresponds to sampling direction A and is also close to the radial pressure measurements.

Visual inspection together with the results from the sampling, see Section 5.6.4, showed that there was a rather clear, vertical, erosion channel along most of the deposition hole. The channel started in direction A (sampling levels L1 and L2), continued thereafter in direction C all the way along the canister and one section above (sampling levels L3 to L7), and the last distance to the top (sampling levels L8 and L9) in direction D. The position of the erosion channel had thus changed at two different levels. At most sampling levels, a clear erosion channel with wetted parts around it, could be identified, Figure 5-16. Close-ups of the erosion channel are provided in Figure 5-17. From the photos, it is obvious that the finest clay particles have eroded away leaving the coarser grains left in the channel.

Figure 5-16. *Test 1. Upper left: Photo showing the block including sampling section L9. The most wetted part was clearly in direction D. Upper right: Erosion channel on the buffer surface (approximately sampling section L8). Lower left: Erosion channel along the buffer (canister section). Note that the outer surface of the buffer has been discoloured by the rubber mat. Lower right: Cross-section of the erosion channel along the canister.*

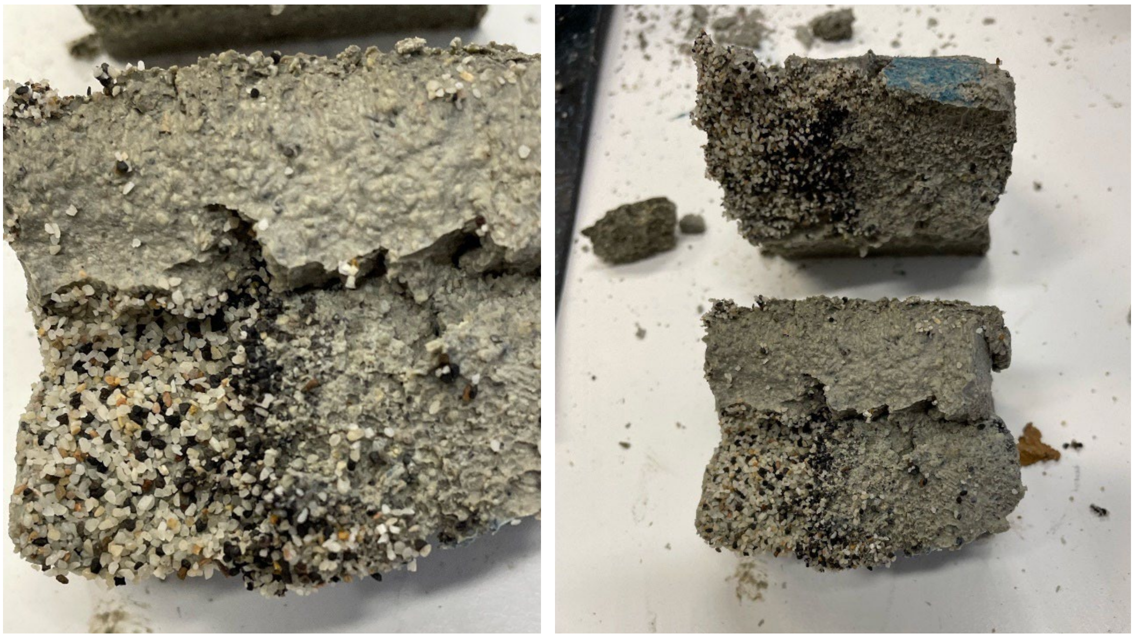


Figure 5-17. *Photos showing close-ups of the erosion channel in Test 1. The finest clay particles have eroded away leaving the coarser grains left in the channel.*

5.6.4 Dismantling and sampling of the deposition hole

Dismantling

The buffer was pushed out from the steel tubes using a hydraulic piston, see photo provided in Figure 5-18. This technique facilitated the following sampling of the buffer.

Figure 5-18. *The buffer was pushed out from the steel tube using a hydraulic piston. The photo shows the removal of the buffer in the section above the canister.*

Water content and dry density distribution

Graphs showing the results from the sampling are provided in Figure 5-19 to Figure 5-27 (corresponding to sampling level L1 to L9). In each figure, there are three graphs showing the water content (upper graph), the dry density (middle graph), and the degree of saturation (lower graph) plotted versus the radial distance from the centre of the deposition hole.

The graphs show that at all sampling levels, there is one direction in which the water content has increased more than in the others. In this direction the dry density has also decreased. This direction is the same as where the erosion channel is positioned. As mentioned in Section 4.6.3, the erosion channel started in direction A (sampling levels L1 and L2), continued thereafter in direction C all the way along the canister and one section above (sampling levels L3 to L7), and the last distance to the top (sampling levels L8 and L9) in direction D. The position of the erosion channel had thus changed at two different levels, at the beginning of the canister and at the end of the canister. It was also noted that the wetting of the buffer had occurred at more than one direction at four of the sampling levels:

- **Sampling level L2**. Besides the wetting in direction A, where the erosion channel seemed to be, the buffer had an increased water content in direction C.
- **Sampling level L3**. Besides the wetting in direction C, where the erosion channel seemed to be, the buffer had an increased water content in direction D.
- **Sampling level L4**. Besides the wetting in direction C, where the erosion channel seemed to be, the buffer had an increased water content in all other directions.
- **Sampling level L7**. Besides the wetting in direction C, where the erosion channel seemed to be, the buffer had an increased water content in direction D.

The sampling shows thus that there was a rather clear vertical erosion channel, but it seems to have changed the periphery position at some levels, and it has also changed position at different times during the test.

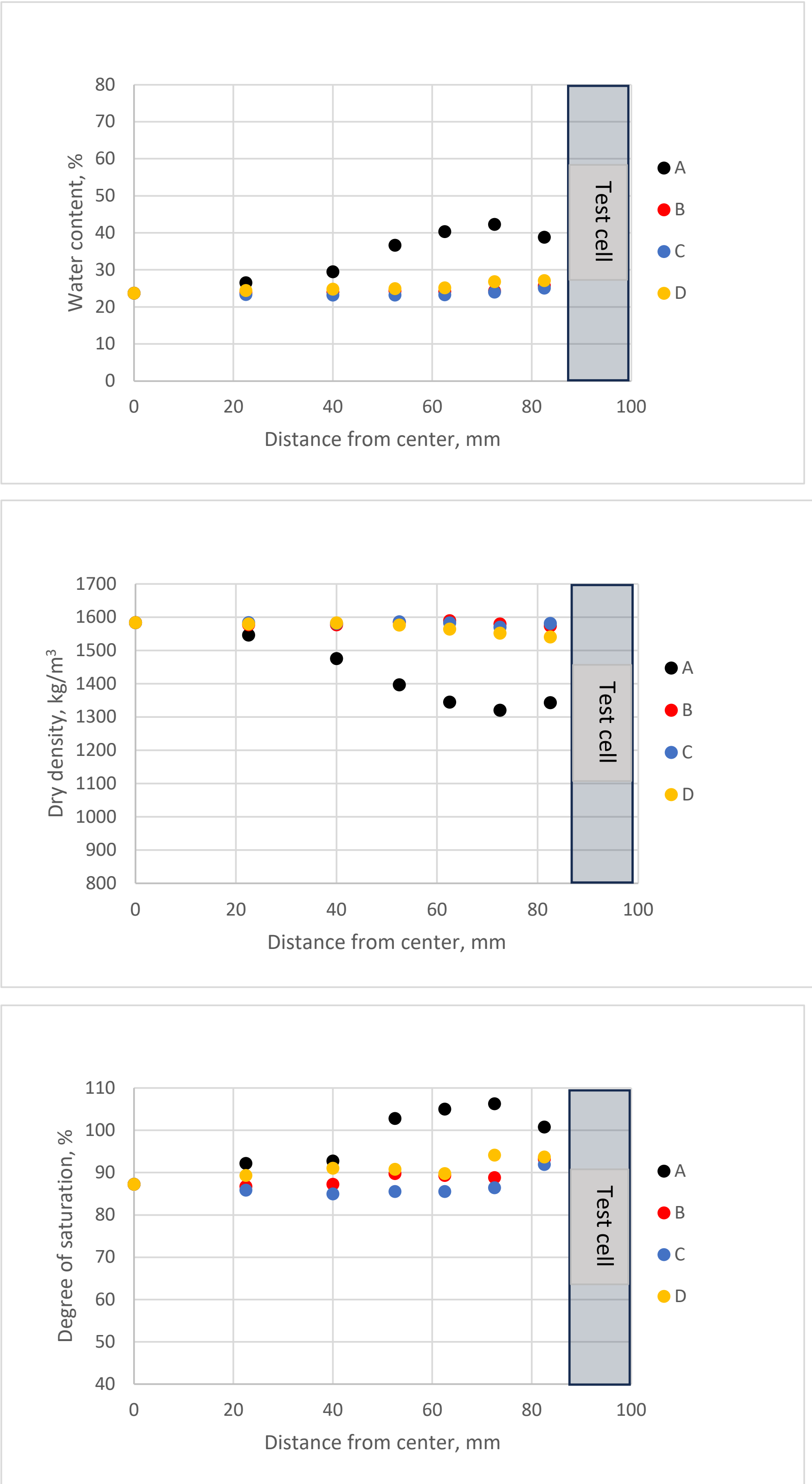


Figure 5-19. *Results from measurements in sample section L1 (bottom block) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

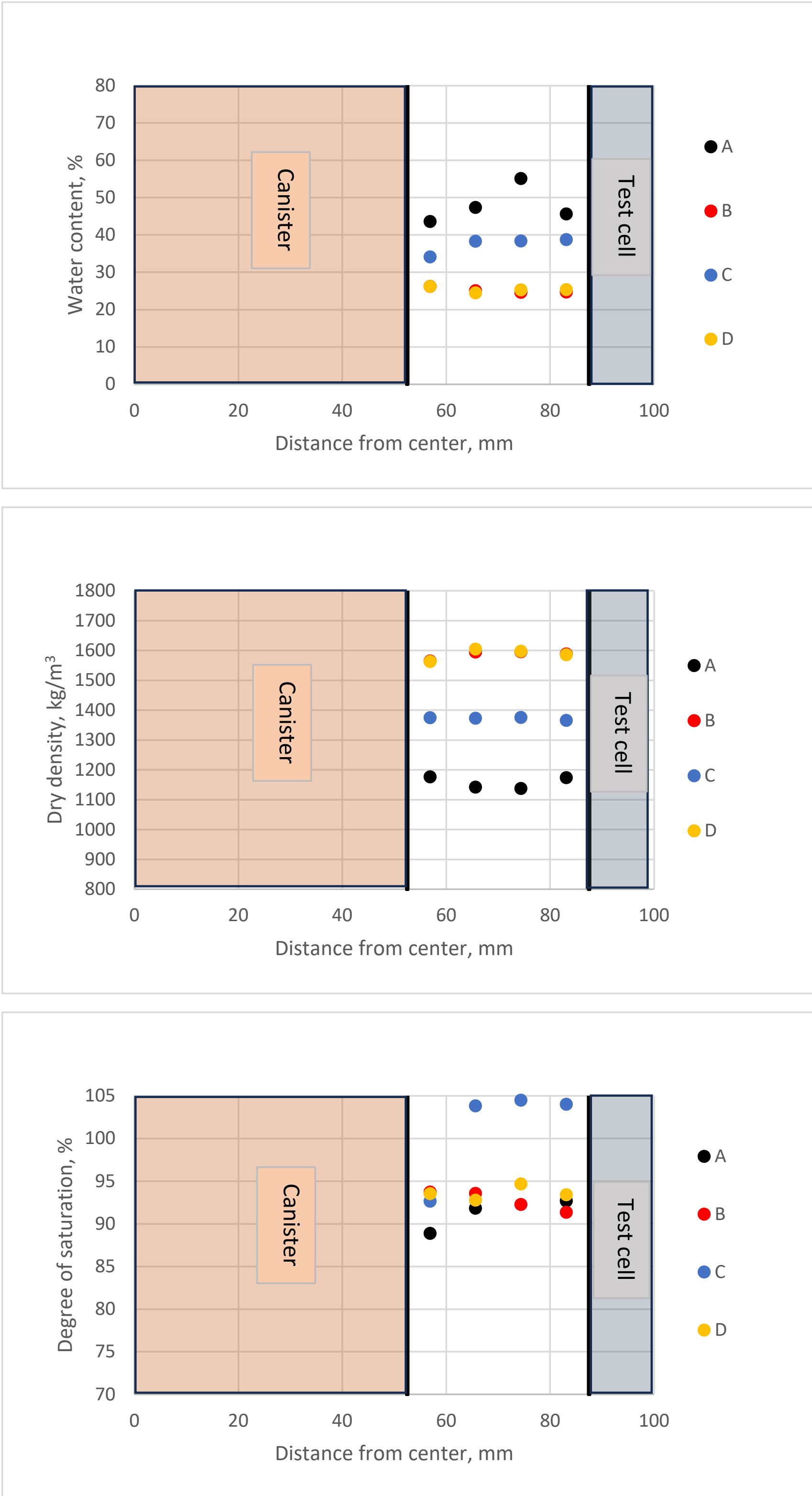


Figure 5-20. *Results from measurements in sample section L2 (along canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

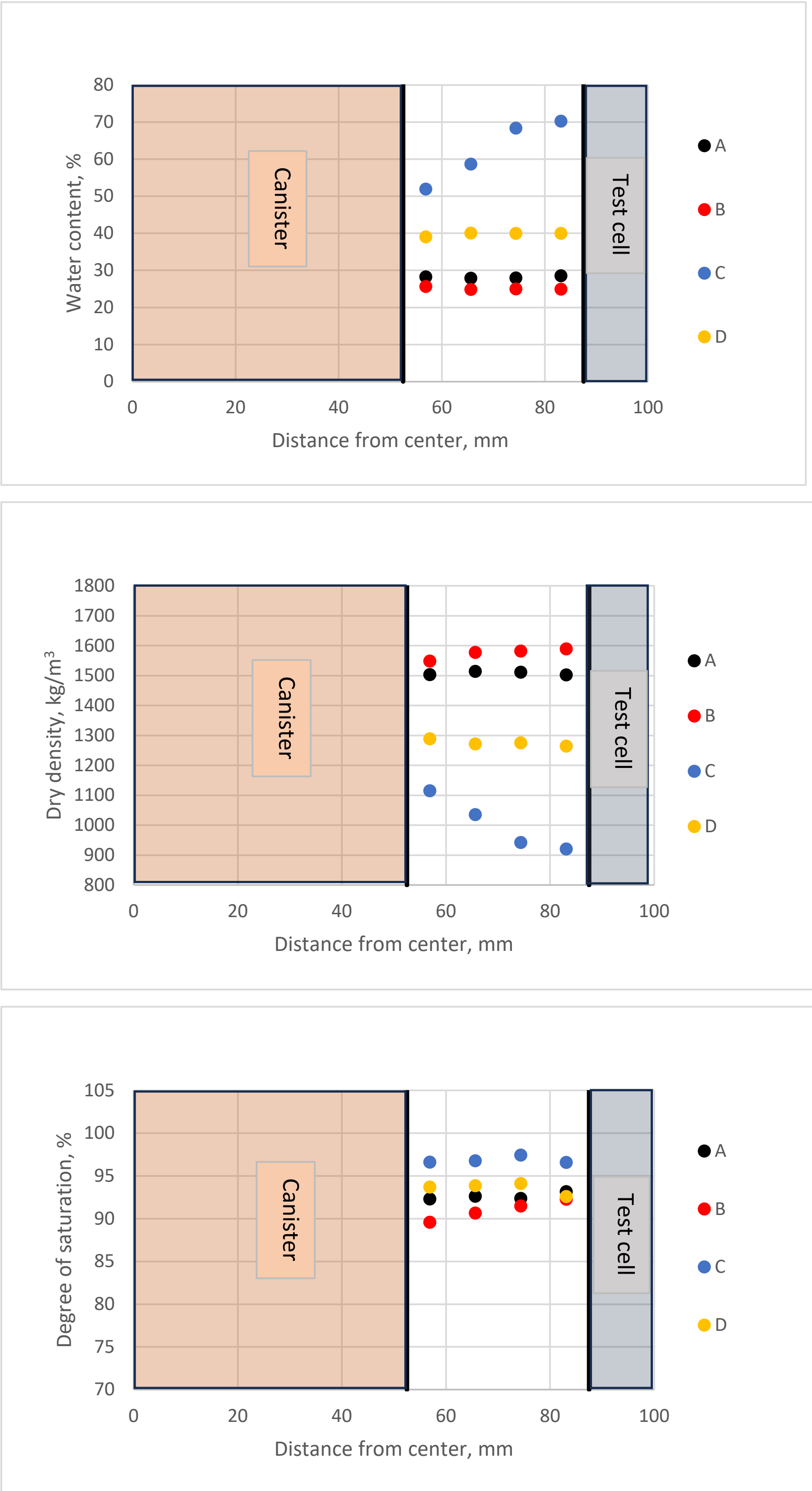


Figure 5-21. *Results from measurements in sample section L3 (along canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

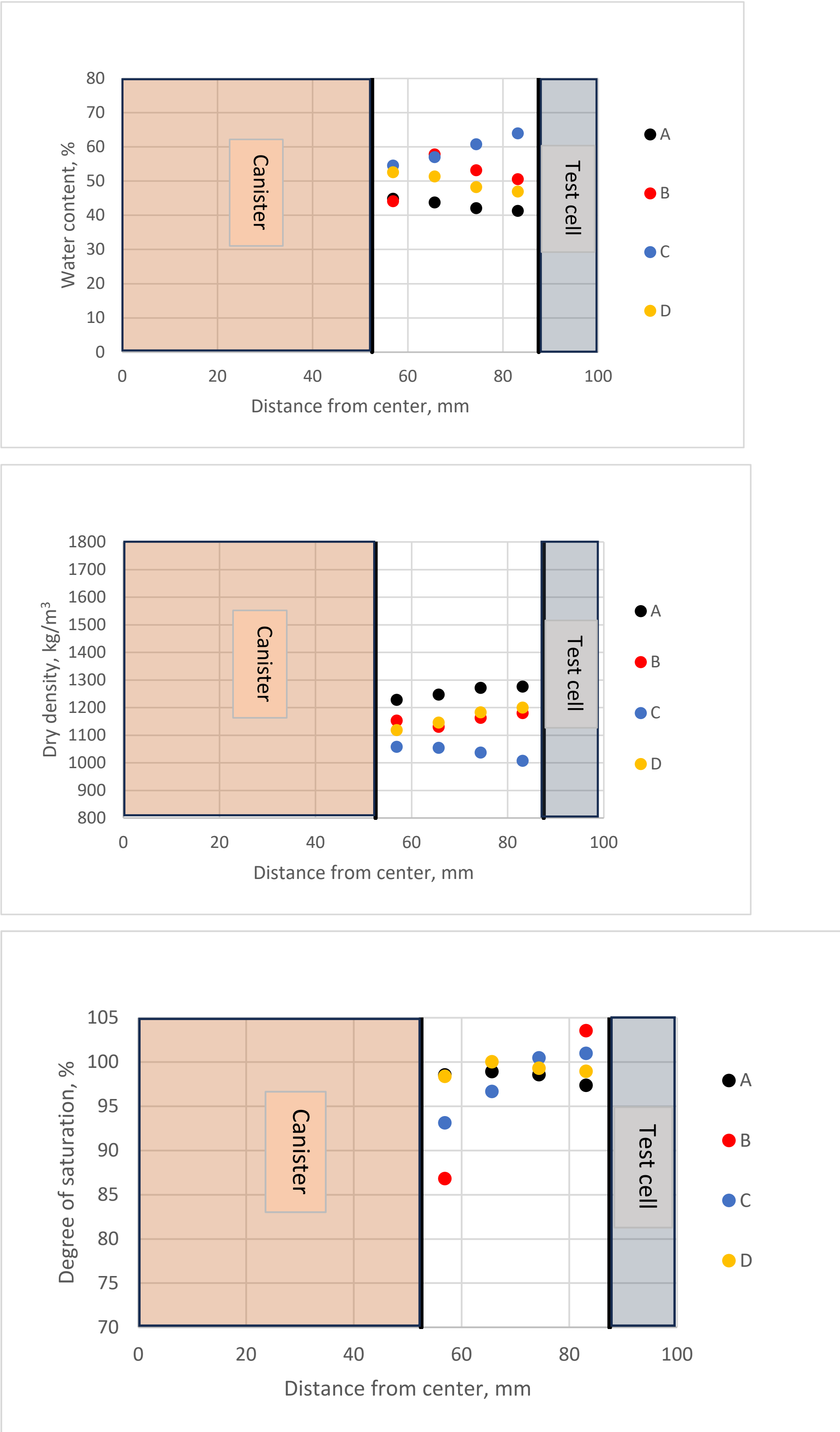


Figure 5-22. *Results from measurements in sample section L4 (along canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

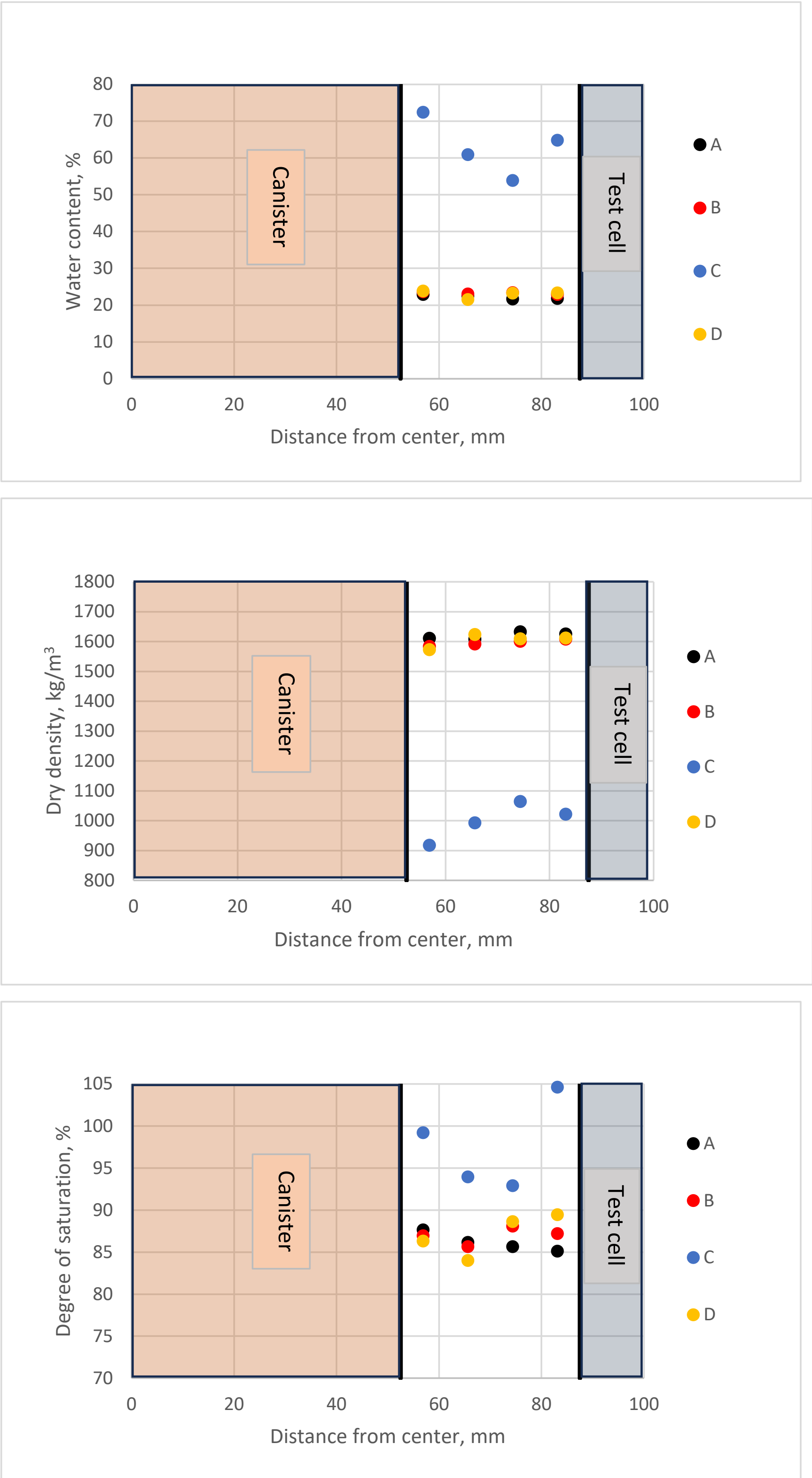


Figure 5-23. *Results from measurements in sample section L5 (along canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

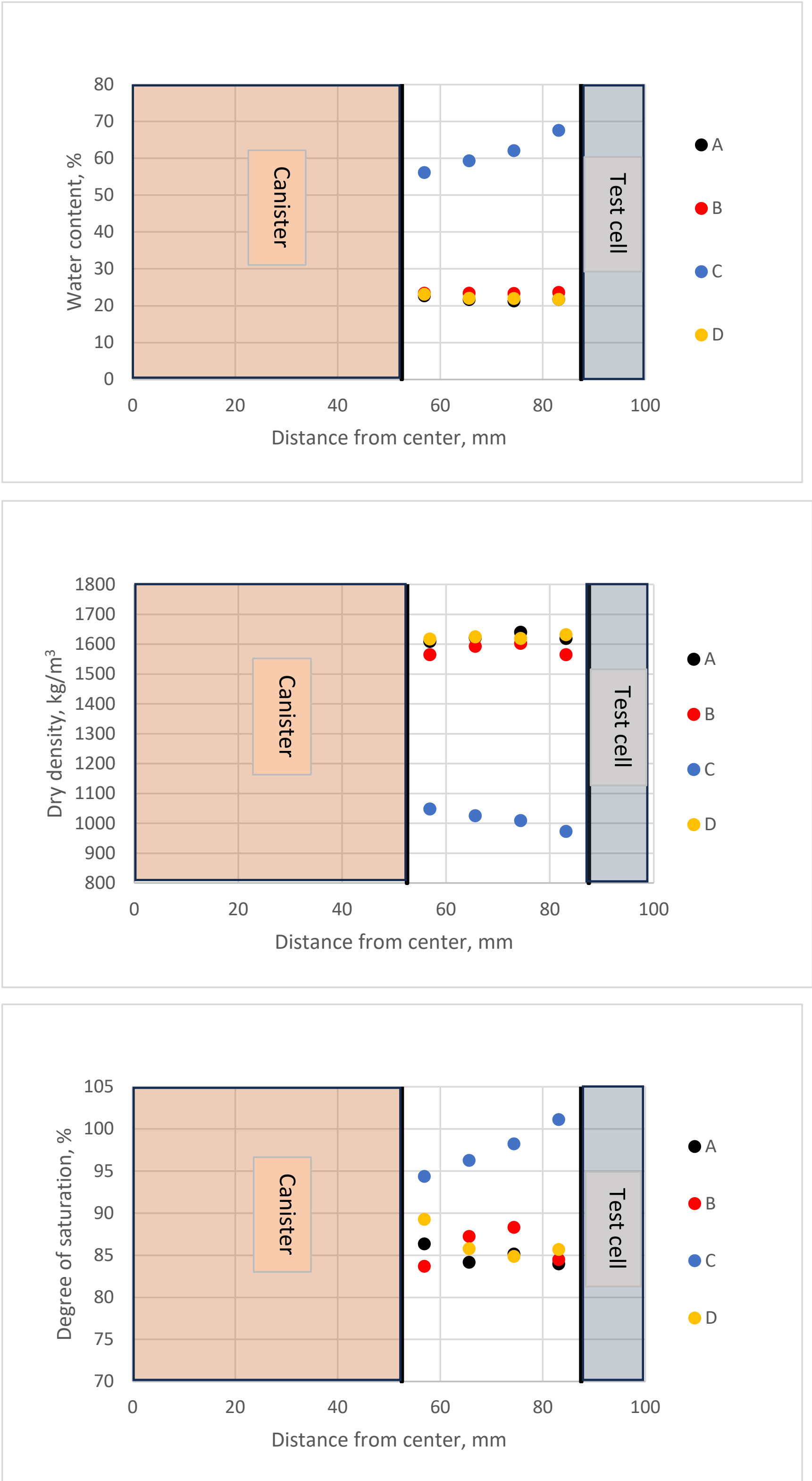


Figure 5-24. *Results from measurements in sample section L6 (along canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

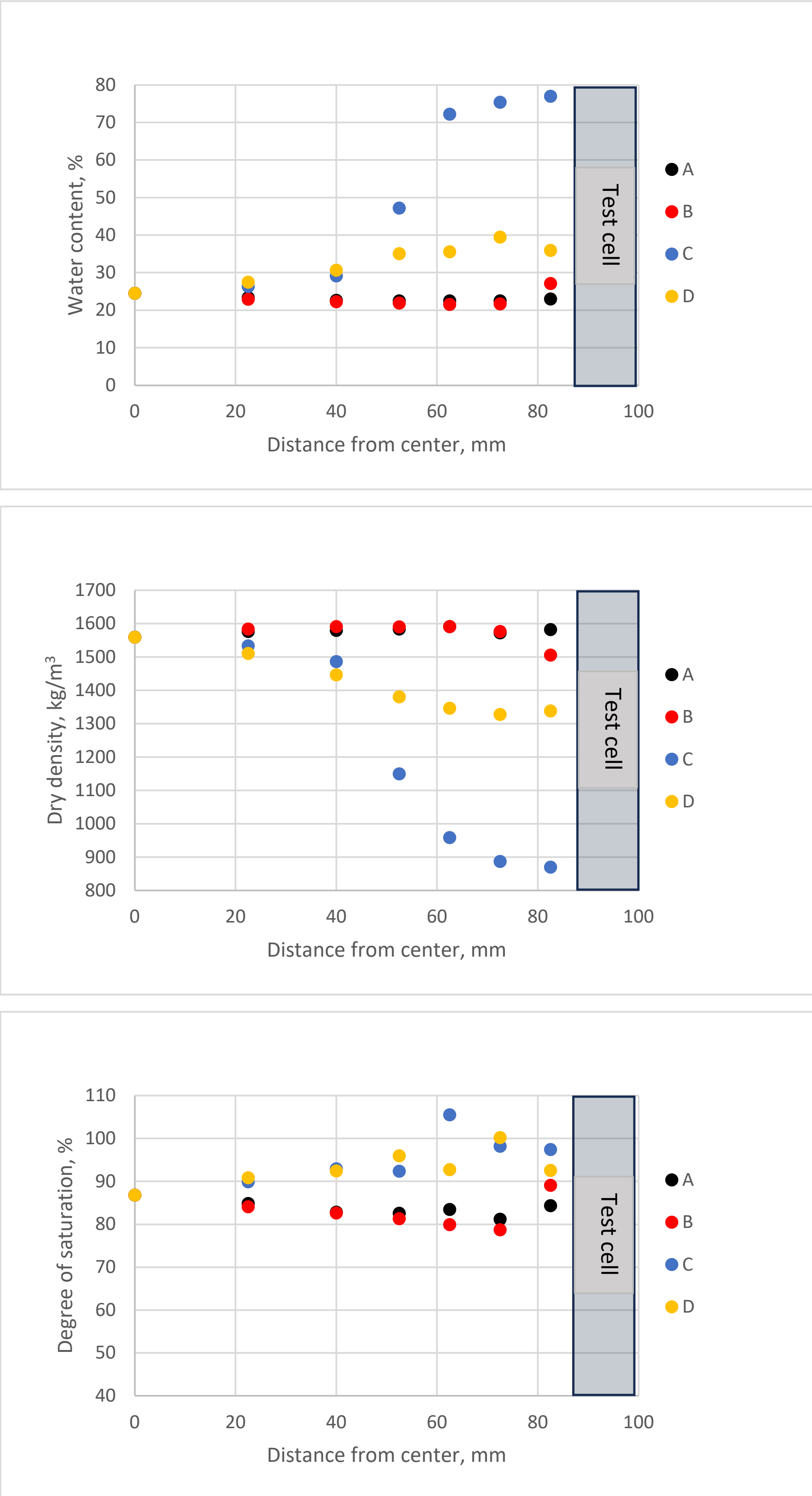


Figure 5-25. *Results from measurements in sample section L7 (above canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

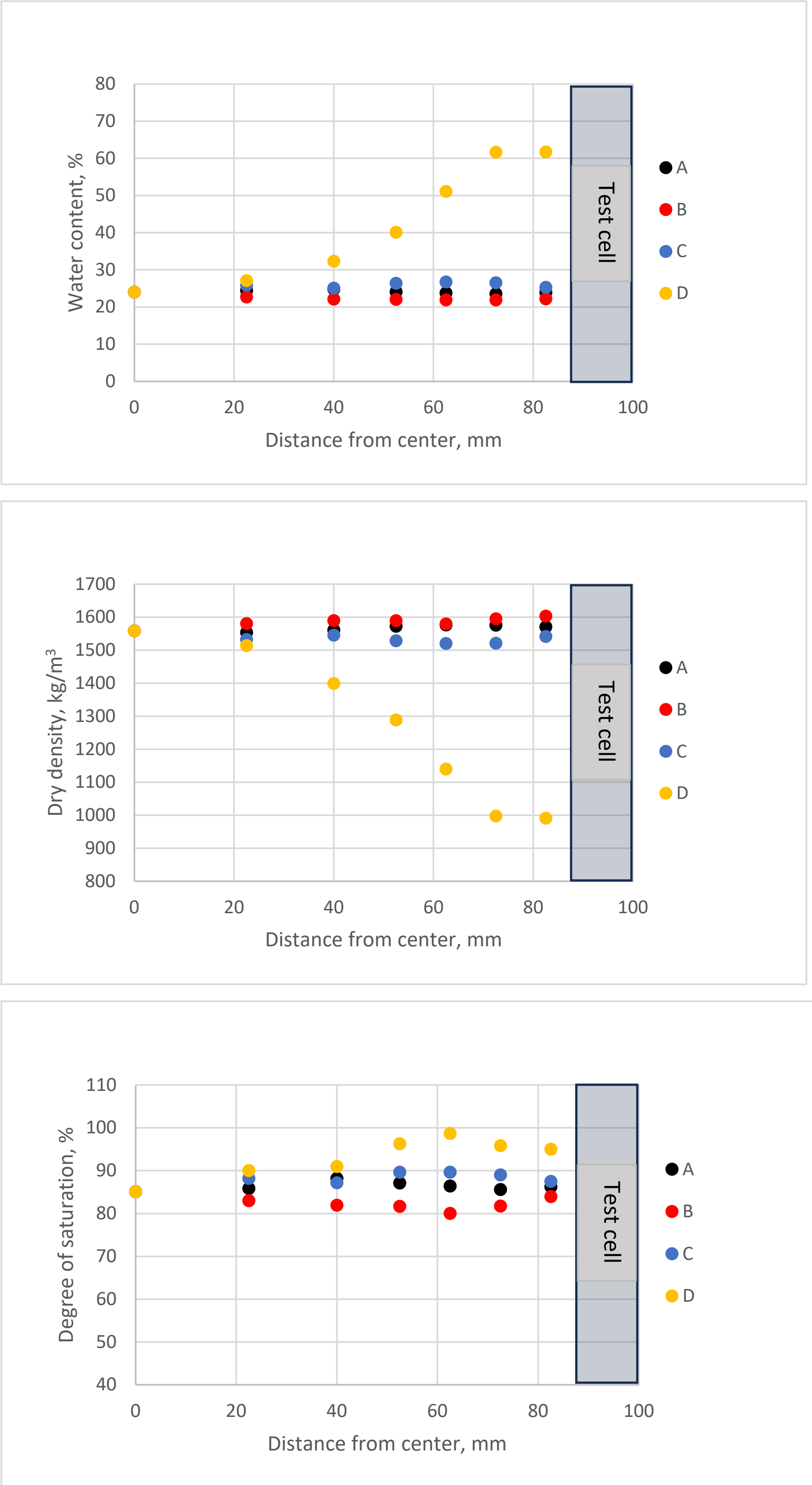


Figure 5-26. *Results from measurements in sample section L8 (above canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

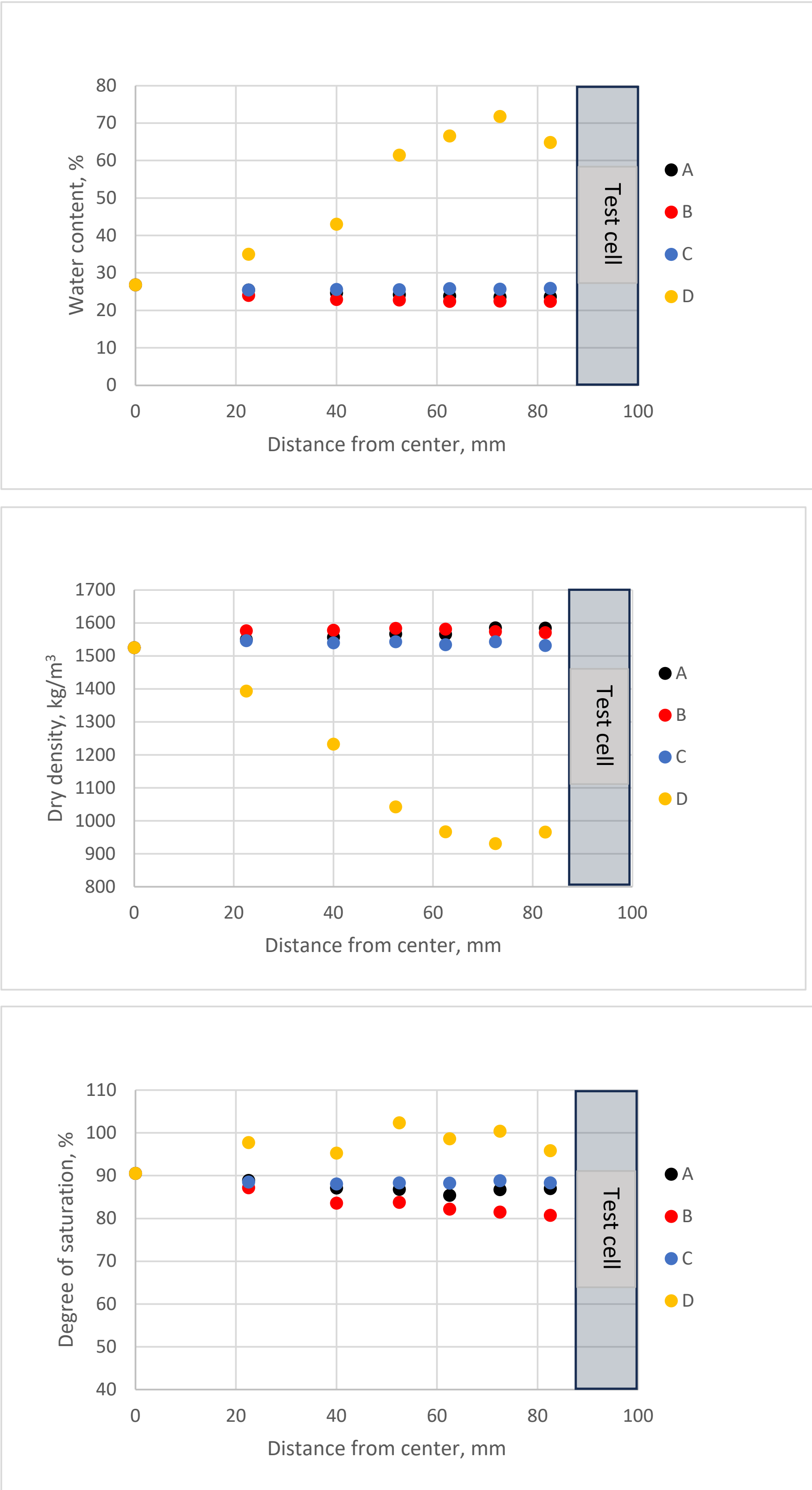


Figure 5-27. *Results from measurements in sample section L9 (above canister) in Test 1. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

5.7 Compilation of data

5.7.1 Water content and dry density distribution of the backfill

The sampling of the backfill is described in Section 5.6.2. The sampling included 195 positions and was judged to give a good picture of the status of the backfill regarding water content and dry density distribution.

From the photos taken in conjunction with the dismantling of the backfill, Figure 5-11 to Figure 5-13, it is obvious that the pellet filling at the top of the tunnel and between the block stack and the walls at the long sides have been largely wetted. This was also shown in the graphs showing the results from the sampling, Figure 5-14 and Figure 5-15. Water has also entered the gaps between the backfill blocks and by that “glued” them together. The blocks have swelled to some extent and by that compressed the low-density pellet fillings.

5.7.2 Water content and dry density distribution of the buffer

To give a picture of the status of the complete deposition hole regarding water content, dry density, and degree of saturation distribution, contour plots were made using an interpolation program, Figure 5-28, Figure 5-29, and Figure 5-30. The contour plots show the water content, the dry density, and the degree of saturation distribution in the four vertically sampled cross-sections (direction A, B, C, and D) of the deposition hole.

The contour plots show clearly that the wetting (erosion channel) has mainly occurred in direction C along the canister and in direction D in the uppermost part of the deposition hole, Figure 5-28. The wetting of the bottom block and the first ring-shaped block was in direction A, but also partly in direction C. The differences in water content between different parts of the buffer are large, in general between 20 and 70 %.

The dry density in the erosion channel (at the top and along the canister) was mainly between 900 and 1400 kg/m^3 which should be compared to the installed average dry density (1564 kg/m^3). This means that significant amounts of bentonite material had eroded away from parts of the deposition hole.

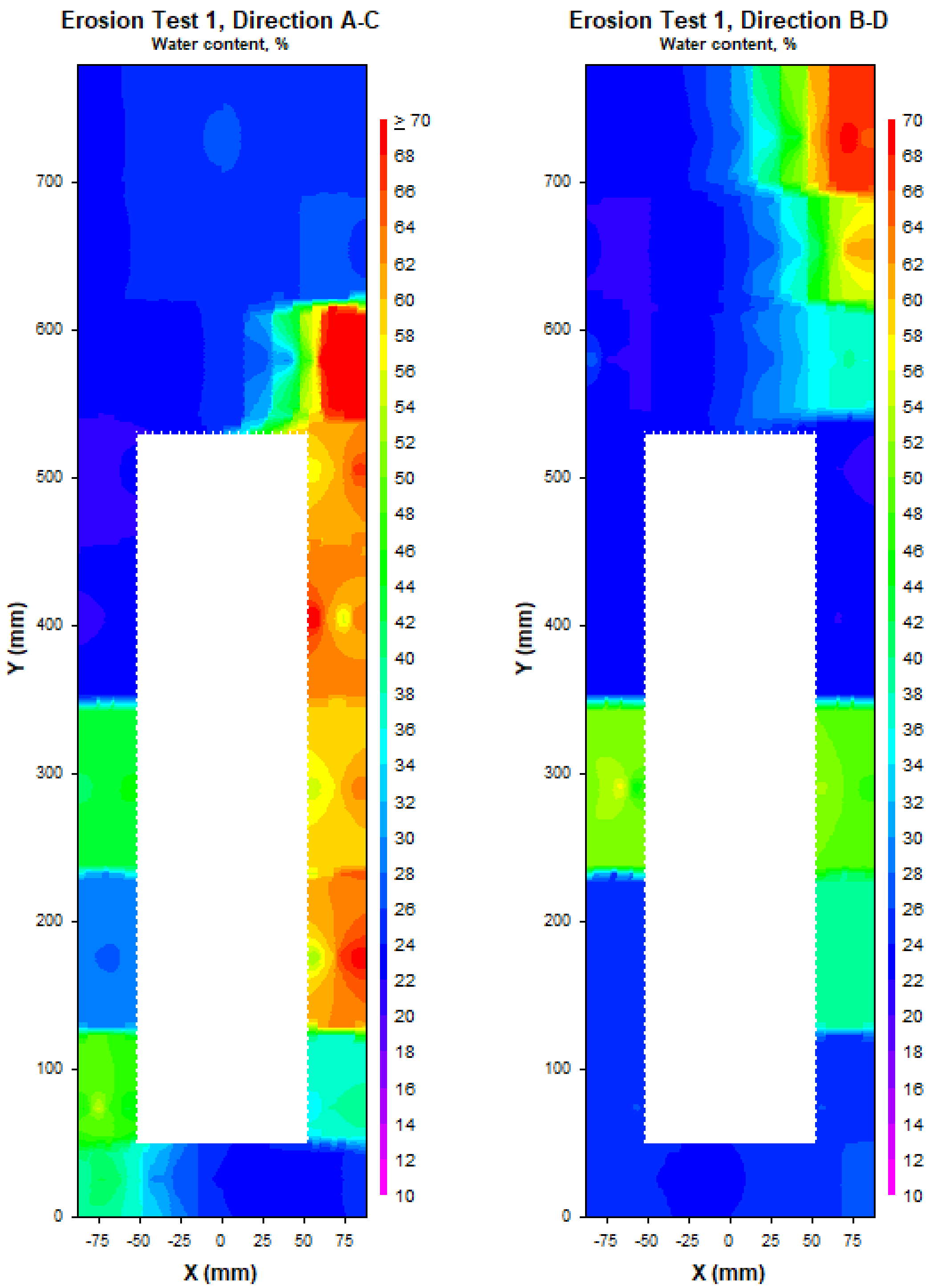


Figure 5-28. *Contour plots showing the water content distribution in the four sampled directions (A, B, C, and D) of the deposition hole in Test 1.*

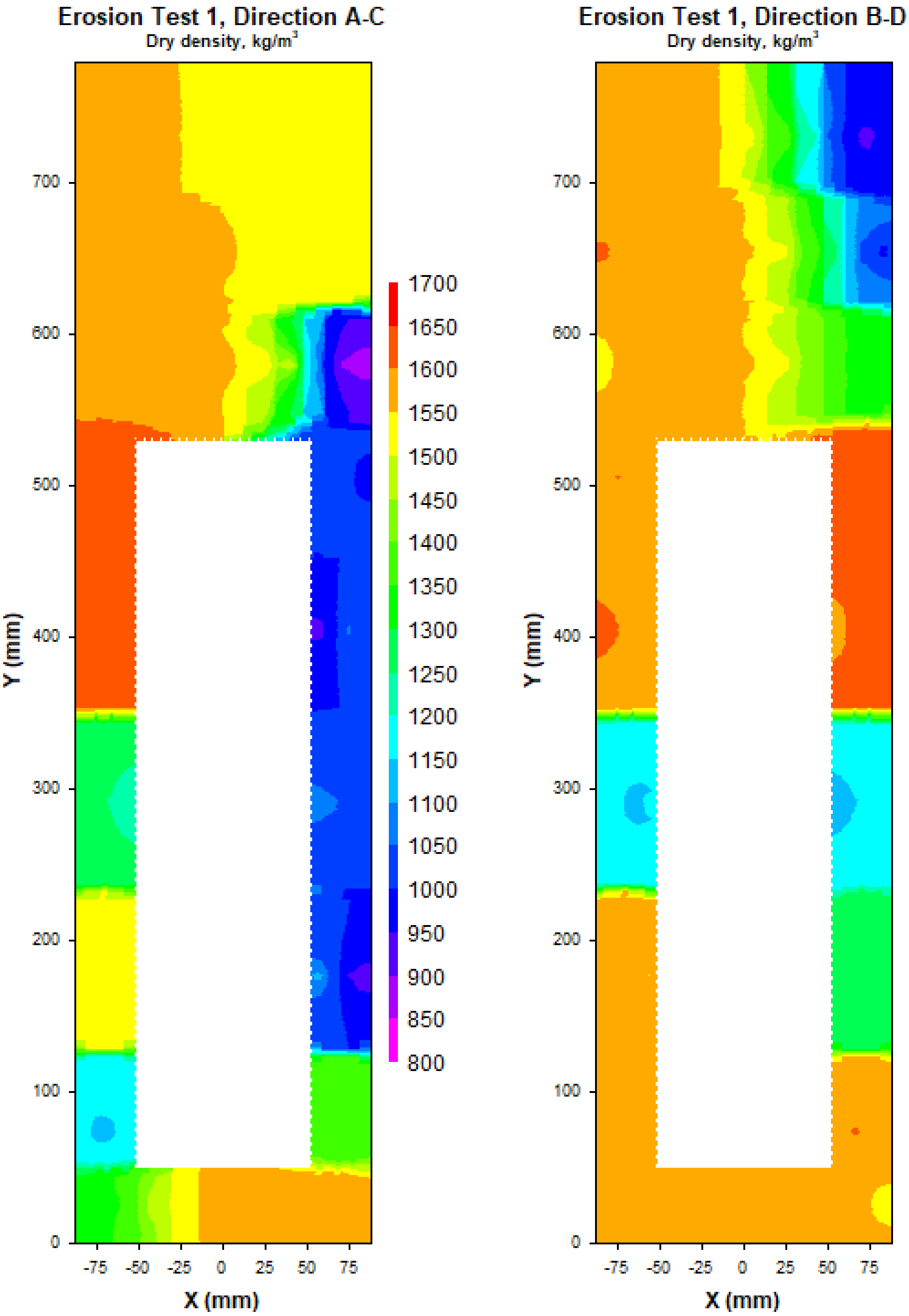


Figure 5-29. *Contour plots showing the dry density distribution in the four sampled directions (A, B, C, and D) of the deposition hole in Test 1.*

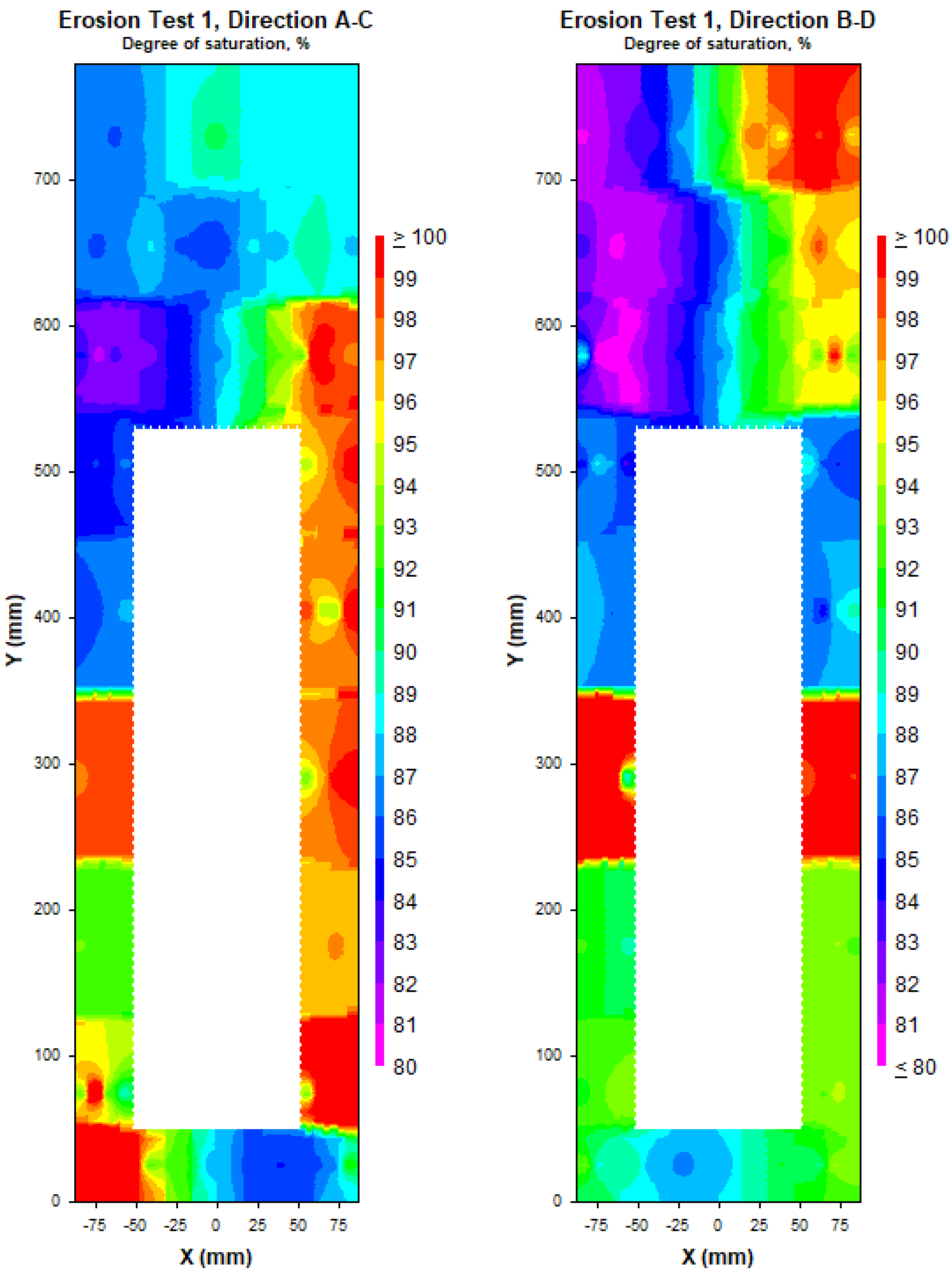


Figure 5-30. *Contour plots showing the degree of saturation distribution in the four sampled directions (A, B, C, and D) of the deposition hole in Test 1.*

5.7.3 Eroded backfill and buffer

General

The total dry mass of bentonite that had eroded from the test setup was 4.8 kg. How this amount was distributed between the deposition hole and the deposition tunnel is not exactly known. However, an attempt to estimate the amount of bentonite eroded from the deposition hole has been made:

1. **Visual inspection**. A visual inspection of the backfill, especially when it comes to the bentonite mass at the tunnel ceiling, showed that a large amount of bentonite seems to have eroded from the backfill here. A visual inspection of the buffer, see e.g. photos provided in Figure 5-16, showed that the erosion channel was very easy to identify but also that the amount of bentonite lost from the buffer must be smaller compared to the backfill.
2. **Weighting the samples against their representative volume.** In conjunction with the excavation, samples were taken at 180 positions in the deposition hole. The average of each measured density was weighted against the volume of the buffer that it represented (a function of the radius of the location of the sample and the vertical distance to the samples below and above). With this method it was possible to calculate a weighted dry density in the deposition hole. Since the buffer volume was known it was possible to calculate the dry total mass that this new density represented and then compare this mass with the total installed mass.

Buffer

The average dry density of the buffer after installation was determined to 1564 kg/m^3 (installed dry mass=22.8 kg). The new average dry density of the buffer after having performed the erosion test was calculated in three separate ways:

1. Average dry density. The average dry density using data from all sampling positions in the deposition hole.
2. Weighting 1. The sampling was done in four directions and one of these directions was towards the erosion channel (minor adjustments of the sampling directions were made in conjunction with excavation so that one direction always was pointing at the erosion channel). The samples from this direction represents thus a quarter of the buffer volume (25 %).
3. Weighting 2. When looking at the photos of the buffer and the erosion channel, Figure 5-16, it is obvious that the part of the buffer including the erosion channel must be much smaller than 25 %, perhaps half of this volume. A calculation where it was assumed that the erosion channel proportion instead is 12.5 % was also made.

Data from the three types of evaluation are provided in Table 5-1. The mass loss from the buffer varies between 1.63 and 2.36 kg which corresponds to between 7.1 and 10.3 % of the installed dry mass.

Table 5-1 Installation and erosion data (upper part of the table) and calculations of the proportion of eroded material from the buffer and from the backfill (lower part of the table).

Test 1	**Dry density** kg/m^3	**Mass** kg
Buffer installation	1564	22.8
Backfill installation	1496	245.1
Measured erosion		4.8

Calculations after erosion	**Buffer**			
Type of evaluation	**Dry density** kg/m^3	**Mass** kg	**Mass loss** kg	**Mass loss** %
Average density (not weighted)	1426	20.78	2.03	8.9
Weighted density (1/4)	1403	20.45	2.36	10.3
Weighted density (1/8)	1453	21.18	1.63	7.1

Backfill

The total installed dry mass of the backfill was 245.1 kg. The total eroded dry mass from the test setup was determined to be approximately 4.8 kg. According to the calculations described above, the loss of material from the buffer was between 1.63 and 2.36 kg. This means that the loss of backfill material due to erosion was approximately 2-3 kg, which corresponds to approximately 1 % of the dry backfill mass installed in the test.

6 Test 2 (0.02 l/min)

6.1 Preparation of the test

The assembling of the deposition hole and the deposition tunnel was done in the same way as for Test 1, see description in Section 5.1 and 5.2.

6.2 Installation data

Detailed data regarding the blocks and pellets in the deposition hole and the deposition tunnel is provided in Appendix 3 and 4. A compilation of the most important data is provided below.

6.2.1 Deposition hole

The dry density of the ring-shaped blocks varied between 1690 to 1734 kg/m^3 and between 1647 and 1674 kg/m^3 for the solid blocks. The dry density of the pellet filling was 971 kg/m^3.

The average dry density of the buffer in the deposition hole was 1565 kg/m^3 (1550 kg/m^3 for the section with ring-shaped blocks and 1582 kg/m^3 for the sections with solid blocks). The density of the section with ring-shaped blocks was somewhat lower than the target dry density which was 1580 kg/m^3.

6.2.2 Deposition tunnel

The total dry mass of the installed backfill blocks was 193.53 kg. The total dry mass of the pellets was 52.91 kg. The backfill block stack had a dry density of 1732 kg/m^3 and the pellet filling had a dry density of 1016 kg/m^3. The block filling degree in the tunnel was 68.2 % and the average dry density of the backfill in the deposition tunnel was 1505 kg/m^3.

6.3 Registered data

6.3.1 Test start and regular control of test parameters

Test start

In Test 1 (0.05 l/min) there were large water pressure changes during the first eight days after test start, see graph provided in Figure 5-7, indicating that the bentonite swelled and sealed the piping/erosion channels. With the lower inflow rate used in Test 2 (0.02 l/min), problems were expected regarding high water pressures since the bentonite probably could seal any piping/erosion channels easier. Therefore, it was decided to apply a higher water flow rate, 0.05 l/min, until a piping/erosion channel had been established, and after that decrease the flow rate to 0.02 l/min.

After having started the test, it took about six hours until the first water outflow from the deposition tunnel was noticed. This means that approximately eighteen litres were injected before any outflow occurred. The water inflow rate was after 23 hours test duration adjusted to 0.02 l/min. No problems with high water pressure occurred.

Water flow rate

The flow rate out from the deposition tunnel was checked regularly. Before emptying the sedimentation vessels to determine the amount of eroded material, the outflowing water from the last sedimentation vessel was collected during a defined time (20 minutes). The amount of water flowing out during this test time was weighed and then the flow rate could be calculated. These measurements were made to ensure that the intended flow rate was kept at the right level.

Results from the water flow measurements are presented in Figure 6-1. After the higher initial flow rate of 0.05 l/min for 23 hours, the set flow rate was adjusted to 0.02 l/min. The deviations from the set value on the dose pump were rather small.

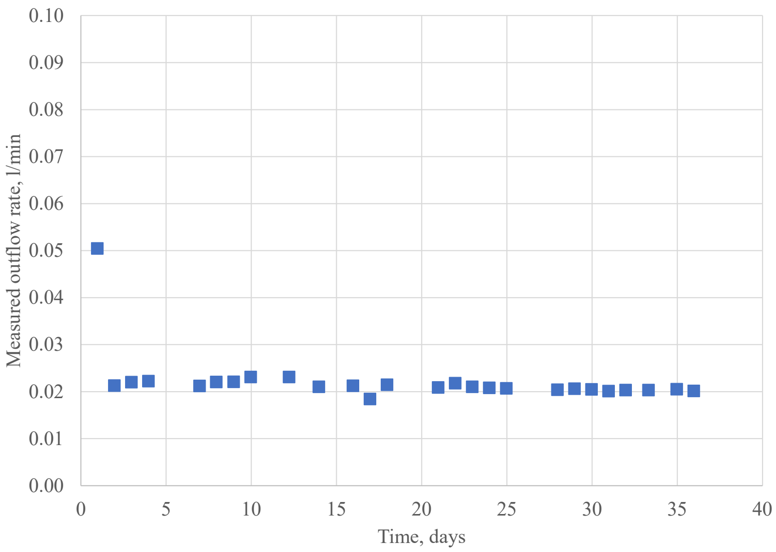


Figure 6-1. *The measured outflow rate plotted versus time for Test 2. The inflow rate was at test start 0.05 l/min but was after 23 hours test duration decreased to 0.02 l/min.*

Salinity of water

The salt content in the water is believed to be an important parameter influencing the erosion properties of bentonite. In conjunction with the determinations of the water flow rate, see above, one sample was taken from the reservoir with mixed water. The sample, approximately 0.8 litres, was weighed and dried in an oven and the amount of salt left determined.

The results from the measurements are presented in Figure 6-2. The results are quite consistent with the intended target although the salt content has varied somewhat, mainly between 0.95 and 0.99 %.

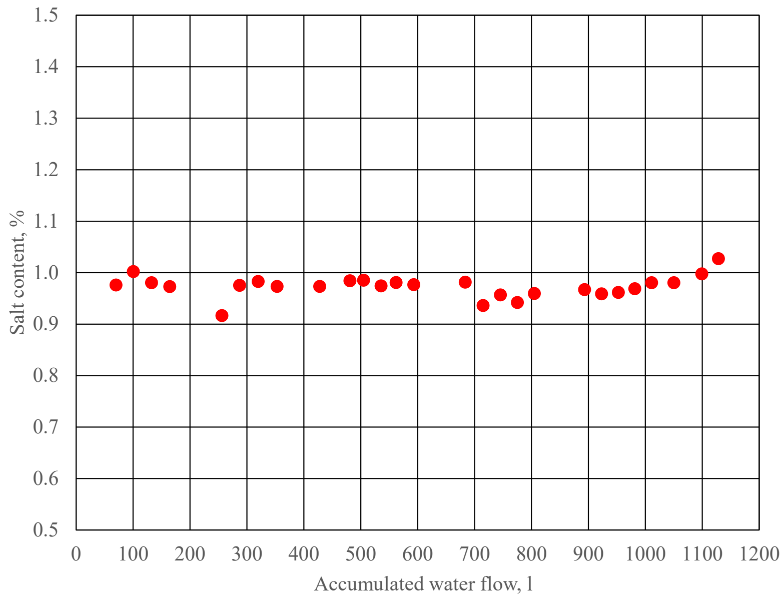


Figure 6-2. *Results from measurements of the salt content plotted versus the accumulated water flow for Test 2.*

6.3.2 Erosion measurements

The erosion rate was determined by collecting all sedimented material from the three sedimentation vessels at decided intervals, normally between three to five times a week. The accumulated amount of sedimented material during a known period was collected and decanted. The bentonite solution was put in aluminium vessels with a determined weight. The vessels, including the solution of bentonite and water, were weighed and thereafter put in an oven at a temperature of 105°C. After drying, which took about 48 hours, the vessels including the dry mass were weighed again and the amount of dry bentonite could be calculated. In the calculations it was compensated for the mass of salt present in the evaporated water.

The results from the erosion measurements are provided in Figure 6-3 and Figure 6-4. In Figure 6-3 the results are presented as the accumulated amount of eroded material plotted versus the accumulated amount of water outflow (upper figure shows the result in a lin-lin graph and the lower in a log-log graph). The graph provided in Figure 6-4 shows the results as the bentonite concentration in the outflowing water plotted versus the accumulated amount of water outflow.

The erosion rate was rather constant the first two weeks but on day 15 (after just over 500 litres outflow) there was a stop in the water outflow. Because of this stop, the water injection pressure increased to almost 0.4 MPa, see graph in Figure 6-5. The outflow stop lasted for approximately four hours, and after that the erosion rate increased largely the next 24 hours, see graphs provided in Figure 6-3. The bentonite concentration in the outflowing water generally varied between 1 and 13 g/l during the test, and after the outflow stop, the concentration reached a maximum of 16 g/l, Figure 6-4.

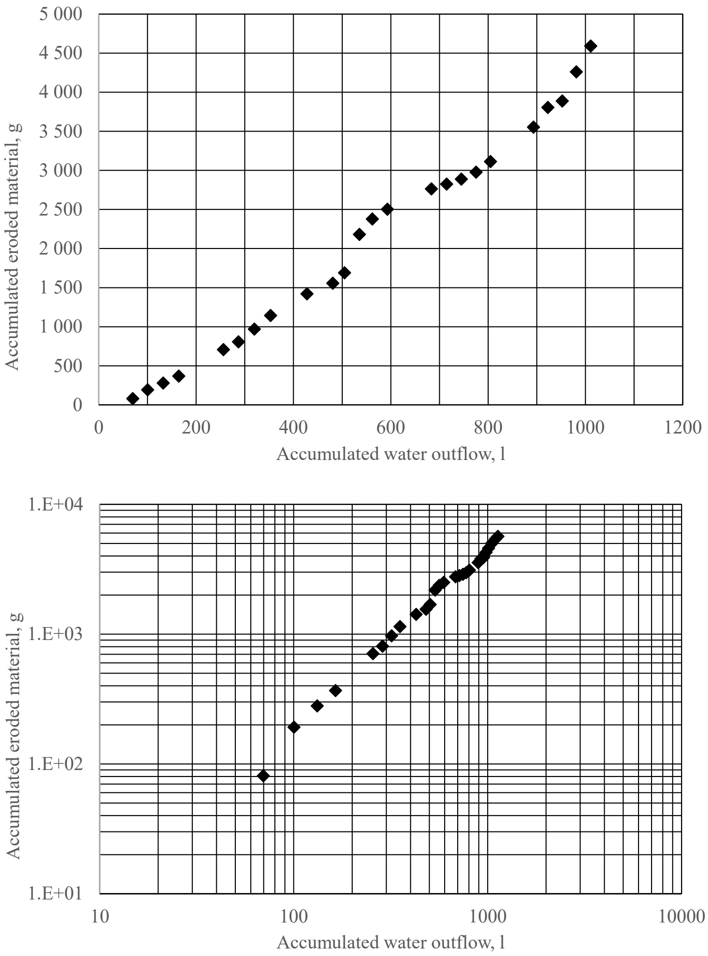


Figure 6-3. *The accumulated eroded material plotted versus the accumulated water outflow for Test 2. Upper: The results presented in a lin-lin graph. Lower: The results presented in a log-log graph.*

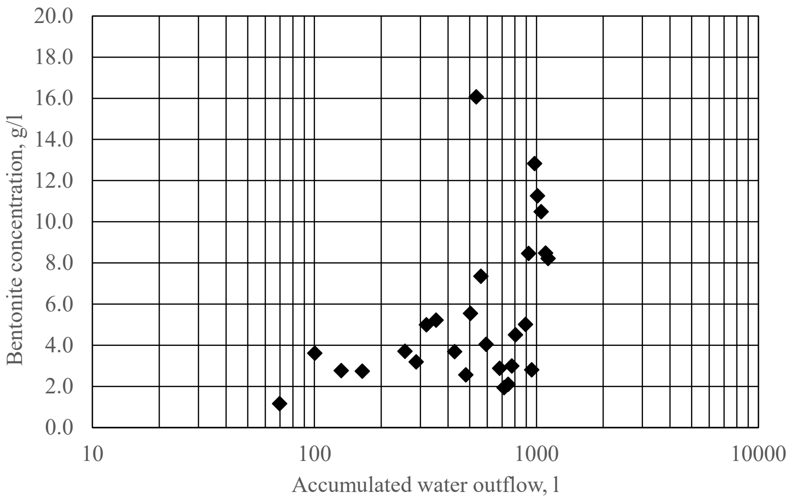


Figure 6-4. *The bentonite concentration plotted versus the accumulated water outflow for Test 2.*

6.3.3 Water injection pressure

A dose pump was used to achieve a constant water inflow rate to the test. Keeping the inflow at a constant level caused the water pressure to increase if the flow resistance in the test cell increased e.g. depending on swelling bentonite.

The water injection pressure on the inflowing water was registered continuously during the test time. The results from the water injection pressure measurements are presented in Figure 6-5 (blue line) together with the measurements of the radial total pressure in the deposition hole. As shown in the graph, the water injection pressure varied somewhat during the first two days, mainly between 0.1 to 0.2 MPa, but after these two days the registered pressure was at a very low level. However, after 15 days of test duration, there was a sudden increase in the water injection pressure. This was due to a stop of the outflowing water, see description in Section 6.3.2. After this short-term pressure increase, the injection pressure again dropped to a very low level.

6.3.4 Radial total pressure in deposition hole

The radial total pressure was measured at three positions along the deposition hole, see description in Section 2.3.2. The results from the measurements are presented in Figure 6-5.

All three sensors reacted almost immediately after the test started and registered after about 24 h a pressure between 0.2 and 0.65 MPa. After that, there was a decrease in pressure for the Lower and Middle sensor. After 10 days test duration, all three sensors showed an increase in pressure and before dismantling, the registered pressure varied between 0.85 and 0.95 MPa at all three positions. The registered pressure was low and indicated that the buffer was far from saturation.

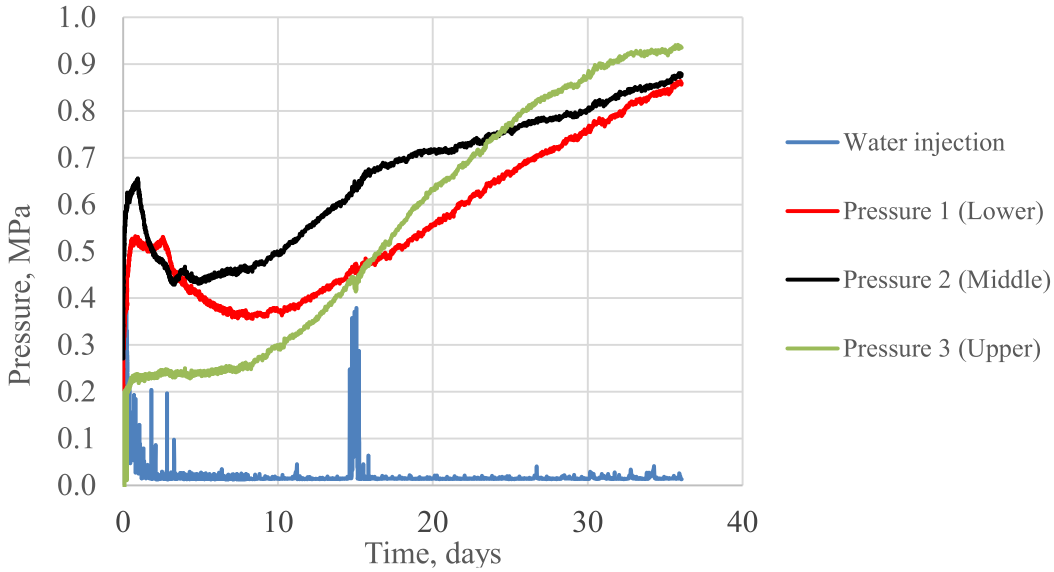


Figure 6-5. *Applied water injection pressure (blue line) and radial total pressure for Test 2, registered at three levels in the deposition hole (red, black and green lines) plotted versus time.*

6.4 Dismantling

The dismantling of the test and the sampling were performed in the same way as described for Test 1, see Section 5.5.

6.5 Results from sampling

In addition to the sampling to determine the water content and dry density distribution, it was important to identify how the water has been flowing and if there were any clear erosion channels within the buffer and backfill.

6.5.1 Erosion channels in backfill

In conjunction with removal of the tunnel ceiling, a large amount of bentonite also was removed (the same as in Test 1), see upper photo in Figure 6-6. The water flowing from the deposition hole has reached the tunnel ceiling in the corner shown on the upper left side in the photos, see also photos provided in Figure 6-7.

After having finished the sampling of the bentonite stuck on the ceiling, the rest of the bentonite was removed. As shown in the lower photo in Figure 6-6, the erosion channel could be seen very clearly on the ceiling surface. The channel started in one of the tunnel corners close to the deposition hole, see red arrow in Figure 6-6, and has thereafter proceeded forward in some loops into the top of the tunnel ceiling, before entering the outflow point.

The left photo in Figure 6-7 shows the position where water flowing from the deposition hole has reached the upper corner of the tunnel (the same corner of the tunnel as in Test 1). The bentonite was very loose here, and it was possible to easily push down a steel rod. The loose bentonite had a water content of about 169 %. The right photo in Figure 6-7 shows the exposed top surface of the deposition hole. The buffer on the left side of the deposition hole (in the photo) was clearly loose and the water inflow from the bottom of the deposition hole seems to have reached the backfill at this point (same side as in Test 1).

Figure 6-6. *Upper: Photo showing the tunnel ceiling after removal of the steel lid in Test 2. Parts of the pellet filling was left on the top of the block stack, see also photos provided in Figure 6-7. Lower: All bentonite has been removed and the erosion channel along the tunnel ceiling can clearly be seen. The red arrow shows the point where the vertical flow from the deposition hole has reached the ceiling. The water then flowed along the ceiling, with some curves against the mid, and has finally reached the outflow point (red/orange flow path).*

Figure 6-7. *Left: Photo showing the tunnel corner were water flowing from the deposition hole have reached the upper corner of the tunnel in Test 2 (see corresponding photo of the tunnel ceiling in the photo above). Right: After removal of all the backfill, the upper part of the buffer in the deposition hole was exposed. The buffer on the left side of the deposition hole was clearly loose and the water inflow from the bottom of the deposition hole seems to have reached the backfill at this point.*

6.5.2 Dismantling and sampling of the deposition tunnel.

Dismantling

After having finished the first sampling of the backfill stuck on the ceiling, see Section 6.5.1, the sampling of the tunnel continued, see photos provided in Figure 6-8. The pellet filled gap between the block stack and the walls had clearly been wet. Water seemed also to partly have entered the small gaps between the blocks and by that "glued" them together. The wetting of the backfill looked very similar to the wetting of the backfill in Test 1

As in Test 1, the sampling of the softer material in the pellet filled gap was done using sharp tools. The backfill blocks were removed using hammer and sharp tools. Most of them could be loosened one by one (some of them fractured), and the following sampling was made using a bandsaw.

Figure 6-8. *Test 2. Upper left: The top lid has been removed. Upper right: The first block layer has been removed. Lower left: The second block layer has been removed. Lower right: The bottom block layer.*

Water content and dry density distribution

The results from the sampling of the backfill are shown in the graphs provided in Figure 6-9 (sampling along five central vertical lines with sampling direction A upwards) and in Figure 6-10 (sampling along five central horizontal lines of the tunnel with sampling direction B upwards), see also sampling plans provided in Figure 5-8 and Figure 5-9. The graphs show the water content (upper graph), the dry density (middle graph), and the degree of saturation (lower graph) plotted versus the tunnel height and the tunnel width respectively.

The graphs show that the water content had increased in most positions in the backfill, but mostly in the pellet filled gaps on the long side walls and in the pellet-filling positioned at the top of the block stack. The influence of the flowing water on the pellet filling on the floor was more limited. The water content had mainly increased in the pellet filling on the floor close to the deposition hole.

The wetting of the backfill had also resulted in an increase of the density in the pellet fillings and a certain decrease of the density in the block stack. Since the test duration was limited, the homogenization process of the backfill had only started.

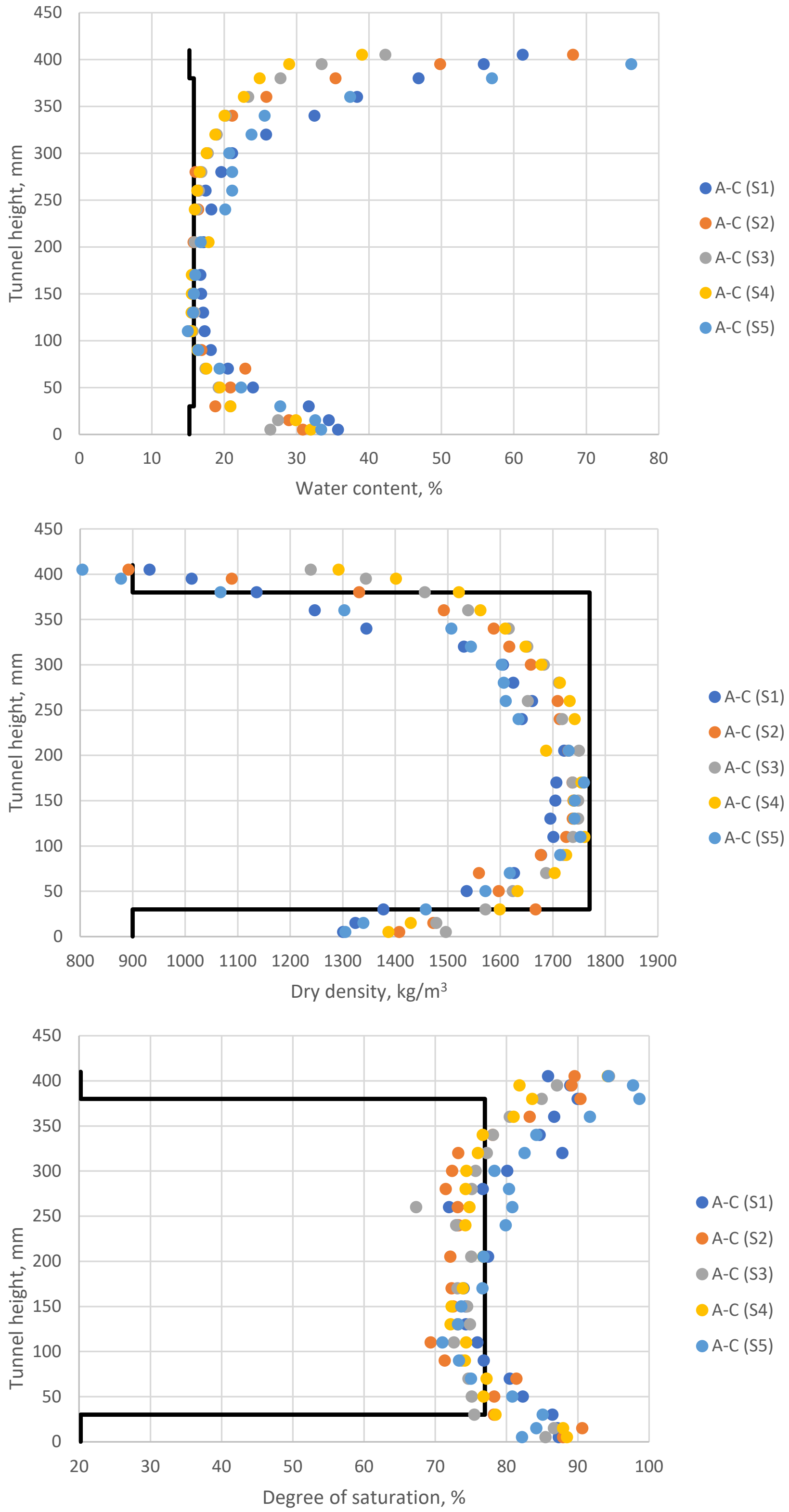


Figure 6-9. *Water content (upper), dry density (middle), and degree of saturation (lower) along central vertical lines at five different sections in Test 2, see Figure 5-8 and Figure 5-9. The black lines indicate the initial values. Sampling direction A upwards.*

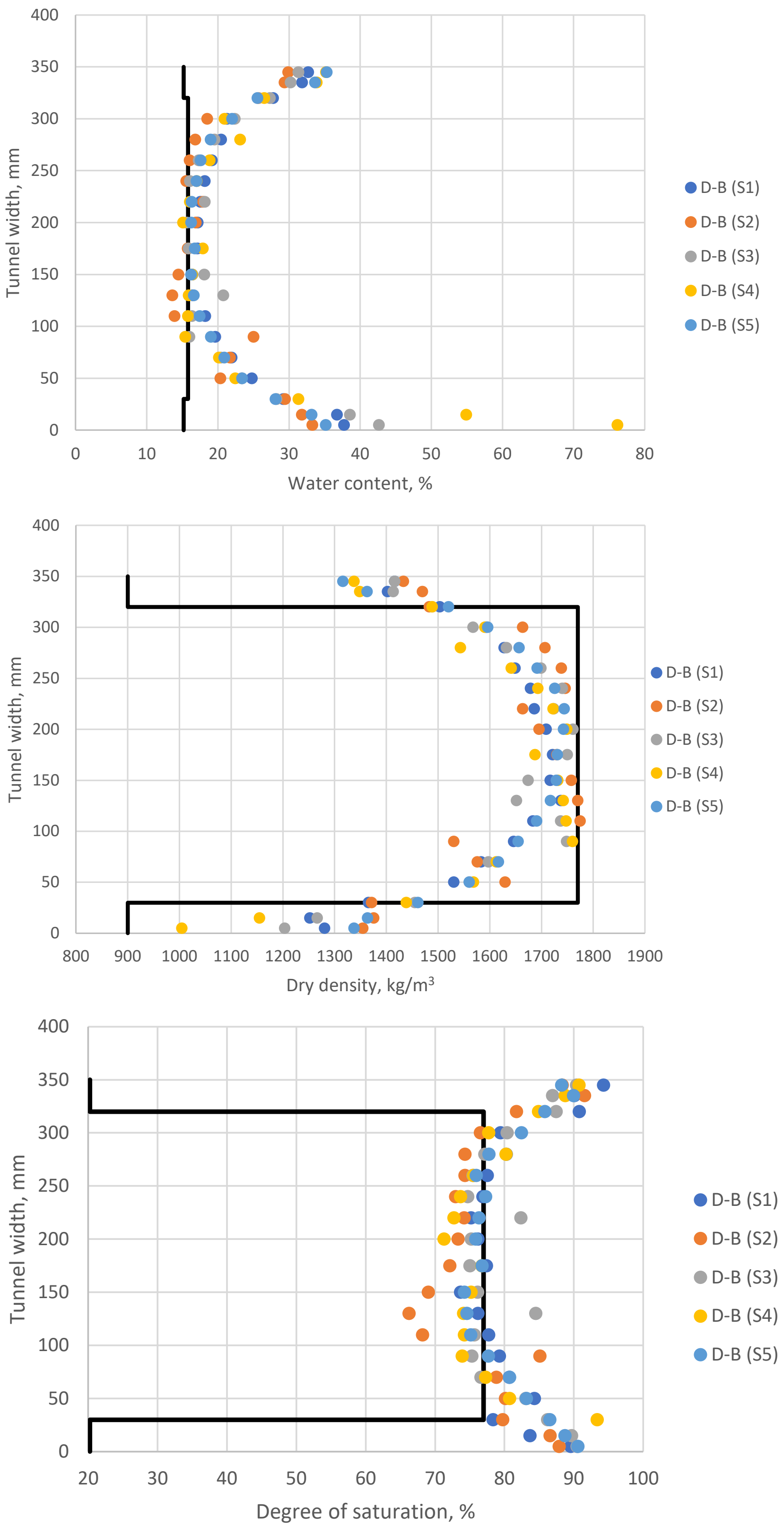


***Figure 6-10.** Water content (upper), dry density (middle), and degree of saturation (lower) along a horizontal line, positioned at the mid-height of the tunnel, at five different sections in Test 2, see Figure 5-8 and Figure 5-9. The black lines indicate the initial values. Sampling direction B upwards.*

6.5.3 Erosion channels in buffer

The sampling directions of the buffer were the same as in Test 1, see right photo in Figure 5-12. The inflow point at the bottom of the deposition hole corresponds to sampling direction A and is also close to the radial pressure measurements.

Visual inspection together with the results from the sampling, see Section 6.5.4, showed that there was a rather clear, vertical, erosion channel along most of the deposition hole (except for the bottom block), Figure 6-11. The channel started in the direction of A (sampling level L2), continued thereafter in the direction of C (sampling levels L3 and L4) and then further in the direction B (sampling level L5) and in the direction of A (sampling level L6). Above the canister, the main erosion channel was positioned in the direction D (sampling level L7, L8 and L9) but also partly in direction A (sampling level L8). The position of the erosion channel has thus changed several times. Close-ups of the erosion channel are provided in Figure 6-12. From the photos, it is obvious that the finest clay particles have eroded away leaving the coarser grains left in the channel.

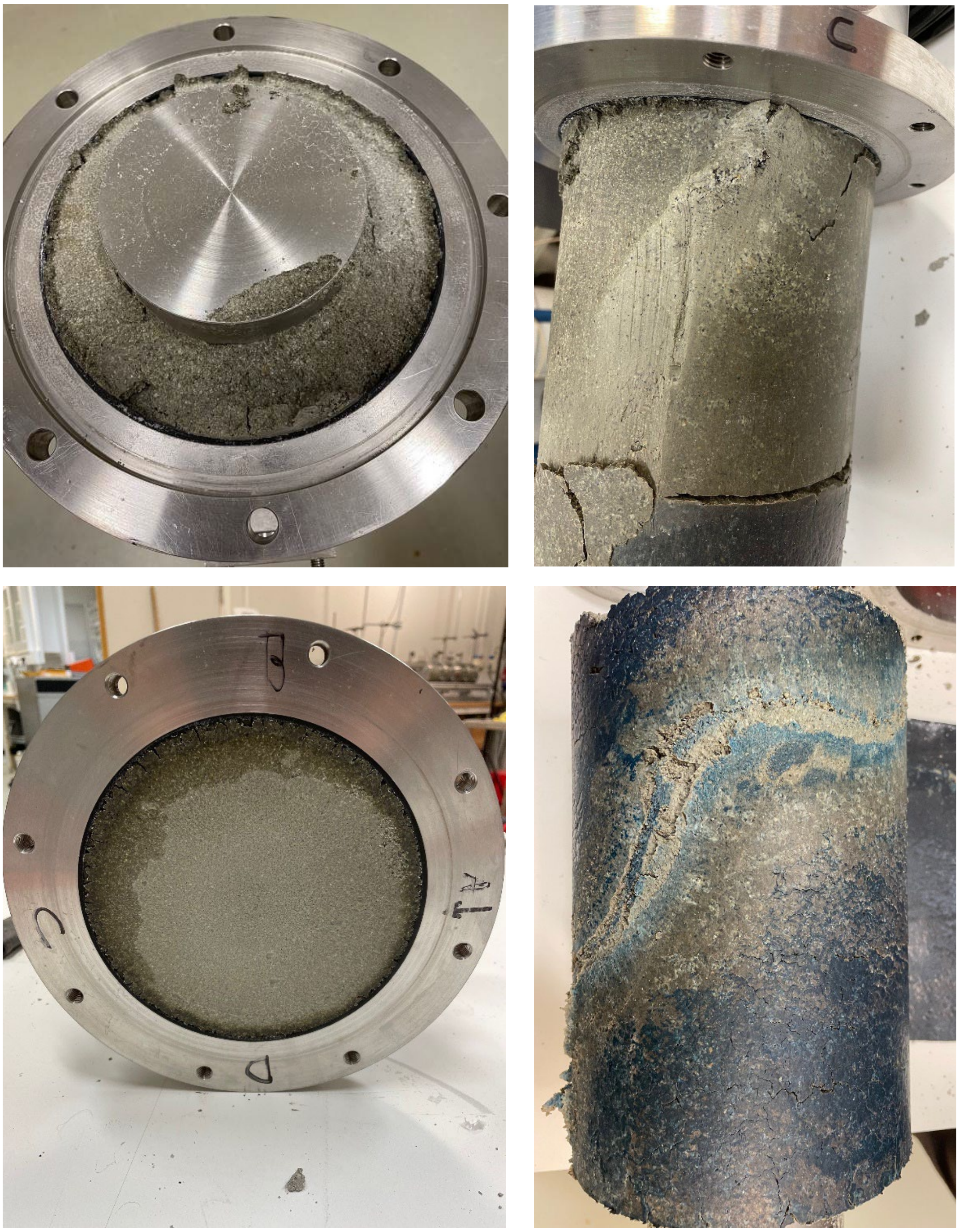


Figure 6-11. *Test 2. Upper left: Photo showing the top of the canister. The wettest part can be seen as a dark field (between direction A and D). Upper right: Erosion channel on the buffer surface along the lower part of the canister. Lower left: Photo showing the bottom block from below. Lower right: Erosion channel along the upper part of the canister. Note that the outer surface of the buffer has been discoloured by the rubber mat.*

Figure 6-12. Photos showing close-ups of the erosion channel in Test 2. The finest clay particles have eroded away leaving the coarser grains left in the channel.

6.5.4 Dismantling and sampling of the deposition hole

Dismantling

The buffer was pushed out from the steel tubes using the same equipment as for Test 1, see photo provided in Figure 5-18. This technique facilitates the following sampling of the buffer.

Water content and dry density distribution

Graphs showing the results from the sampling are provided in Figure 6-13 to Figure 6-21 (corresponding to sampling level L1 to L9). In each figure, there are three graphs showing the water content (upper graph), the dry density (middle graph), and the degree of saturation (lower graph) plotted versus the radial distance from the centre of the deposition hole.

The graphs show that at most sampling levels, except for the level below the canister, there is one direction in which the water content has increased more than in the others. In this direction the dry density has also decreased. As mentioned in Section 6.5.3, the channel started in the direction of A (sampling level L2), continued thereafter in the direction of C (sampling levels L3 and L4) and then further in the direction of B (sampling level L5) and in the direction of A (sampling level L6). Above the canister, the main erosion channel was positioned in direction D but also partly in direction A (sampling level L8). The position of the erosion channel has thus changed several times. It was also noted that an increased water content of the buffer had occurred in more than one direction at three of the sampling levels:

- **Sampling level L2**. Besides the increased water content in direction A, where the erosion channel seemed to be, the buffer had an increased water content in direction D.
- **Sampling level L6**. Besides the increased water content in direction A, where the erosion channel seemed to be, the buffer had an increased water content in direction D.
- **Sampling level L8**. The buffer had an increased water content in both direction A and D.

The sampling shows thus that there was a rather clear vertical erosion channel, but it seems to have changed the periphery position at some levels, and it has also changed position at different times during the test.

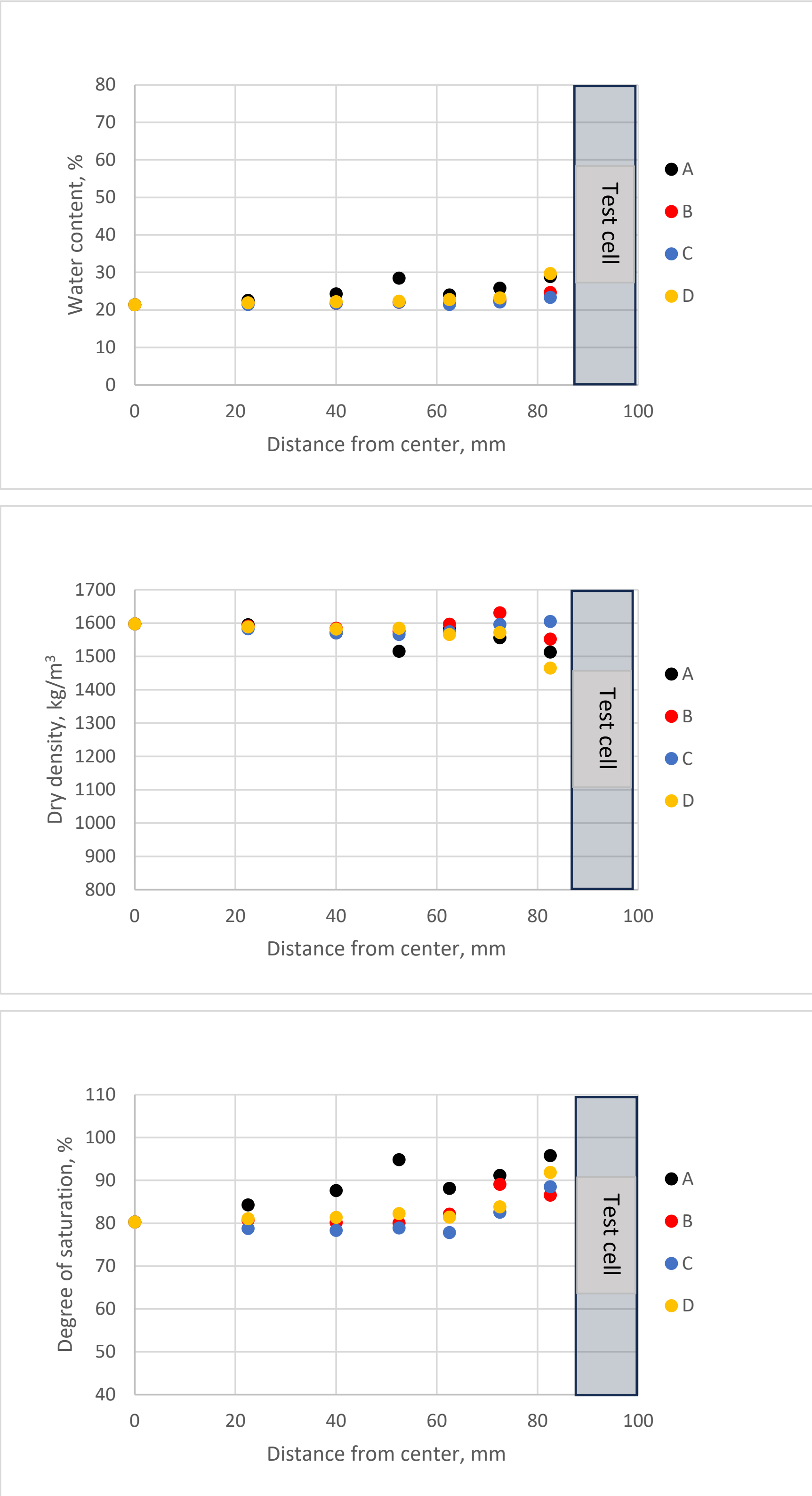


Figure 6-13. *Results from measurements in sample section L1 (bottom block) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

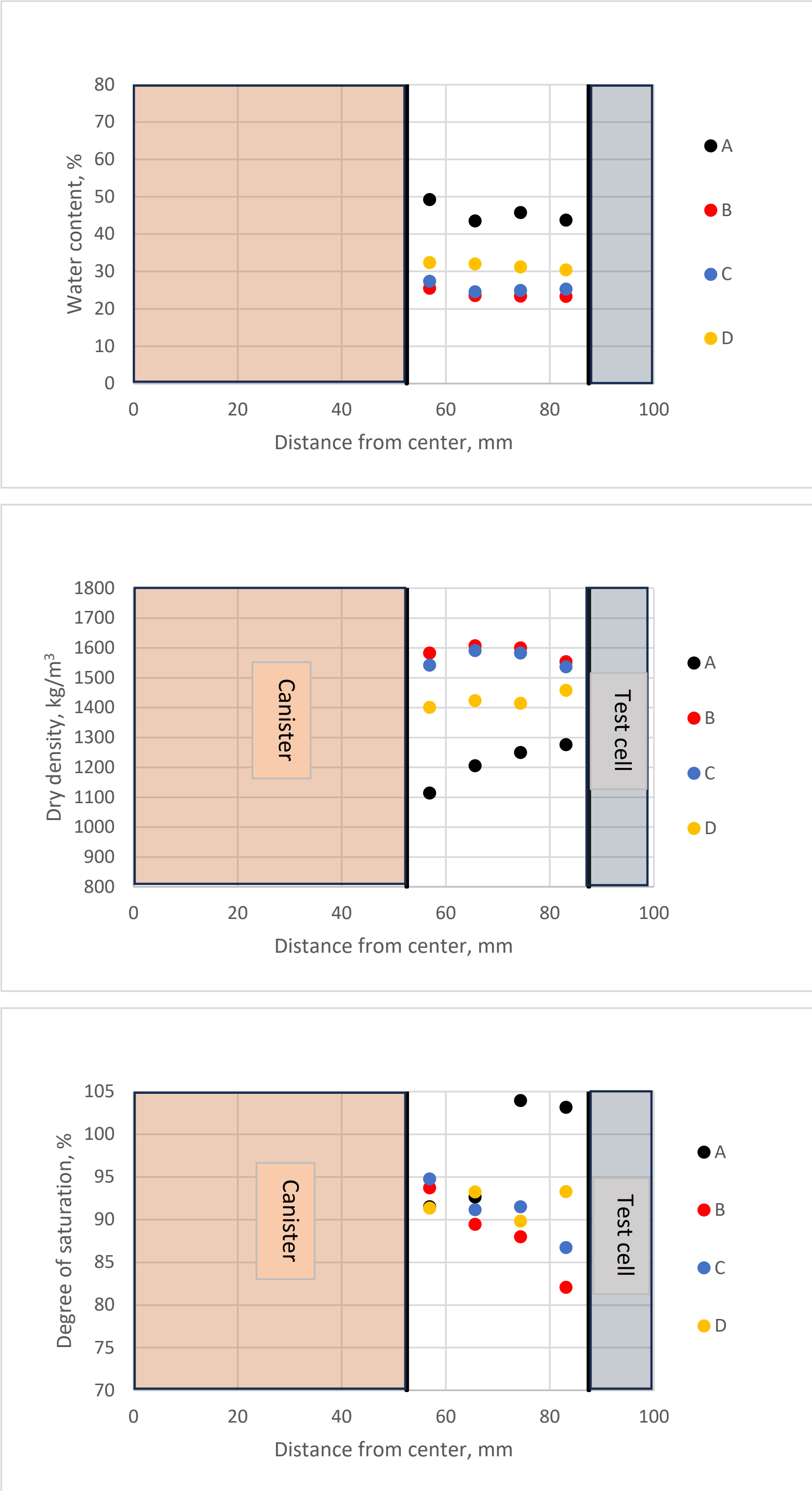


Figure 6-14. *Results from measurements in sample section L2 (along canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

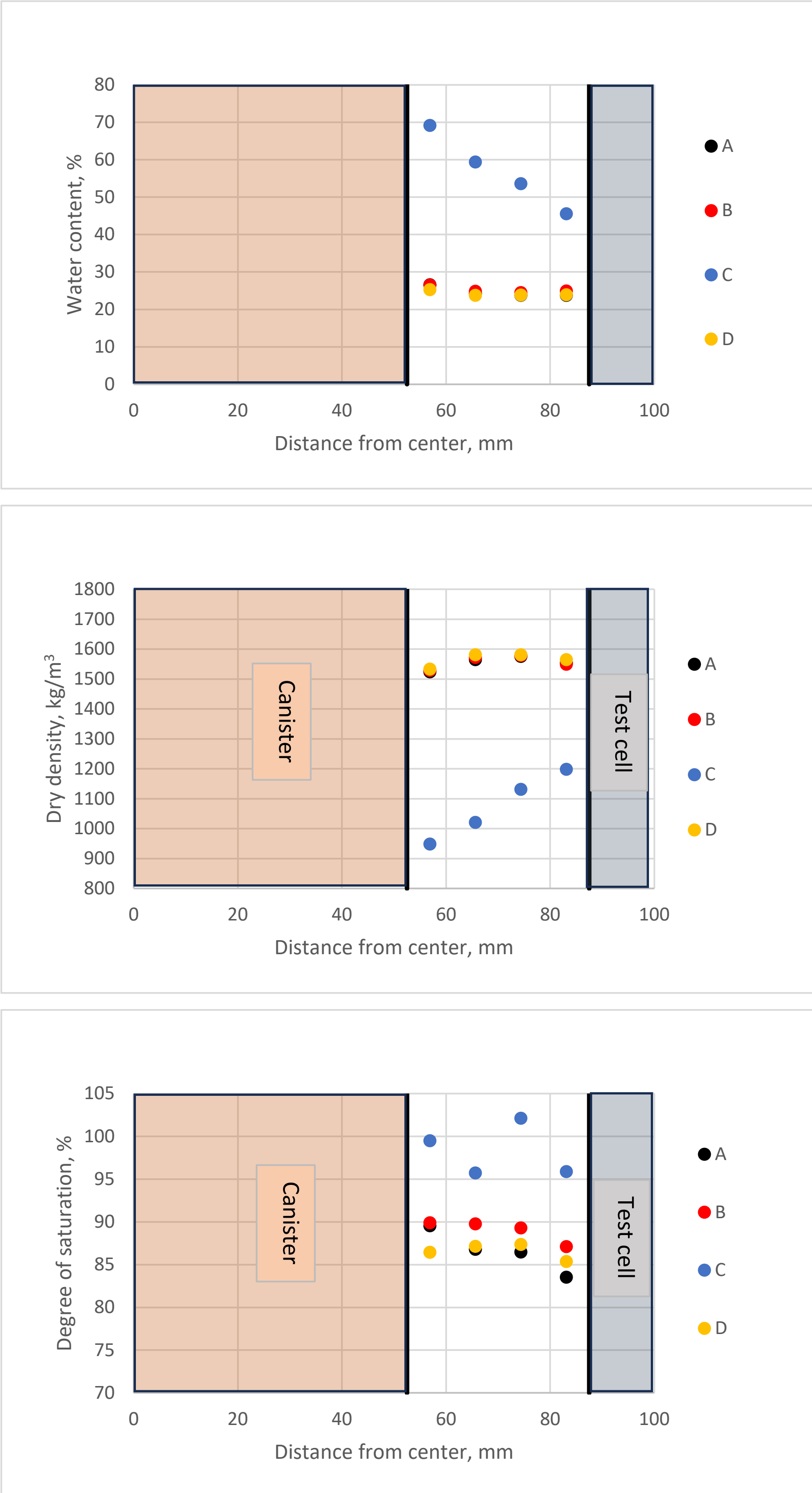


Figure 6-15. *Results from measurements in sample section L3 (along canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

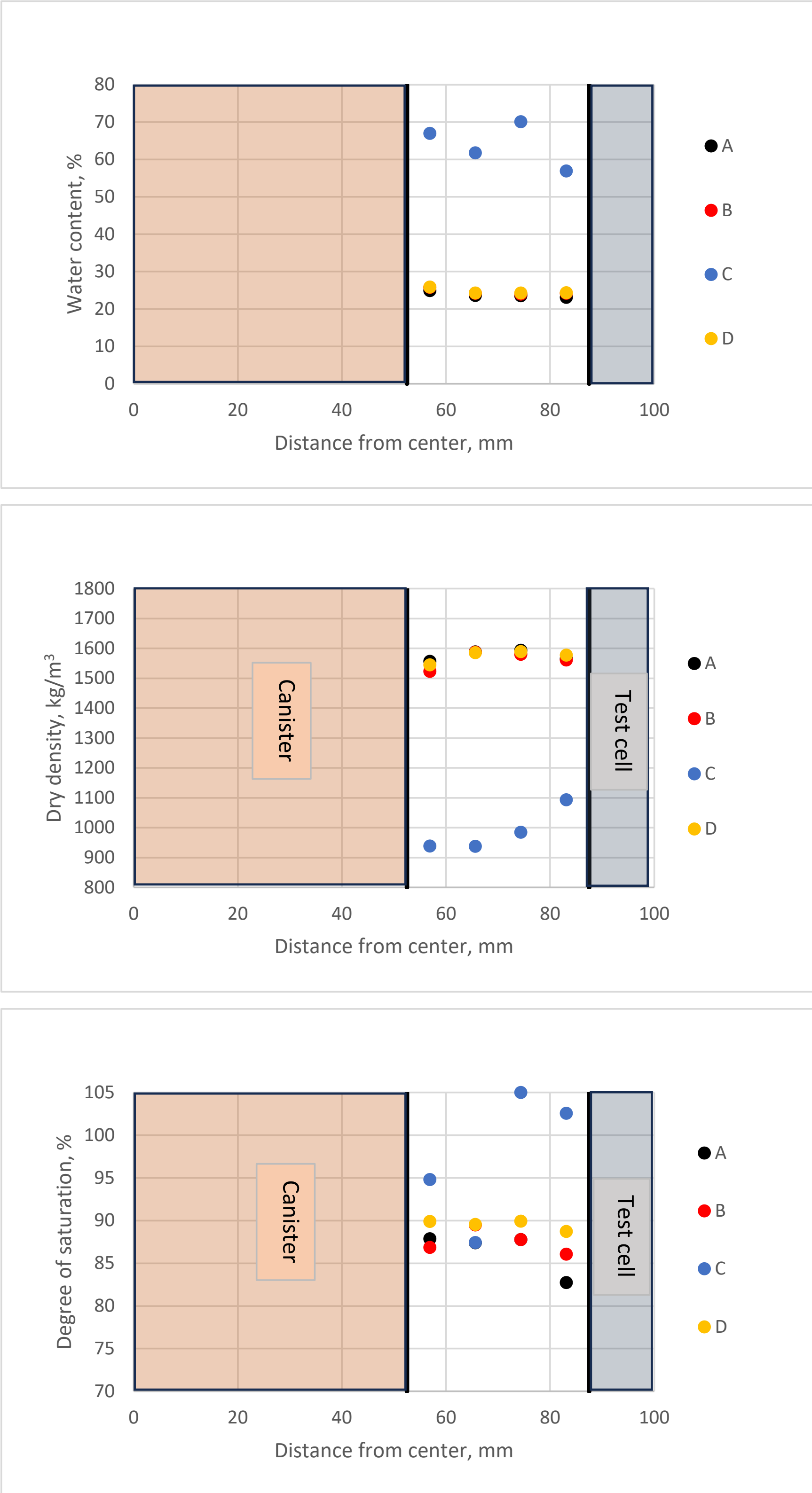


Figure 6-16. *Results from measurements in sample section L4 (along canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

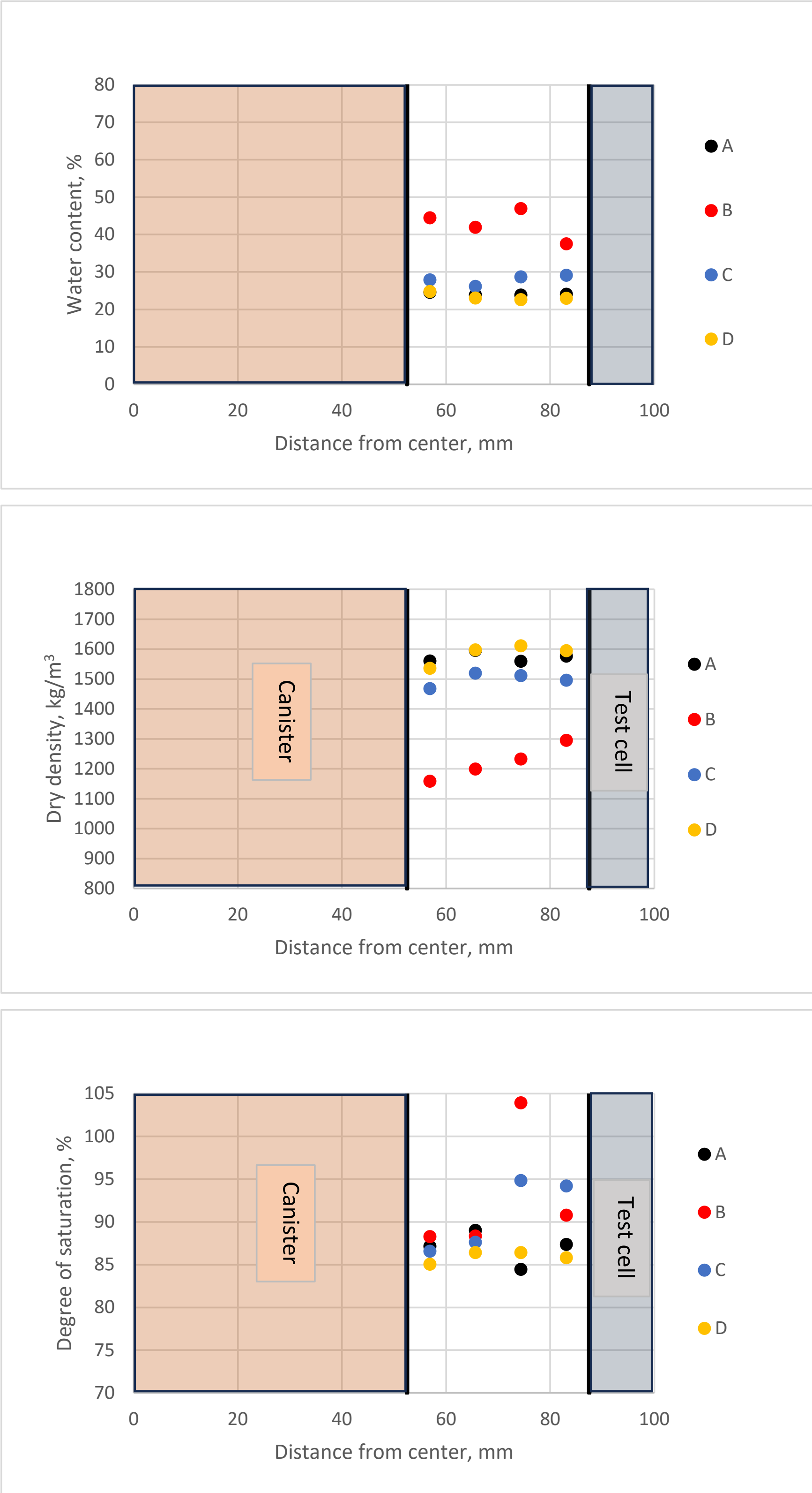


Figure 6-17. *Results from measurements in sample section L5 (along canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

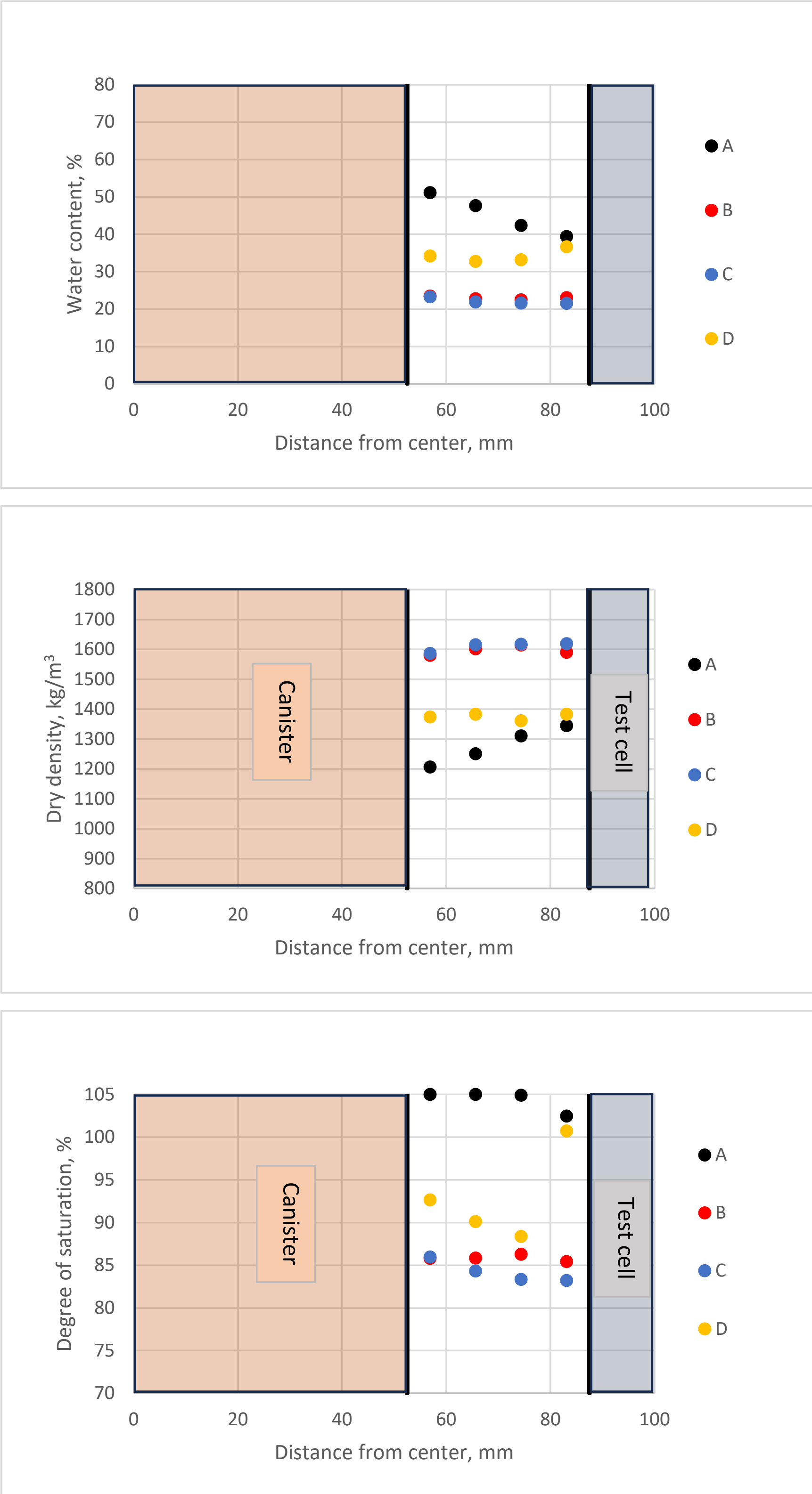


Figure 6-18. *Results from measurements in sample section L6 (along canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

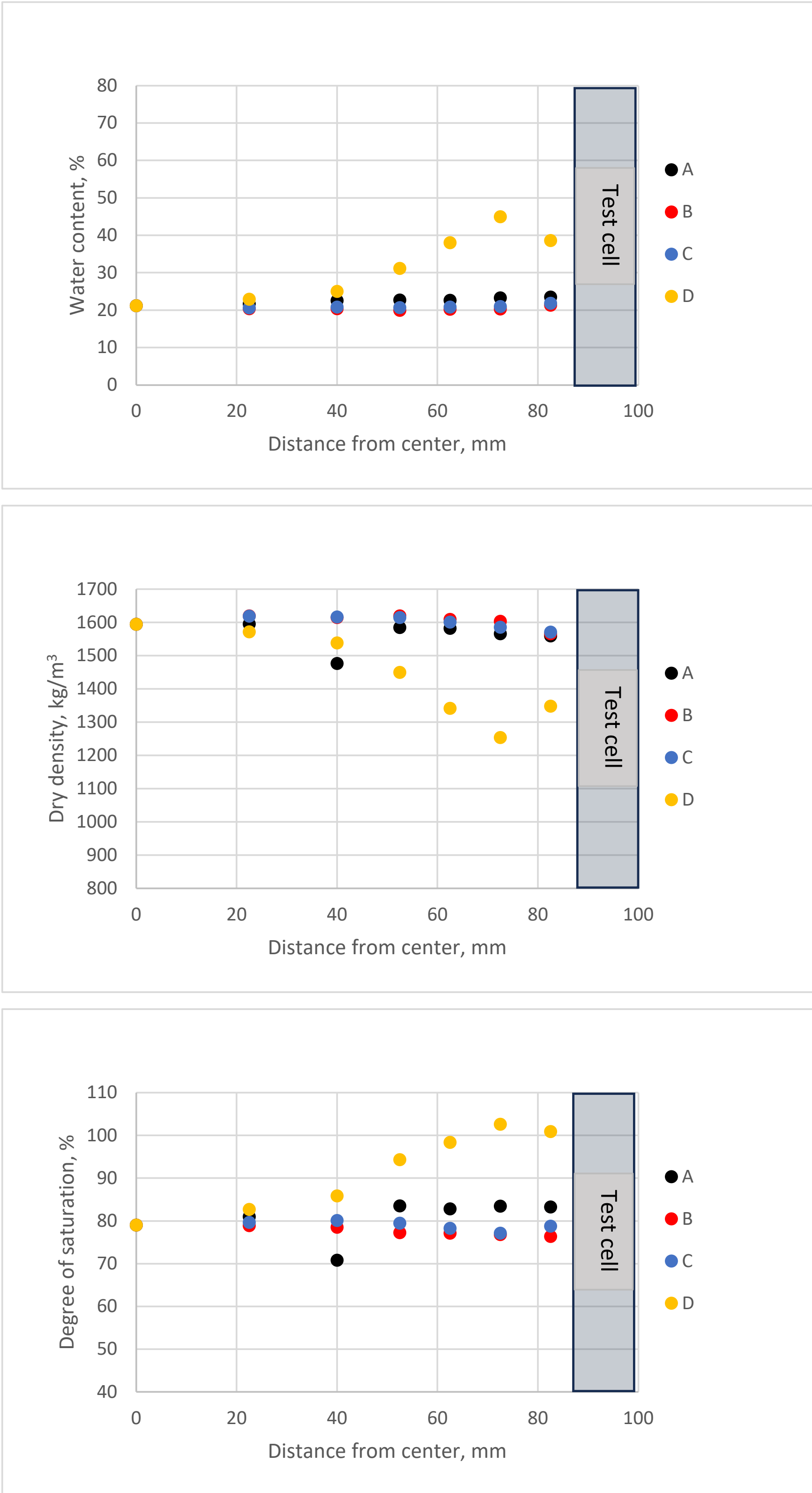
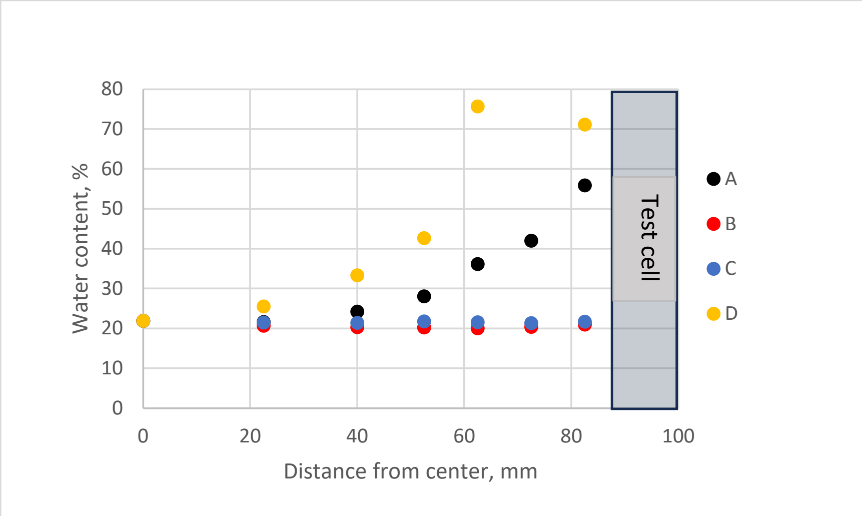
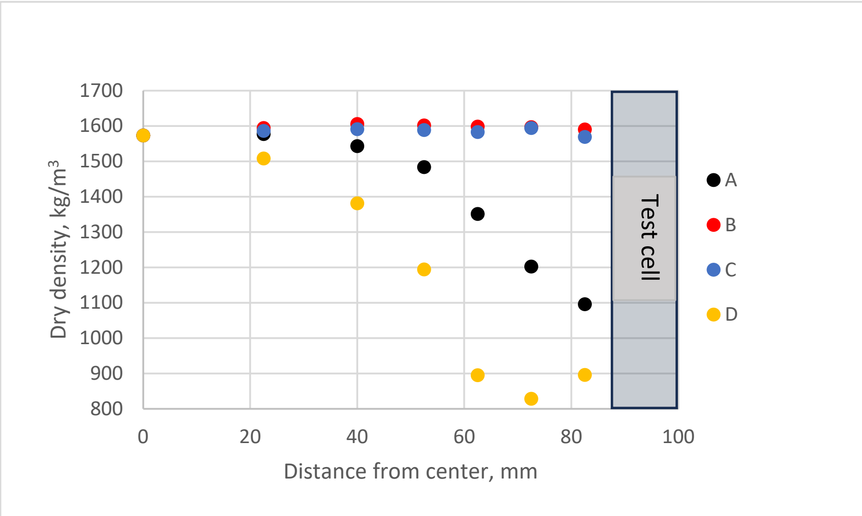


Figure 6-19. *Results from measurements in sample section L7 (above canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*





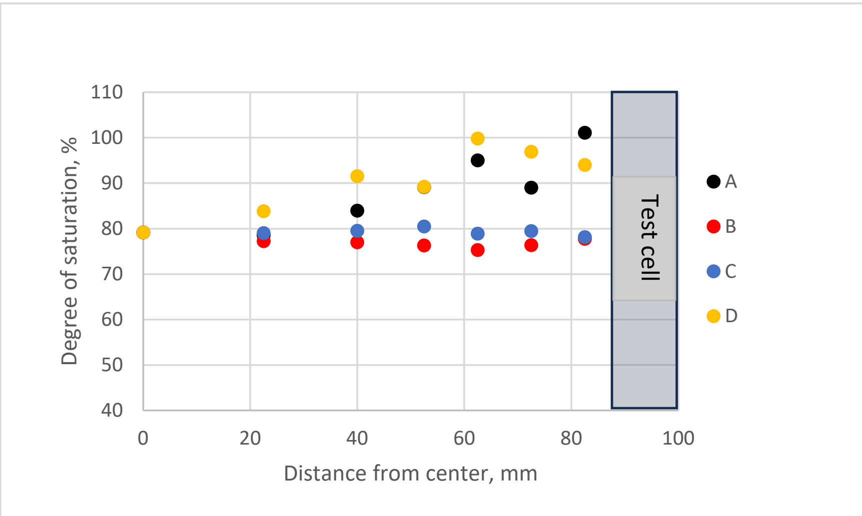
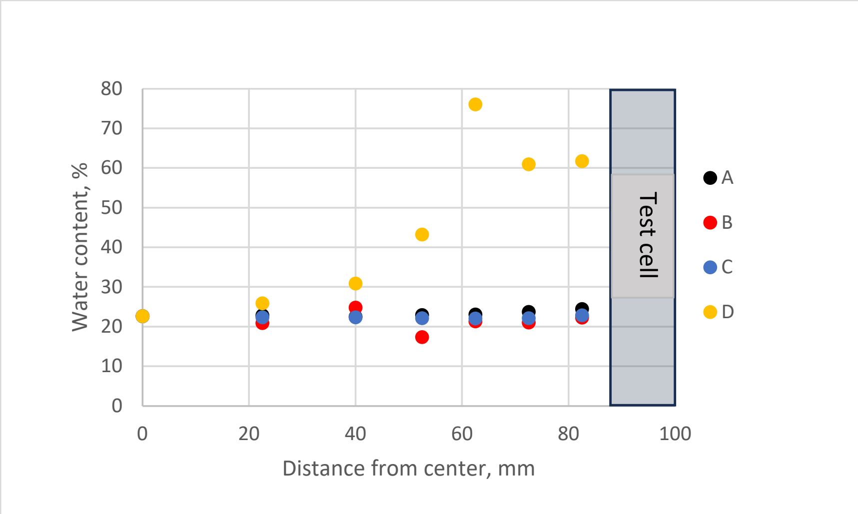
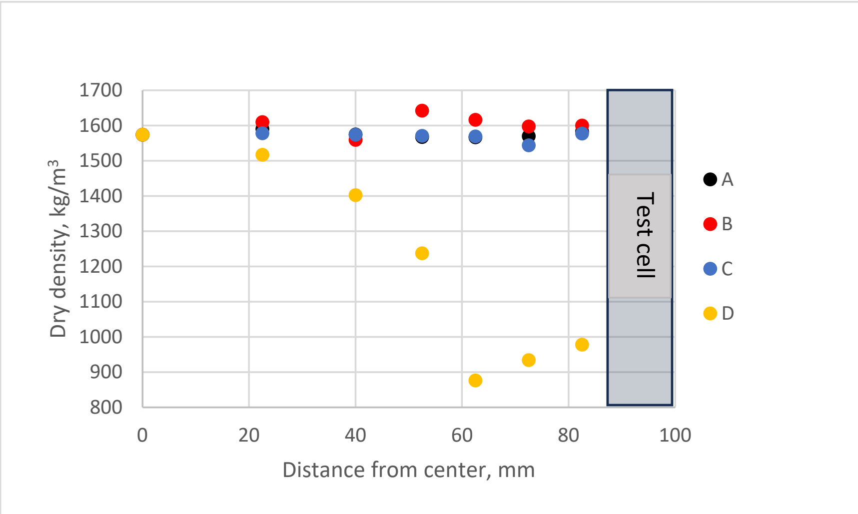


Figure 6-20. *Results from measurements in sample section L8 (above canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*





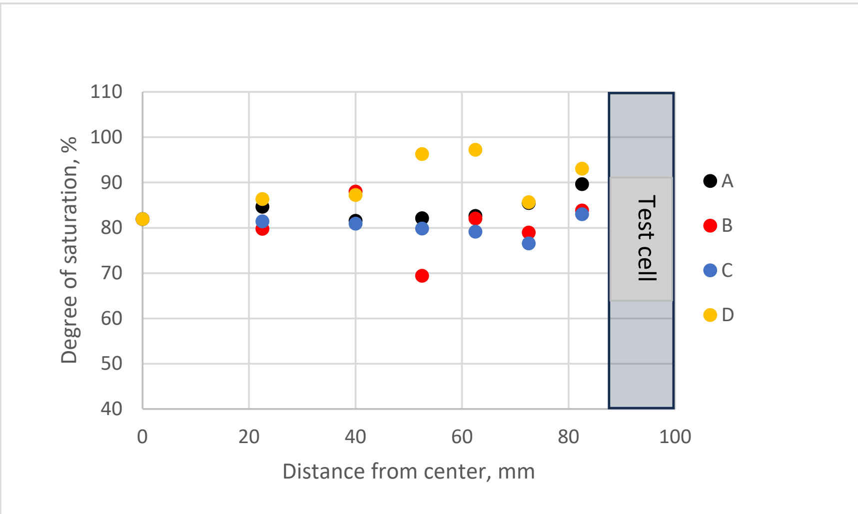


Figure 6-21. *Results from measurements in sample section L9 (above canister) in Test 2. Upper: Water content plotted versus distance from the centre. Middle: Dry density plotted versus distance from the centre. Lower: Degree of saturation plotted versus distance from the centre.*

6.6 Compilation of data

6.6.1 Water content and dry density distribution of the backfill in the deposition tunnel

The sampling of the backfill is described in Section 5.5. The sampling included 195 positions and was judged to give a good picture of the status of the backfill regarding water content and dry density distribution.

From the photos taken in conjunction with the dismantling of the backfill, Figure 6-6 to Figure 6-8, it is obvious that the pellet filling at the top of the tunnel and between the block stack and the walls at the long sides have been largely wetted. This was also shown in the graphs showing the results from the sampling, Figure 6-9 and Figure 6-10. Water has also entered the gaps between the backfill blocks and by that "glued" them together. The blocks have swelled to some extent and by that compressed the low-density pellet fillings. The wetting pattern was almost the same as in Test 1, but the pellet fillings along the walls, and also along the floor and the ceiling, had a somewhat higher water content.

6.6.2 Water content and dry density distribution of the buffer in the deposition hole

To give a picture of the status of the complete deposition hole regarding water content, dry density, and degree of saturation distribution contour plots were made using an interpolation program, Figure 6-22, Figure 6-23, and Figure 6-24. The contour plots show the water content, the dry density, and the degree of saturation distribution in the four vertically sampled cross-sections (direction A, B, C, and D) of the deposition hole.

The contour plots show clearly that the wetting (erosion channel) has changed direction several times which also can be confirmed from the photos taken in conjunction with dismantling, Figure 6-11.

The dry density in the erosion channel (at the top and along the canister) was mainly between 900 and 1400 kg/m^3 which should be compared to the installed average dry density (1565 kg/m^3). This means that significant amounts of bentonite material had eroded away from parts of the deposition hole.

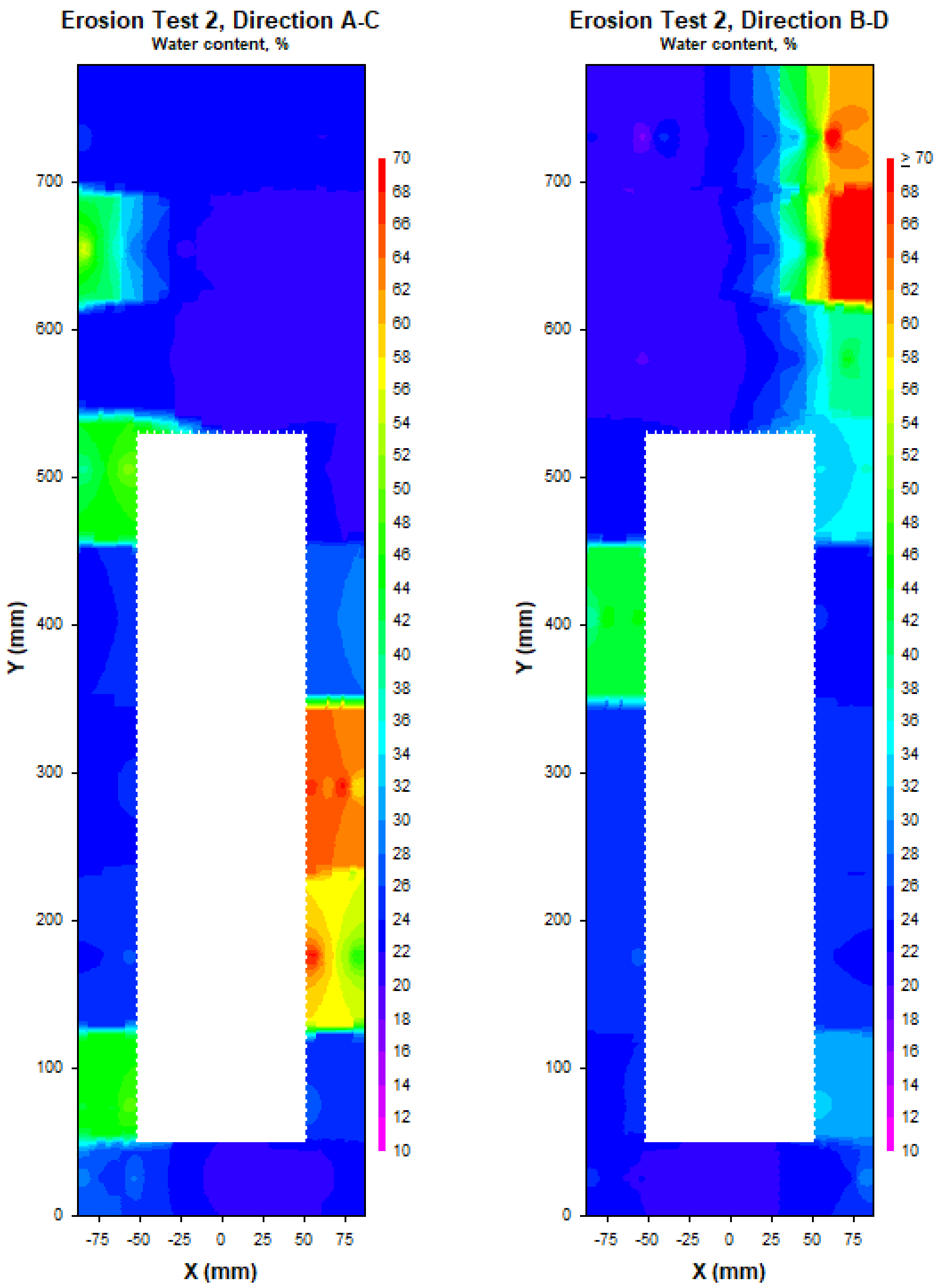


Figure 6-22. *Contour plots showing the water content distribution in the four sampled directions (A, B, C, and D) of the deposition hole in Test 2.*

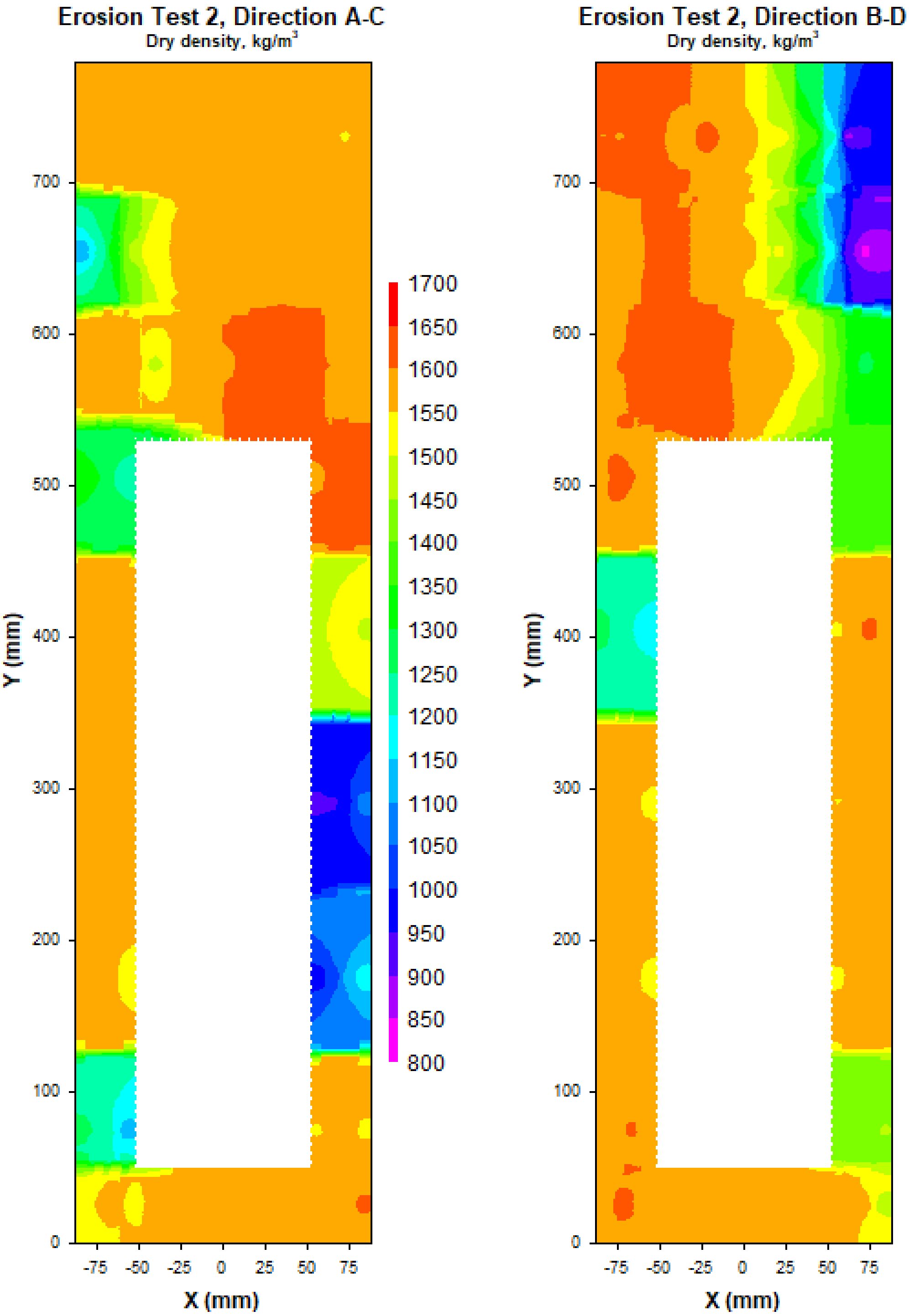


Figure 6-23. *Contour plots showing the dry density distribution in the four sampled directions (A, B, C, and D) of the deposition hole in Test 2.*

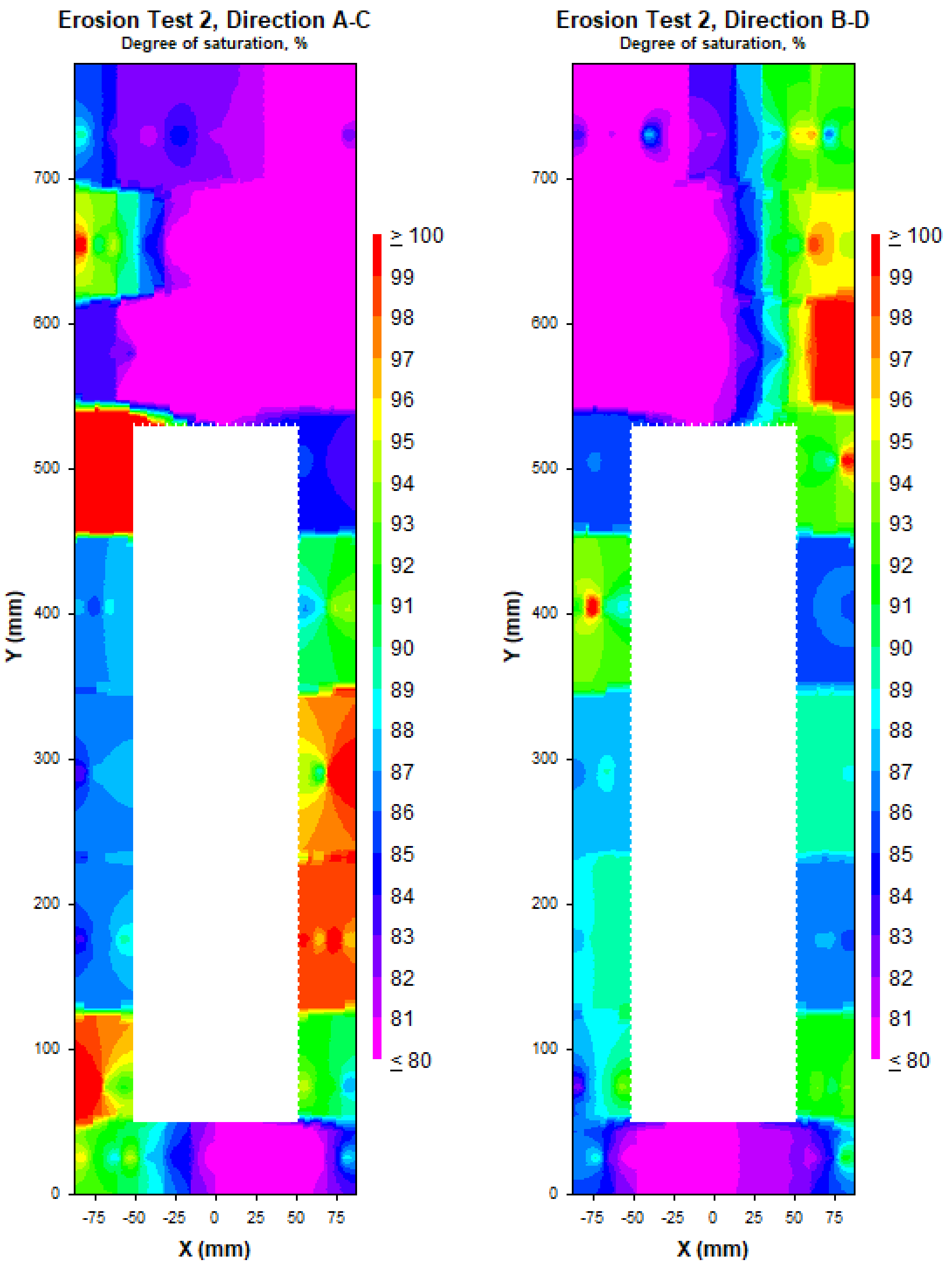


Figure 6-24. *Contour plots showing the degree of saturation distribution in the four sampled directions (A, B, C, and D) of the deposition hole in Test 2.*

6.6.3 Eroded backfill and buffer material

General

The total dry mass of bentonite that had eroded from the test setup was 5.66 kg. How this amount was distributed between the deposition hole and the deposition tunnel is not exactly known. An attempt to estimate the amount of bentonite eroded from the deposition hole was made with the same methods as described for Test 1, see Section 5.7.3.

Buffer

The average dry density of the buffer after installation was determined to 1565 kg/m^3 (installed dry mass=22.8 kg). The new average dry density of the buffer after having performed the erosion test was calculated in the same three separate ways as described in Section 5.7.3.

Data from the three types of evaluation are provided in Table 6-1. The mass loss from the buffer varies between 0.79 and 1.43 kg which corresponds to between 3.5 and 6.3 % of the installed dry mass.

Table 6-1 Installation and erosion data (upper part of the table) and calculations of the proportion of eroded material from the buffer and from the backfill (lower part of the table).

Test 2	Dry density kg/m^3	Mass kg
Buffer installation	1565	22.8
Backfill installation	1505	246.0
Measured erosion		5.7

Calculations after erosion	Buffer			
Type of evaluation	**Dry density** **kg/m^3**	**Mass** **kg**	**Mass loss** **kg**	**Mass loss** **%**
Average density (not weighted)	1481	21.58	1.23	5.4
Weighted density (1/4)	1467	21.38	1.43	6.3
Weighted density (1/8)	1511	22.02	0.79	3.5

Backfill

The total installed dry mass of the backfill was 246 kg. The total eroded dry mass from the test setup was determined to be approximately 5.66 kg. According to the calculations described above, the loss of material from the buffer was between 0.79 and 1.43 kg. This means that the loss of backfill material due to erosion was approximately 4-5 kg, which corresponds to approximately 2 % of the dry backfill mass installed in the test.

7 Discussion

7.1 Summary of test results

The presented tests were performed as scale tests, in scale 1:10, which included a deposition hole and a tunnel segment with a length corresponding to two tunnel sections. The deposition hole was located at one end of the tunnel segment and was equipped with a water inlet close to the bottom. The tunnel segment was equipped with three water outlets positioned close to the ceiling at the tunnel end opposite the deposition hole which meant that the distance between the inlet and outlets was as long as possible.

All bentonite blocks and pellets used in the tests were made of a Bara-Kade bentonite from Wyoming, USA. The target dry density for the buffer blocks was 1652 kg/m^3 (solid blocks) and 1747 kg/m^3 (ring-shaped blocks). The brick-shaped blocks used for the backfill had a dry density of 1770 kg/m^3. Compacted pillow-shaped pellets were used for the buffer and were crushed and sieved to achieve a particle size of 2 - 4 mm prior to installation. Extruded pellets were used for the backfill.

Water was injected into the inlet with a constant flow rate (Table 7-1) with either a dose pump or a high-pressure pump, and the injection pressure were measured continuously. 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 water flowing out from the deposition tunnel was collected and let through a sequence of sedimentation vessels. For quantifying the erosion rate, all accumulated sediment was collected, dried and weighted at 3 - 5 occasions per week.

At the end of each test, the bentonite was dismantled and sampled with the intention to determine the water content and the dry density distribution in the backfill and the buffer. Samples were therefore taken at 195 positions in the backfill and in 180 positions in the buffer. The buffer data was used to calculate an average dry density at the end of the test. By comparing this value with the average dry density at installation, a buffer mass loss for each test was quantified.

Table 7-1. Key data and results for the two scale tests.

	Test 1	Test 2
Test conditions	Flow rate: 0.05 l/min Duration: 10 weeks	Flow rate: 0.02 l/min Duration: 5 weeks
Total dry mass:	Buffer: 22.8 kg Backfill: 245 kg	Buffer: 22.8 kg Backfill: 246 kg
Average dry density	Buffer: 1571 kg/m^3 Backfill: 1496 kg/m^3	Buffer: 1565 kg/m^3 Backfill: 1505 kg/m^3
Injection pressure	0-8 days: 0.1 - 0.5 MPa with occasional peaks up to 1.7 MPa. <0.03 MPa otherwise.	0-2 days: 0.1 - 0.2 MPa. Peak of 0.4 MPa at day 15. <0.04 MPa otherwise.
Total measured erosion	4.8 kg	5.7 kg
Buffer mass loss	1.6-2.4 kg	0.8-1.4 kg

7.2 Piping channels in buffer and backfill

The piping/erosion channels in the buffer were rather similar in these two tests. Visual inspection together with the results from the sampling showed that there were clear vertical channels along the deposition holes. The channels were not straight but changed position a few times on the way up from the deposition hole. In both tests, the channels reached the backfill in almost the same position (sampling direction D). The channels in the buffer were not empty but contained bentonite with high water content and visual inspection showed that the finest clay particles have eroded away leaving the coarser grains left in the channels.

The piping/erosion channels in the backfill were easily detected for both tests. From the deposition holes there were channels upwards to the tunnel ceiling, close to one of the tunnel corners. These channels contained loose bentonite with high water content. The water had thereafter flowed along the tunnel ceiling and/or at the edge between tunnel walls and ceiling. The flowing water left rather clear marks on the ceiling (on the steel and on the painted surface) which made it possible to take photos showing how the flowing water had found its way forward to the outlets at the other side of the tunnel (Figure 5-11 and Figure 6-6). The erosion channels in the backfill along the ceiling were not straight forward but included several loops in both tests.

7.3 Erosion

The results from the two erosion tests described in this report are plotted in Figure 7-1. The graph shows the accumulated dry mass of eroded material as a function of the accumulated water flow in a double logarithmic diagram. The straight black lines describe a model of expected maximum and minimum accumulated eroded material. The model is described in (Sandén et al, 2008) and (Sandén and Börgesson, 2010).

A somewhat surprising result from the erosion measurements was that the total erosion from Test 2 was somewhat higher than in Test 1 despite the lower flow rate and the shorter test duration (4.83 kg eroded from Test 1 and 5.66 from Test 2). The reason for this difference is not known, but it can be noted from the dismantling data shown in Figure 5-14 and Figure 6-9, that the backfill material in Test 2 generally displayed a higher water content and a lower dry density in the peripheral parts in comparison with the backfill material in Test 1. This may therefore suggest that injected water was more evenly distributed in Test 2, possibly as a result of a lower flow rate, which in turn may have enabled a more sustained bentonite concentration in the outflowing water from that test.

An attempt to determine the origin of the eroded material, i.e. how much came from the deposition hole and how much came from the deposition tunnel, was made. The density of all buffer samples where weighted against the volume they represented. The results from these calculations varied between 1.63-2.36 kg for Test 1 and between 0.79 and 1.43 kg for Test 2. The variation in results depends on how the weighting was made, i.e. which volume of the samples taken from the erosion channels represents. The lower values of the erosion were based on a visual estimation of the channel volume compared to the complete buffer volume.

It is interesting, however, that the calculated erosion from the deposition hole in Test 2 is smaller than from Test 1 despite a higher value of the total erosion from the complete test setup. The calculations indicate thus that the high erosion measured in Test 2 mainly originates from the backfill.

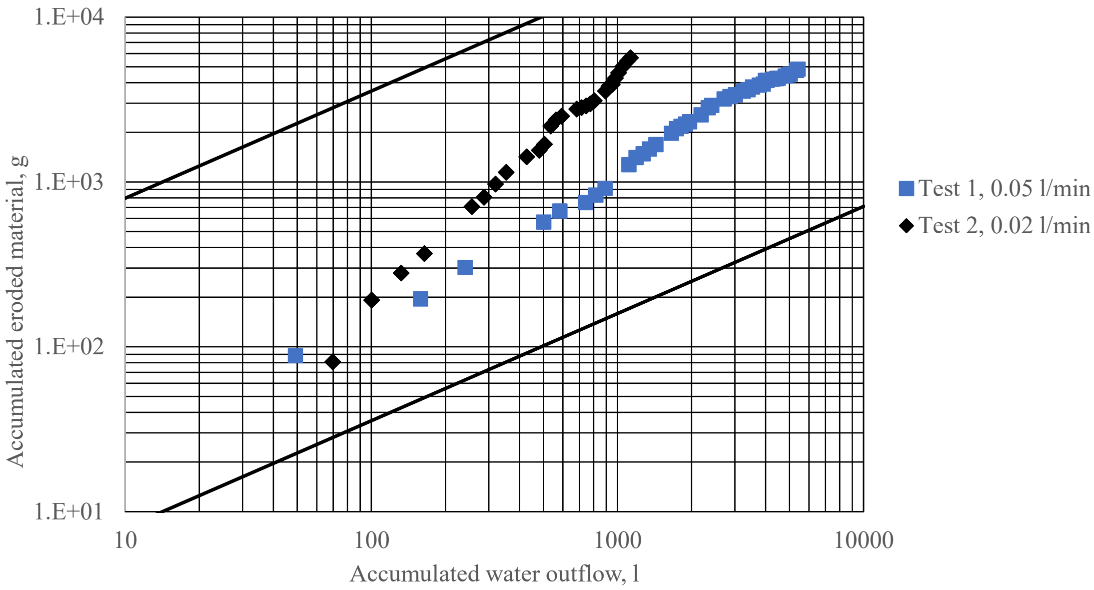


***Figure 7-1.** The accumulated eroded material plotted versus the accumulated outflow. The straight black lines describe a model of expected maximum and minimum accumulated eroded material (Sandén et al, 2008).*

7.4 Estimations of buffer mass loss

A scale test can be used as a physical model of an actual system; in this case a deposition hole and a 12 m long tunnel section. An extrapolation of experimental results from a scale test to an actual system can be based on the assumption that some (intensive) properties are independent of scale; in this case measured dry densities and bentonite concentrations. This means that the measured dry density of the buffer at the end of the tests ($\rho_d = m_s/V$) can be regarded as representative for the dry density in the actual system under similar conditions ($\rho_d^* = m_s^*/V^*$). Correspondingly, the average bentonite concentration of the eroding water that left the deposition hole in the scale test ($c_b = \Delta m_s/V_w$) can be regarded as representative for average concentration in the actual system under similar conditions ($c_b^* = \Delta m_s^*/V_w^*$). Of main interest for the safety assessment is the mass loss of bentonite buffer from the deposition hole, which for the scale test can be calculated as: $\Delta m_s = \left(\rho_d^{init} - \rho_d\right) \cdot V$, where ρ_d^{init} is the initial dry density installed in the deposition hole, while the corresponding mass loss for the actual system can be calculated as: $\Delta m_s^* = \left(\rho_d^{init} - \rho_d^*\right) \cdot V^*$. Since both the initial and the final dry density in the actual system can be assumed to be the same as the corresponding dry densities in the scale test, this means that the ratio of mass losses for the actual system and the scale test is the same as the corresponding ratio for the buffer volumes: $\Delta m_s^*/\Delta m_s = V^*/V$. Similarly, since the average bentonite concentration of the eroding water in the actual system can be assumed to be the same as the corresponding concentration in the scale test, this means that the ratio of the water volumes for the actual system and the scale test is the same as the corresponding ratio for the buffer volumes: $V_w^*/V_w = V^*/V$. Finally, the test scale of 1:10 implies that the ratio for the buffer volumes (V^*/V) is 10^3. This means that the representative values for the mass loss and the water volume for the actual system are 10^3 times larger than the corresponding values for the scale test.

The main goal of the performed scale tests was to quantify the buffer mass loss for specified inflow rates and test durations. The selection of test durations was guided by the time to fill up a full-scale deposition tunnel with an accessible pore volume of approximately 900 m^3 (Börgesson et al. 2015). For an inflow rate of 0.1 L/min from one single inflow point, this filling time is approximately 18 years. The test duration chosen for Test 1 was based on this filling time, and the notion that the extent of water uptake reached during that timeframe is to a large extent driven by diffusion. This means that the time to reach a similar water uptake in the laboratory test can be estimated from the square of the length scale ($t \sim L^2$), which thereby amounts to approximately 10 weeks. However, together with the chosen flow rate of 0.05 L/min, this meant that the total volume for Test 1 was 5 m^3. The ratio between this and the corresponding full-scale volume was approximately 0.005, which illustrates that the chosen volume was approximately 5 times larger than if the water volume had been calculated from the cube of the length scale ($V_w \sim L^3$). The test duration and the flow rate applied for Test 2 was therefore chosen so that the ratio between the total water volume and the corresponding full-scale volume would be approximately 10^{-3}. The motive for selecting a flow rate of 0.02 L/min was that the system might seal and lead to high injection pressures if a lower flow rate was chosen, and together with this flow rate a time period of 5 weeks was chosen.

The buffer mass loss in the scale tests was found to be 1-2 kg. The test scale of 1:10 implies that the mass loss for the corresponding full-scale case would be a factor of 10^3 higher, i.e. 1-2 tons. This would exceed the requirement for the maximum acceptable mass loss due to piping/erosion, SKB (2022), with approximately one order of magnitude (see Figure 7-2). Earlier estimations of the mass loss from a deposition hole which acts as the sole inflow point in an entire tunnel were based on the empirical model which in turn was based on results from several erosion tests performed in vertical tubes and circular slots filled with pellets (Börgesson et al. 2015). The total water volume used in those earlier tests was limited to approximately 0.1-1 m^3, which means that the accumulated water volume had to be extrapolated with three orders of magnitude in order to estimate the total mass loss, Figure 7-2. In general, those earlier tests were associated with two limitations. On one hand, the observed rate of erosion may have been exaggerated due to the test configuration in which the outlet holes occasionally may have enabled gel, i.e. water with high concentration of bentonite, to leave the system, SKB (2019). One the other hand, the declining trend of the erosion rates observed in these tests may also be exaggerated, since the total mass of bentonite in those earlier tests was limited to 10 – 40 kg. Measured mass loss from the current tests, implies that the average bentonite concentration in the water that left the deposition hole was 0.4 and 1 g/L for Test 1 and Test 2, respectively. These concentrations are fairly similar to the initial concentration that typically is obtained in tests with pellets-filled slots. In this respect the new results are quite consistent with earlier test results.

It should however be noted that the used method is associated with a number of uncertainties and limitations:

Difficulties with scale. For instance, and as noted above, there is no clear-cut way to choose a relevant test duration. Moreover, it is not possible to scale the inflow rate, since if this is sufficiently low then the buffer at the injection point would absorb the entire inflow and seal the system. Finally, it is not possible to scale the particle size of the pellets without reducing the pore size distribution, which in turn means that the ability to form channels will be influenced.

Limited length of tunnel section. A length corresponding to two tunnel sections á 6 m was chosen for the performed tests. It can be assumed that if a significantly longer tunnel representation would have been used instead, then it would be more likely that there would be a significant increase in the injection pressure. This in itself would perhaps not reduce the erosion rates, but it illustrates that the inflow rates in the full-scale case may be reduced due to the pore pressure build-up which in-turn would reduce the erosion.

Precondition to quantify erosion rates. The aim to quantify the mass loss for a specified flow rate and test duration excludes the possibility that the bentonite may swell and seal the system and thereby significantly reduce the inflow rate and the mass loss.

Based on these concerns, a way forward to make a realistic assessment of the potential mass loss of the buffer should acknowledge that: i) the inflow rate into a deposition hole is likely to be reduced due to the build-up of pore pressure in the pellets-filled slot; ii) the inflow rate, and thus also the erosion rate, is likely to stop once the water uptake in the buffer close to the injection point has reached such an extent that the system will be sealed; and iii) a precondition for this to occur is that the initial inflow rate is sufficiently low, so that the actual erosion rate does not prevent the build-up of pore pressure and the sealing of the system. This implies that the process of piping/erosion is strongly related to the process of water-transport at unsaturated conditions. For instance, recently performed water uptake tests in pressurized tunnel scale tests showed that a water inflow rate of 0.2 mL/min into a bentonite-filled cylinder with a diameter of 0.3 m led to sealing and high injection pressure after approximately 60 days (Sandén et al. 2025). The assessment of the extent of erosion should therefore be based on the expected cumulative volume with rapid (advective) water inflow into the deposition holes.

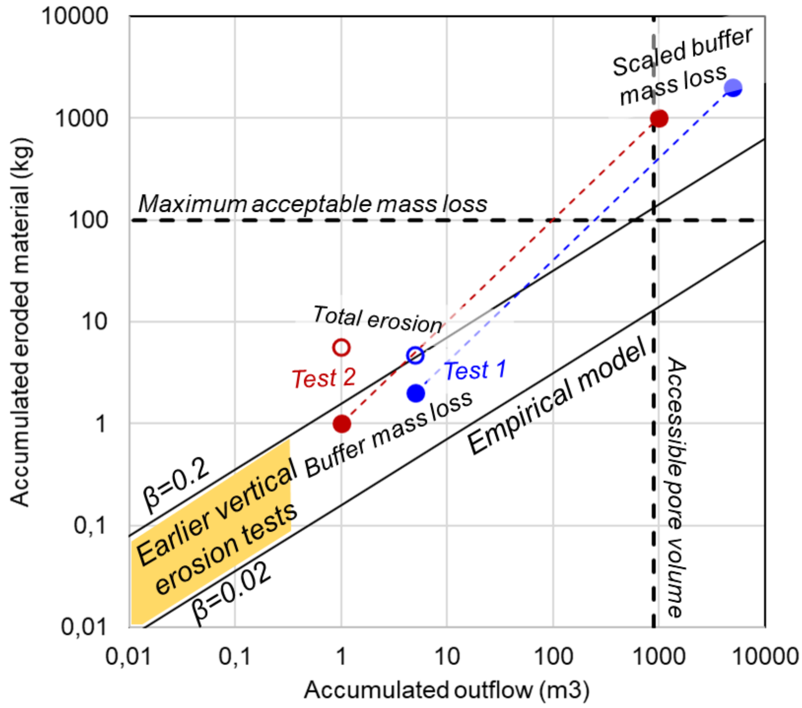


Figure 7-2. *Estimation of buffer mass loss from a deposition hole which acts as the sole inflow point in an entire deposition tunnel: i) with empirical model, i.e. through extrapolation of data from earlier erosion tests; and ii) trough scaling of experimental data from test presented in this study; Test 1 (blue) and Test 2 (red).*

8 Concluding remarks

The presented scale tests in scale 1:10 were performed with the objective to quantify the buffer mass loss for specific inflow rates and test durations, which together corresponds to total volumes flowing through the test setup. It was found that the buffer mass loss for a total volume of 1 and 5 m^3 amounted to approximately 1 and 2 kg, respectively. The test scale implied that the mass loss and the total volume for a full-scale case would be 1000 times higher, i.e. 1-2 tons for a volume of 1000-5000 m^3. This loss seems to be representative for a full-scale tunnel with the main part of the groundwater inflow entering through a single deposition hole, since the accessible pore volume of the pellets filling in a backfilled tunnel is approximately 1000 m^3. However, this would exceed the requirement for the maximum acceptable mass loss with approximately one order of magnitude.

The ultimate goal of investigating the piping and erosion processes is to estimate the number of deposition holes that potentially may exhibit an unacceptable mass loss. Such estimations have previously been based on the empirical model, which describes a relation between the accumulated water volume and the mass loss. The presented scale tests indicate however that this model quite significantly underestimates the mass loss for the typical case with a volume that corresponds to the total accessible pore volume of a backfilled deposition tunnel. An alternative, and possibly less conservative approach, may therefore be to estimate the total water volume that actually enters a deposition hole through rapid channel transport before the water uptake in the buffer leads to the build-up of pore pressure, and ultimately the sealing of such channels.

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Appendix 1 Installation of buffer in deposition hole, Test 1.

No.	Buffer blocks							Pellets installation						
	Dy	di	Height	Mass	Bulk density	Water content	Dry density	Dy	di	Height	Mass	Bulk density	Water content	Dry density
	mm	mm	mm	kg	kg/m3	%	kg/m3	mm	mm	mm	kg	kg/m3	%	kg/m3
Cyl.1	164.7	0	49.2	2.026	1933	17.7	1642	175	164	49.2	0.128	888	12.4	790
Ring1	164.7	106.0	50.1	1.271	2033	17.7	1727	175	164	50.1	0.128	872	12.4	776
Ring2	164.7	106.0	49.8	1.259	2026	17.7	1721	175	164	49.8	0.142	974	12.4	866
Ring3	164.7	106.0	50.0	1.269	2034	17.7	1728	175	164	50.0	0.142	970	12.4	863
Ring4	164.7	106.0	49.6	1.269	2050	17.7	1742	175	164	49.6	0.135	929	12.4	827
Ring5	164.7	106.0	50.0	1.262	2022	17.7	1718	175	164	50.0	0.128	874	12.4	778
Ring6	164.7	106.0	50.1	1.274	2038	17.7	1731	175	164	50.1	0.128	872	12.4	776
Ring7	164.7	106.0	49.4	1.257	2041	17.7	1734	175	164	49.4	0.126	872	12.4	775
Ring8	164.7	106.0	49.4	1.268	2057	17.7	1747	175	164	49.4	0.126	871	12.4	775
Ring9	164.7	106.0	49.6	1.261	2037	17.7	1731	175	164	49.6	0.122	840	12.4	747
Ring10	164.7	106.0	36.2	0.923	2043	17.7	1736	175	164	36.2	0.113	1066	12.4	948
Cyl 2	164.7	0	49.2	2.052	1958	17.7	1663	175	164	49.2	0.113	784	12.4	698
Cyl 3	164.7	0	49.1	2.057	1966	17.7	1671	175	164	49.1	0.113	786	12.4	699
Cyl 4	164.7	0	49.2	2.057	1962	17.7	1667	175	164	49.2	0.144	999	12.4	889
Cyl 5	164.7	0	48.9	2.053	1971	17.7	1674	175	164	48.9	0.144	1005	12.4	895
Cyl 6	164.7	0	49.1	2.053	1963	17.7	1667	175	164	49.1	0.192	1335	12.4	1188
Sum			778.9	24.611							2.124			

Appendix 2 Installation of backfill in the deposition tunnel, Test 1.

Layer	Backfill blocks			Pellets		
	Bulk mass	Water content	Dry mass	Bulk mass	Water content	Dry mass
	kg	%	kg	kg	%	kg
Bottom layer				18.54	15.2	16.10
Layer 1	34.88	15.8	30.12	4.09	15.2	3.55
Layer 2	34.98	15.8	30.20	4.25	15.2	3.69
Layer 3	35.02	15.8	30.24	4.31	15.2	3.74
Layer 4	34.80	15.8	30.05	4.00	15.2	3.48
Layer 5	34.87	15.8	30.11	3.87	15.2	3.36
Layer 6	34.74	15.8	30.00	3.98	15.2	3.46
Layer 7	14.55	15.8	12.57	16.62	15.2	14.43
Sum	223.83		193.29	59.67		51.80

Appendix 3 Installation of buffer in deposition hole, Test 2.

No.	Buffer blocks							Pellets installation						
	Dy	di	Height	Mass	Bulk density	Water content	Dry density	Dy	di	Height	Mass	Bulk density	Water content	Dry density
	mm	mm	mm	kg	kg/m3	%	kg/m3	mm	mm	mm	kg	kg/m3	%	kg/m3
Cyl.1	164.7	0	49.5	2.046	1940	17.7	1648	175	164	49.5	0.119	821	12.4	730
Ring1	164.7	106.0	50.3	1.254	1998	17.7	1697	175	164	50.3	0.121	821	12.4	731
Ring2	164.7	106.0	50.3	1.264	2014	17.7	1711	175	164	50.3	0.121	821	12.4	731
Ring3	164.7	106.0	50.5	1.256	1993	17.7	1693	175	164	50.5	0.158	1068	12.4	950
Ring4	164.7	106.0	50.3	1.270	2023	17.7	1719	175	164	50.3	0.158	1073	12.4	954
Ring5	164.7	106.0	49.8	1.268	2040	17.7	1733	175	164	49.8	0.144	987	12.4	878
Ring6	164.7	106.0	50.5	1.254	1990	17.7	1690	175	164	50.5	0.144	974	12.4	866
Ring7	164.7	106.0	49.9	1.266	2033	17.7	1727	175	164	49.9	0.144	985	12.4	877
Ring8	164.7	106.0	50.2	1.266	2021	17.7	1717	175	164	50.2	0.121	820	12.4	729
Ring9	164.7	106.0	49.4	1.250	2028	17.7	1723	175	164	49.4	0.121	833	12.4	741
Ring10	164.7	106.0	32.0	0.815	2041	17.7	1734	175	164	32.0	0.132	1405	12.4	1250
Cyl 2	164.7	0	49.2	2.060	1965	17.7	1670	175	164	49.2	0.132	914	12.4	813
Cyl 3	164.7	0	49.2	2.060	1965	17.7	1670	175	164	49.2	0.132	914	12.4	813
Cyl 4	164.7	0	49.2	2.032	1939	17.7	1647	175	164	49.2	0.163	1131	12.4	1006
Cyl 5	164.7	0	48.8	2.049	1971	17.7	1674	175	164	48.8	0.163	1140	12.4	1015
Cyl 6	164.7	0	49.3	2.058	1959	17.7	1665	175	164	49.3	0.202	1399	12.4	1245
Sum			778.4	24.468							2.273			

Appendix 4 Installation of backfill in the deposition tunnel, Test 2.

Layer	Backfill blocks			Pellets		
	Bulk mass	Water content	Dry mass	Bulk mass	Water content	Dry mass
	kg	%	kg	kg	%	kg
Bottom layer				19.92	15.2	17.29
Layer 1	34.96	15.8	30.19	3.92	15.2	3.40
Layer 2	35.61	15.8	30.75	4.55	15.2	3.95
Layer 3	34.89	15.8	30.13	4.01	15.2	3.48
Layer 4	34.99	15.8	30.22	4.20	15.2	3.65
Layer 5	34.45	15.8	29.75	4.01	15.2	3.48
Layer 6	35.04	15.8	30.26	4.01	15.2	3.48
Layer 7	14.17	15.8	12.23	16.34	15.2	14.19
Sum	224.11		193.53	60.95		52.91