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Vapor circulation in a buffer-backfill system

Laboratory tests

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Abstract

The KBS-3V concept for a repository for spent nuclear fuel consists of an underground facility with more than 200 tunnels, each measuring several hundred meters. In the tunnel floors, eight-meter-deep deposition holes will be bored vertically. The spent fuel is encapsulated in copper canisters which are placed in the deposition holes. The canisters are surrounded by highly compacted buffer blocks, and the deposition tunnels backfilled with bentonite materials. Heat will be produced from the decay of the radioactive waste.

This report presents experimental work performed with the aim of investigating the moisture redistribution due to natural convection in the buffer and backfill when these are installed in dry conditions. The understanding regarding the influence of this natural convection on the moisture redistribution within the buffer and backfill is important to assess the risk of extensive dehydration of the buffer and possible enrichment of salt.

Two types of tests were performed: 1) Scale tests in scale ~ 1:5 and 2) Gap tests with a horizontal thermal gradient. The aim of the scale tests was to mimic the conditions in a dry deposition hole and a dry tunnel section as far as possible. Tests were performed using both solid buffer blocks and segmented buffer blocks. The tests had a simplified test geometry and well-defined boundary conditions. The aim of the gap tests was to achieve basic information regarding the influence of the natural convection on the moisture redistribution within the buffer. The gap tests were performed using both pellets and blocks.

Sammanfattning

KBS3-V konceptet för ett slutförvar för utbränt kärnbränsle består av en underjordsanläggning med hundratals meter långa deponeringstunnlar, längs vilka åtta meter djupa deponeringshål skall borras i tunnelgolvet. Kärnbränslet skall placeras i kopparkapslar som i sin tur skall placeras i deponeringshålen. Kopparkapslarna skall omges av högkompakterade buffertblock tillverkade av bentonit. Värme kommer att produceras som följd av sönderfall av det radioaktiva avfallet.

Denna rapport presenterar olika försök som genomförts med syfte att undersöka hur buffert och återfyllning som installerats under torra förhållande påverkas av naturlig konvektion och därav följande omfördelning av fukt. Förståelsen för den naturliga konvektionens betydelse för omfördelningen av fukt i buffert och återfyllning är viktig för att kunna bedöma risken för omfattande uttorkning av bufferten och möjlig anrikning av salt.

Två typer av försök har genomförts: 1) Skalförsök i skala ~1:5 och 2) Spaltförsök med en horisontellt riktad termisk gradient. Syftet med skalförsöken var att, så långt som möjligt, efterlikna förhållandena i ett torrt deponeringshål i en torr tunnelsektion. Försök gjordes dels med solida buffertblock och dels med segmenterade block. Försöken har haft en förenklad geometri och väldefinierade randvillkor. Syftet med spaltförsöken var att erhålla grundläggande information om hur termisk konvektion påverkar fuktomfördelningen i bufferten. I dessa försök har både pellets och block testats.

Contents

1	**Introduction**		**7**
2	**Material**		**9**
2.1	Block manufacturing		9
2.2	Pellets		10
3	**Tests in scale ~1:5**		**11**
3.1	General		11
3.2	Test equipment		12
	3.2.1	Design requirements	12
	3.2.2	Deposition hole and deposition tunnel	12
	3.2.3	Bentonite blocks and pellets	12
	3.2.4	Heater	12
	3.2.5	Top lid and bottom plate	13
	3.2.6	Insulation	13
	3.2.7	Instrumentation	13
	3.2.8	Gas pressure	14
3.3	Test matrix		15
3.4	Scale test 1: Buffer blocks (cylindrical and ring-shaped)		15
	3.4.1	Test preparation	15
	3.4.2	Registered data during test time	17
	3.4.3	Power consumption	20
	3.4.4	Dismantling	21
	3.4.5	Results from sampling	23
3.5	Scale test 2: Segmented buffer blocks		31
	3.5.1	Test preparation	31
	3.5.2	Registered data during test time	33
	3.5.3	Power consumption	35
	3.5.4	Dismantling	36
	3.5.5	Results from sampling	36
4	**Gap tests with horizontal thermal gradient**		**45**
4.1	General		45
4.2	Test equipment		45
	4.2.1	Test box	45
	4.2.2	Heating	45
	4.2.3	Instrumentation	45
4.3	Test matrix		46
4.4	Pretest		46
4.5	Gap test 1: Pellets		47
	4.5.1	Test preparation	47
	4.5.2	Registered data during test time	47
	4.5.3	Power consumption	49
	4.5.4	Dismantling and sampling	50
4.6	Gap test 2: Blocks		53
	4.6.1	Block manufacturing	53
	4.6.2	Test preparation	53
	4.6.3	Registered data during test time	54
	4.6.4	Power consumption	56
	4.6.5	Dismantling and sampling	56
5	**Comments and discussion**		**59**
5.1	Tests in scale 1:5		59
	5.1.1	Temperature distribution	59
	5.1.2	RH evolution	60
	5.1.3	Water content distribution	60

5.2 Gap tests with horizontal thermal gradient 62
5.2.1 Gap test 1: Pellets 62
5.2.2 Gap test 2: Blocks 62
5.3 Evaluation of water content vs temperature relations 63
6 Concluding remarks 65
References 67
Appendix 1 Scale test 1 69
Appendix 2 Scale test 2 71
Appendix 3 Gap test with blocks 75
Appendix 4 Result from Scale test 1, direction B 77
Appendix 5 Result from Scale test 1, direction C 79
Appendix 6 Result from Scale test 1, direction D 81
Appendix 7 Results from Scale test 2, direction B 83
Appendix 8 Results from Scale test 2, direction C 85
Appendix 9 Results from Scale test 2, direction D 87

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. Backfilling of the deposition tunnels above the deposition holes is planned to be installed as pre-compacted blocks placed in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls.

Heat will be produced from the decay of the radioactive waste placed in the canisters. In sections where both the deposition hole and the tunnel above is dry i.e., the water inflow from the rock is negligible, the heat will result in a redistribution of the moisture present in the bentonite from warm to cold parts of the buffer and backfill. The understanding regarding the influence of the natural convection on the moisture redistribution is important to assess the risk of extensive dehydration of the buffer and possible enrichment of salt.

The newly suggested change of the buffer design, including segmented buffer blocks, will introduce a lot of gaps within the buffer volume and this is also believed to affect the transport of vapor (Nord et al. 2020). Tests were therefore performed using both solid buffer blocks and segmented buffer blocks.

This report describes two types of laboratory experiments that were performed with the aim to investigate the influence of natural convection on the moisture redistribution within the buffer and backfill.

Tests in scale ~1:5

The aim of these tests was to, as far as possible, mimic the conditions in a dry deposition hole and a dry tunnel section. The tests had a simplified test geometry and well-defined boundary conditions. They were thus not an exact physical model of the real case, but instead a test case which was intended to be used for model validation. Two tests were performed, one with solid buffer blocks (cylindrical and ring-shaped) and one with segmented buffer blocks.

Gap tests with a horizontal thermal gradient

The aim of these tests was to achieve basic information regarding the influence of the natural convection on the moisture redistribution within the buffer. The test arrangement was rather similar to the tests with thermal gradient presented in Åkesson et al. (2020), but with the important differences that 1) the temperature gradient in the new tests was horizontally oriented and 2) that the relation between the bottom area and the length was considerably larger compared to the earlier tests. Two tests were performed, one with a pellet filling and one with buffer blocks.

The bentonite materials used in the tests, both blocks and pellets, are described in Chapter 2. The scale tests and the gap tests are presented in Chapter 3 and 4, respectively. The test results are briefly discussed in Chapter 5, and some concluding remarks are given in Chapter 6. Detailed descriptions of the installations and the results, especially from the scale tests, are given in a set of appendices at the end of the report.

2 Material

2.1 Block manufacturing

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

The as-delivered material had a water content of 12 %. Before compaction to blocks, the material was mixed with water in an Eirich-mixer, to achieve a target water content of 17 %. The target dry density for the compacted blocks was 1 650 kg/m^3. This density is somewhat low compared to the reference design but was chosen to decrease the possible swelling pressure that may occur at some positions due to vapor transport from the heated volume to the colder surrounding volume. A high swelling pressure could be problematic for the test equipment which mainly was manufactured of plastic materials, see further description in Section 3.2.

Two different compaction moulds were used. The difference in block size also made it necessary to use different press equipment to achieve the desired compaction pressure.

- **Cylindrical and ring-shaped blocks with an outer diameter of 275/280 mm**. These blocks were compacted in a large press available at LTH in Lund, see photo to the right in Figure 2-1. The ring-shaped blocks had an inner diameter of 110 mm. The blocks were somewhat conical which means that the diameter at the top was 275 mm and at the bottom 280 mm. The compaction pressure was approximately 20 MPa. Bricks with the approximate dimensions 200 × 100 × 98 mm intended to be used in one of the gap tests, were subsequently sawed out from some of the cylindrical blocks by use of a bandsaw.
- **Cylindrical blocks with a diameter of 108 mm**. These blocks were used as a center block in the ring-shaped blocks above the heater in the tests with segmented blocks, see the design of segmented blocks provided in Figure 3-19. The blocks were compacted in Clay Technology´s laboratory, see photo to the left in Figure 2-1. After compaction the blocks had a diameter of 115/117 mm and were therefore machined to the desired diameter, 108 mm, in a lathe. The compaction pressure was approximately 20 MPa.

Figure 2-1. *Left: Block manufacturing at Clay Technology. Right: Block manufacturing of blocks with an outer diameter of 275/280 mm using the 1 000-ton press at LTH Lund.*

2.2 Pellets

The pellets used in the tests came from two old batches originally manufactured for different large-scale tests performed at the Äspö HRL. The pellets have been manufactured at two different occasions with almost the same shape. Both pellet types were manufactured of MX-80 bentonite from Wyoming, USA.

- **Pellets used in the Scale Tests:** These pellets were manufactured by the company Sahut Conreur in France. The individual pellets are shaped as small pillows with the approximate dimensions 16 × 16 × 8 mm, see photo provided in Figure 2-2 (left photo). The initial water content was 14.1 %.
- **Pellets used in the gap test:** These pellets were manufactured by the company Hosokawa Alpine (Bepex), Germany. The individual pellets are shaped as small pillows with the approximate dimensions 16 × 16 × 8 mm, see photo provided in Figure 2-2 (right photo). The initial water content was 11.4 %.

Figure 2-2. *Photo showing the pellets used in the tests. Left photo: Pellets used in the scale tests. Right photo: Pellets used in the gap test.*

3 Tests in scale ~1:5

3.1 General

The aim of these tests was to simulate the conditions in a dry part of a spent fuel repository (deposition hole and tunnel) to evaluate how the heat generated by the spent fuel affects the moisture distribution in the bentonite buffer and backfill. Several simplifications were made when constructing the geometry of the tests, as is described below. However, great care was taken to ensure that the boundary conditions were well defined. Hence, while not an exact physical model of the real case, the results can be used for model validation, as well as to assess the impact of using segmented blocks and to evaluate general trends for the evolution in a dry region of a repository.

The scale of the tests was approximately 1:5. A 2.4-meter-long vertical tube represented the deposition hole and the tunnel backfill above, starting from the bottom ring-shaped block, through the tunnel section above, and up to the tunnel ceiling, see red rectangle in the left figure in Figure 3-1.

The geometry of the deposition hole test was a relatively accurate representation of the real case, with the only notable exception being the design below the canister: the bottom block was not included in the test setup to simplify the power supply to the heater.

The representation of the tunnel section above the deposition hole was, however, greatly simplified. Nevertheless, as in the reference design of the tunnel backfill, the test setup involves a central positioned block stack and a pellet-filled gap along the outer border.

The pellet filled gap at the top had an intended height of 200 mm. Since the pellet filling has a lower density, it will be compressed by the buffer blocks in case these swells due to redistribution of water caused by vapor transport from the warm regions near the heater to the colder regions further away. The height was chosen to minimize the risk of high local swelling pressures near the top of the test setup.

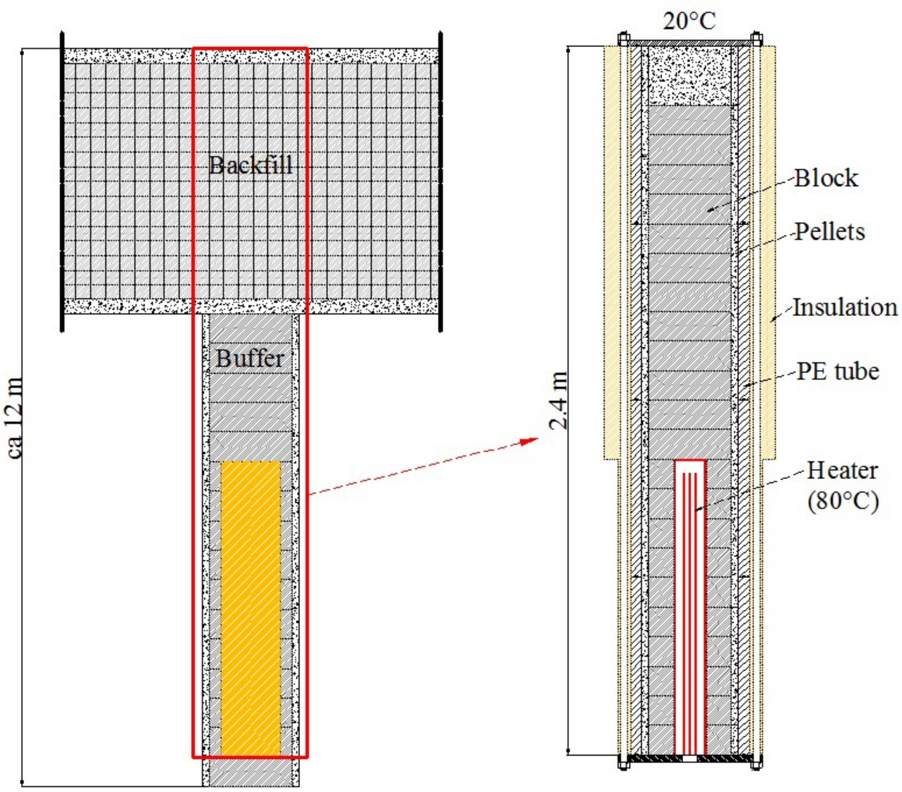


Figure 3-1. *Schematic overview showing the design of the scale tests.*

3.2 Test equipment

3.2.1 Design requirements

The main requirements on the test equipment were:

- **Thermal conductivity**. To make the thermal behavior as realistic as possible, it was important to minimize heat transfer in the test setup. Therefore, most of the parts were manufactured from different plastic materials.
- **Strength**. The construction should be strong enough to withstand a certain swelling pressure from the bentonite. This is a scenario that could happen if water was transported from the heated part to the cold parts. The outer plastic tube could withstand an inner pressure of 1.6 MPa (the expected swelling pressure is well below this limit since no external water will be added during the test).
- **Temperature**. The central heater had a target temperature of 80 °C. The bottom plate, on which the heater was resting, must withstand this temperature for long time.

The detailed design of the test equipment is shown in Figure 3-2. The various parts included in the design are described in the sections below.

3.2.2 Deposition hole and deposition tunnel

The deposition hole and the deposition tunnel were represented by a PE (polyethylene) tube. The tube had an outer diameter of 400 mm and an inner diameter of 327 mm and was divided into four parts, each with a length of 600 mm. The joints were sealed using O-rings and the different sections were locked against each other by threaded rods on the outside. The rods were fastened both in the bottom plate and in the top lid.

The scale of the inner diameter of the PE tube in relation to a full-scale deposition hole was 1:5.4.

3.2.3 Bentonite blocks and pellets

Bentonite blocks

The buffer blocks were manufactured using a material with the trade name Bara-Kade 1002 (sodium bentonite originating from Wyoming, USA). The block manufacturing is described in Chapter 2. The blocks had a target water content of 17 % and a target dry density of 1 650 kg/m^3.

Both ring-shaped and cylindrical blocks were manufactured. Both the ring-shaped and the cylindrical blocks had an outer diameter of 275/280 mm (somewhat conical). The ring-shaped blocks had an inner diameter of 110 mm. The height of the blocks was 100 mm.

Bentonite pellets

The pellets used in the tests are described in Chapter 2. They were manufactured using MX-80 bentonite from Wyoming and had a water content of 14.1 %. The individual pellets were shaped as small pillows with the approximate dimensions 16 × 16 × 8 mm. The width of the pellets-filled slot was approximately 25 mm.

3.2.4 Heater

The heater which represents a canister was manufactured out of a stainless-steel tube with a length of 1 000 mm and an outer diameter of 101.6 mm. The top of the tube had a welded lid while the bottom was open. This design made it possible to install an electric heater from below. The target temperature of the heater was 80 °C, controlled by a thermocouple placed on the top of the heater. In addition, three thermocouples measured the temperature on the heater surface at three different levels: 0.1, 0.5 and 0.9 meters from the bottom, Figure 3-2.

The applied electrical power was regulated to achieve a constant temperature of 80 °C at the top of the heater.

3.2.5 Top lid and bottom plate

The top lid was manufactured of PVC while the bottom plate was manufactured of PTFE. This material was chosen since it can withstand the rather high temperature from the heater (the bottom of the heater rests on the bottom plate). A steel plate was placed below the PTFE plate as a reinforcement.

3.2.6 Insulation

To reproduce the temperature distribution in an actual deposition hole as far as possible, and to achieve a well-defined temperature boundary, insulation made of glass wool was positioned around the test tube. The insulation around the lower meter, where the heater was placed, had a thickness of 45 mm while the insulation above had a thickness of 90 mm. Finally, insulation with a thickness of 180 mm was placed beneath the test equipment.

3.2.7 Instrumentation

The scale tests were relatively sparsely instrumented. In each test, ten thermocouples and three relative humidity sensors were positioned in the buffer, see drawing provided in Figure 3-2 showing the positions. Additionally, three thermocouples measured the temperature along the heater.

Thermocouples

Thermocouples were positioned at five different heights: 0.1, 0.5, 0.9, 1.1 and 2.2 meters from the bottom plate. At all five heights, thermocouples were placed at the inside of the PE tube i.e., at the periphery of the simulated deposition hole. At the three lower heights, thermocouples were also positioned at the inside of the ring-shaped blocks and on the heater surface. At the two higher heights, thermocouples were also positioned in the center of the blocks. In addition, one thermocouple was positioned on the top of the heater (temperature control of the electrical heater). The vertical positions of the thermocouples are shown in Figure 3-2.

The exact position of each thermocouple is described in Table 3-1. The first column gives the height from the bottom of the test setup, the second column the radius from the center of the test, and the last column the horizontal angle (clockwise) from the sampling direction A, see description of the sampling in Section 3.4.4.

Table 3-1. Position of thermocouples in the test setup.

Height mm	Radius mm	Angle °	Remark
100	50.8	180	Contact with heather
100	55	150	Inner gap
100	163.7	120	Outer gap
500	50.8	210	Contact with heather
500	55	180	Inner gap
500	163.7	120	Outer gap
900	50.8	180	Contact with heather
900	55	150	Inner gap
900	163.7	120	Outer gap
1 000	0	0	Top of heather
1 100	0	0	Center of block
1 100	163.7	120	Outer gap
2 200	0	0	Center of block
2 200	163.7	120	Outer gap

Relative Humidity sensors

Relative humidity sensors were positioned at three heights: 0.5, 1.1 and 2.2 meters from the bottom of the simulated deposition hole. The sensors were placed at the inside of the PE tube, i.e. at the periphery of the simulated deposition hole. The positions of the relative humidity sensors are also shown in Figure 3-2. In addition to the measured relative humidity, the sensors also measured temperature. The purpose of these measurements was to monitor the moisture redistribution process with a minimum of interference on the thermal conditions.

3.2.8 Gas pressure

The heating will result in vaporization of the water present in the bentonite which in turn could result in an increased gas pressure within the closed test volume. The gas pressure was measured at the top of the test cell, and it was also possible to open a valve to equalize the pressure with the outside air.

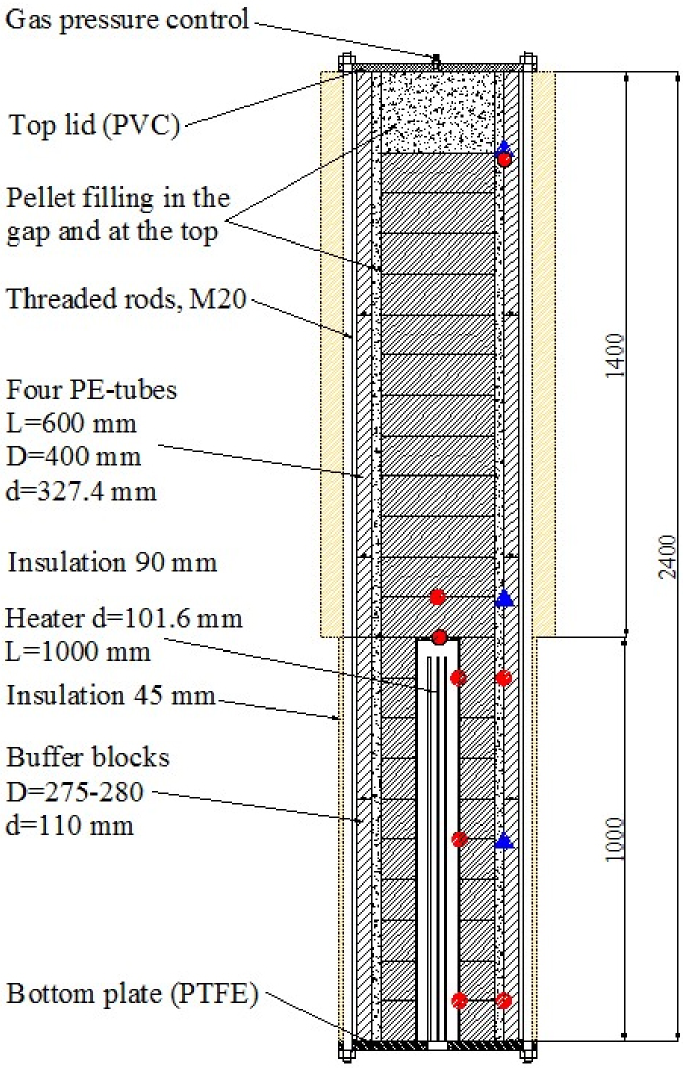


Figure 3-2. Schematic showing the design of the test equipment. The positions of thermocouples are shown by the red dots, and the positions of the relative humidity sensors by the blue triangles.

3.3 Test matrix

Two tests were performed, one simulating standard solid buffer blocks (cylindrical and ring-shaped) and one simulating segmented buffer blocks.

3.4 Scale test 1: Buffer blocks (cylindrical and ring-shaped)

3.4.1 Test preparation

Bentonite blocks

This test was performed using solid buffer blocks (cylindrical and ring-shaped). Ten ring-shaped blocks were positioned along the heater and twelve cylindrical shaped blocks were positioned above the heater. Photos of the two block types are provided in Figure 3-3.

All blocks were measured and weighed before installation, see data provided in Appendix 1.

Bentonite pellets

Pellets were installed in the outer gap between the blocks and the PE-tube. After installation of between one to three blocks (depending on whether the blocks were instrumented), pellets were filled up in the outer gap. The weight of the installed pellets was determined, see data provided in Appendix 1.

Assembly

The assembly of the test started with placing the heater on the bottom plate. The first ring-shaped block was thereafter positioned on the bottom plate and then the first section of the outer PE-tube was positioned. The next step was then to install the sensors at this level (0.1 m from the bottom plate).

The outer gap between the installed block and the outer wall was then filled with pellets. Blocks were thereafter installed up to the next instrumented level, 0.5 m from the bottom, see photo to the left in Figure 3-4. After installation of the sensors at this level, pellets were installed in the outer gap. The right photo in Figure 3-4 shows the completed installation of block, pellets, and sensors in the first PE-tube section. The assembly continued according to this procedure until all four PE-tubes were mounted together, and all twenty-two buffer blocks were installed together with all sensors. The uppermost 0.2 meters of the test volume were filled with pellets.

The left photo in Figure 3-5 shows the complete test setup. Four threaded rods kept all PE-tubes together to achieve a sealed test volume. The right photo in Figure 3-5 shows the test setup after wrapping it with insulation. Note the extra insulation around the bottom plate.

Figure 3-3. *Left: Ring-shaped block. Right: Cylindrical shaped block.*

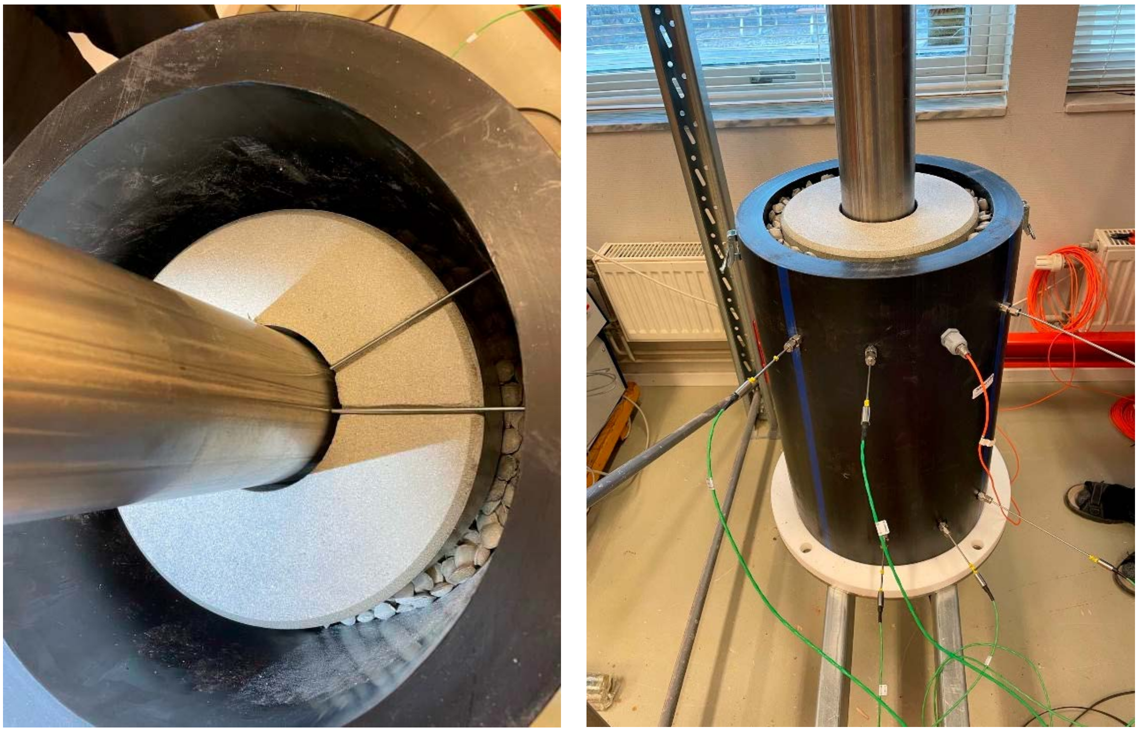


***Figure 3-4.** Left: Two thermocouples positioned on the surface of block no 5. One thermocouple was positioned against the heater, and one was positioned at the edge of the inner block surface. Right: The first section (0.6 m) has been installed.*

***Figure 3-5.** Left: The assembly of all parts have been successfully finished. Right: The test has been covered with insulation. The heater and bottom plate for the second test can be seen to the right in the photos.*

Installation data

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

Blocks

The average bulk density of the blocks was 1 923 kg/m^3. The bentonite had a water content of 17.4 % which means that the average dry density of the blocks was 1 638 kg/m^3.

Pellets

The average bulk density of the installed pellet filling was 1 038 kg/m^3. The pellets had a water content of 14.1 % which means that the average dry density of the pellet filling was 910 kg/m^3.

Test volume

The total test volume was 0.1937 m^3. In total 263.2 kg dry mass bentonite was installed in the test volume (blocks = 202.55 kg and pellets = 60.65 kg). This resulted in an installed average dry density in the test volume of 1 359 kg/m^3.

3.4.2 Registered data during test time

Temperature

The total duration of the test was 384 days. The graphs provided in Figure 3-6 and Figure 3-7 show the temperature development for Scale test 1.

Some comments on the temperature measurements are:

- The temperature on the heater varied between 72–82 °C at the upper half (thermocouples positioned at 0.5 and 0.9 meters) during the first 100 days but thereafter kept stable between 72–74 °C for the rest of the test duration. The temperature at the bottom of the heater (thermocouple positioned at 0.1 meter) was about 49 °C for the complete test duration.
- The temperature on the inner gap on the block side (4.3 mm from the heater surface), was somewhat lower than the heater temperature at the two upper measuring positions (0.5 and 0.9 meters), between 71 and 73 °C, but at the lower measuring point, 0.1 meter, the temperature was the same as on the heater surface, about 49 °C.
- The temperature at the outer gap, i.e., at the simulated rock surface, was about 42 °C at 0.1 meter, 54 °C at 0.5 meter and 58° at 0.9 meter.
- The temperature above the heater, at the 1.1-meter level, varied between 53 °C (at the outer gap) and 58 °C (at the center of the block stack).
- The temperature on the top of the blocks, at the 2.2-meter level, was the same at the outer gap and at the center of the block, approximately 31–32 °C.

The variation in temperature on the heater at level 0.5 and 0.9 meters during the first hundred days could not be seen in Test 2, see Section 3.5. Since the thermocouples were positioned perpendicular to the heater but not attached to it, the contact may be different between the two tests, and this is probably the explanation for the variation in temperature readings. Especially during the heating phase where some movements could occur.

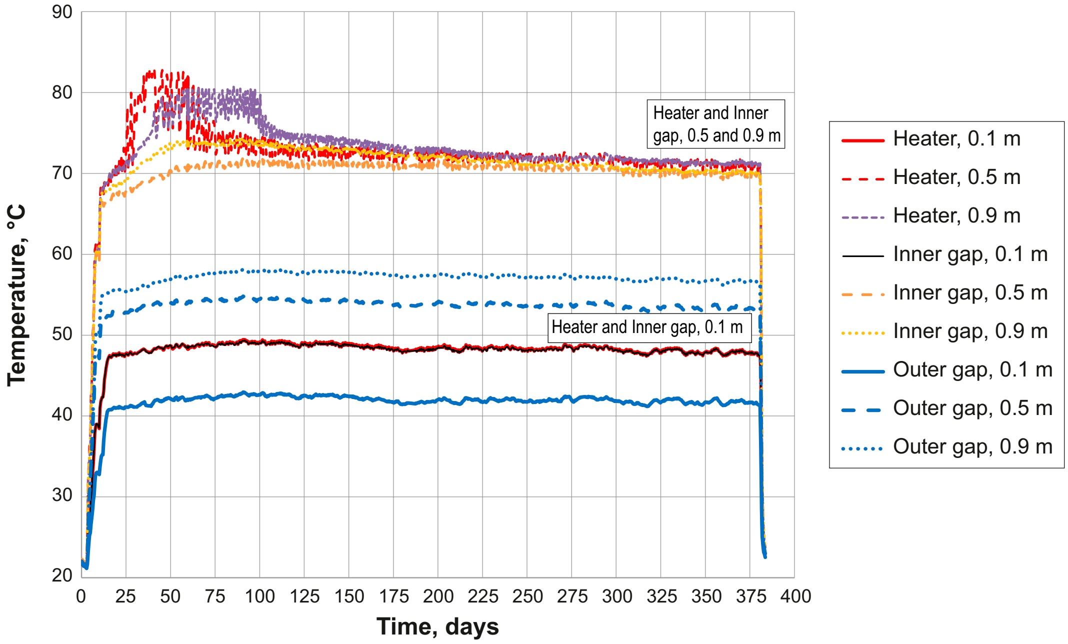


Figure 3-6. *Temperature development for the thermocouples in Scale test 1 placed at levels 0.1, 0.5 and 0.9 meters from the bottom.*

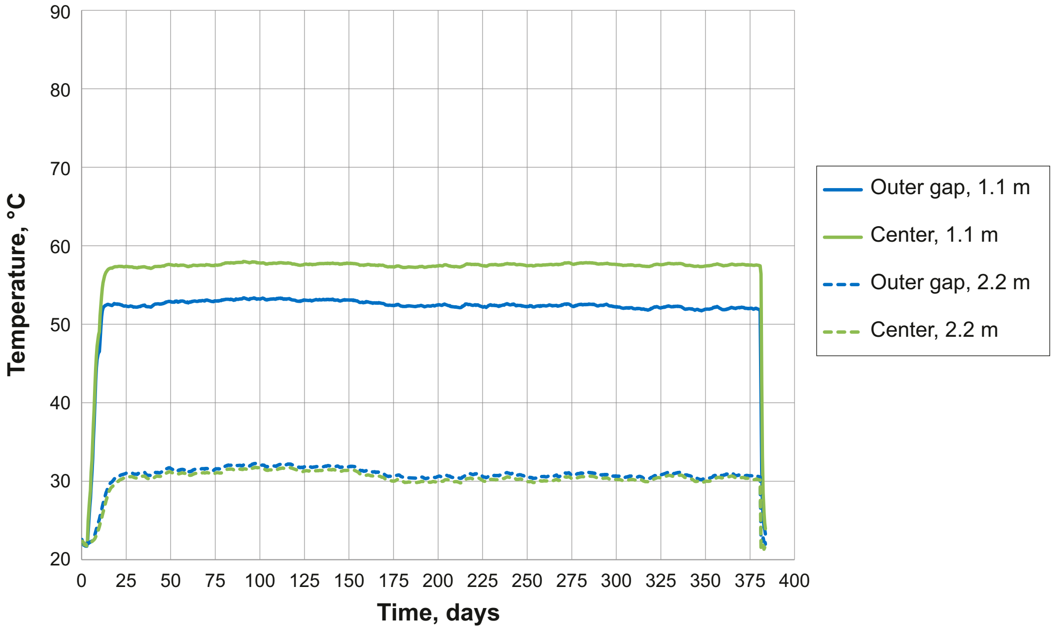


Figure 3-7. *Temperature development for the thermocouples in Scale test 1 placed at levels 1.1 and 2.2 meters from the bottom.*

Relative Humidity

The graph in Figure 3-8 shows the development of the measured relative humidity in Scale test 1.

Some comments on the relative humidity measurements:

- The start value of the relative humidity was between 65–67 % for all three sensors. This corresponds well with the water content of the installed MX-80 pellets which was 14.1 % (Dueck and Nilsson, 2010).
- The RH-sensor positioned 0.5 meters from the bottom reacted immediately when the temperature increased. The measured relative humidity reached 100 % after approximately 4 to 5 days which indicated that thermally induced vapor transport occurred horizontally from the heater towards the simulated rock wall. After an additional two weeks the sensor stopped delivering data, both relative humidity and temperature. The reason was probably that liquid water had reached the sensor body resulting in failure.
- The RH-sensor placed 1.1 meters from the bottom reacted shortly after the heating started. The registered relative humidity reached 100 % about one week after the sensor below (at 0.5 m). This indicated that vapor transport occurred horizontally from the heater towards the simulated rock wall also at this level. The sensor did, however, continue to deliver data and the registered relative humidity varied between 90 and 100 % for about five months whereafter the value stabilized at 100 %.
- The RH-sensor positioned 2.2 meters from the bottom reacted very slowly after the heating started. The registered relative humidity increased with time indicating that vertical vapor transport occurred in the bentonite around the heater. After about one month the registered relative humidity was about 72 % and after that there was a very small increase with time up to a maximum value of 79 %.
- The temperatures registered by the RH-sensors correlate well with the temperatures registered by the thermocouples at the same positions.

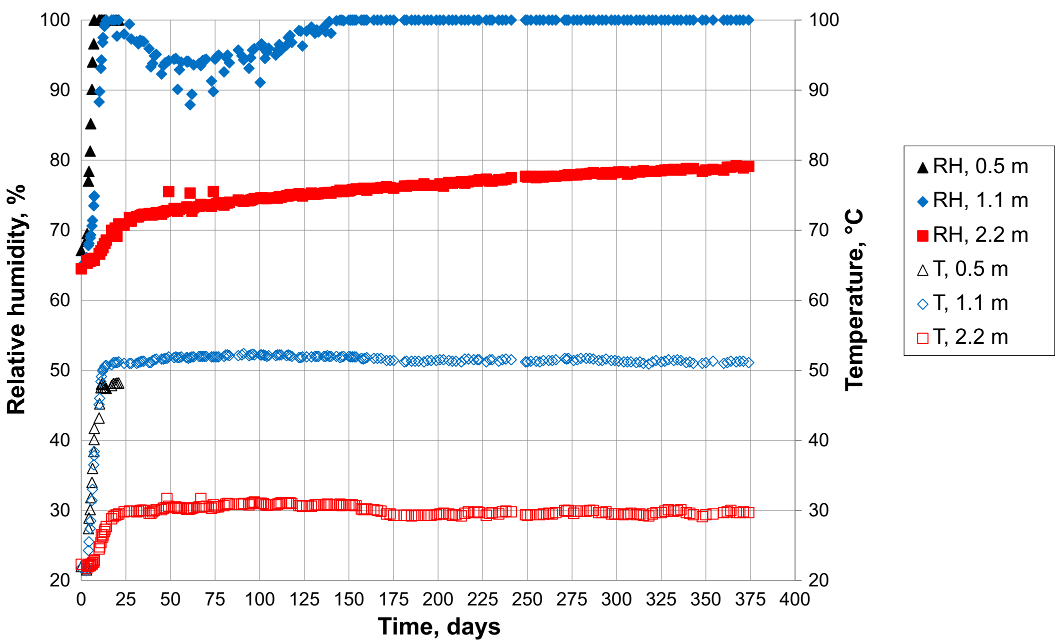


Figure 3-8. *Measured relative humidity in Scale test 1 at three levels (0.5, 1.1 and 2.2 meters from the bottom). The graph also shows the temperature measured with the same sensors at the same positions.*

Gas pressure

The gas pressure was measured at the top of the test cell. The graph in Figure 3-9 shows the measured gas pressure in Scale test 1. As shown in the graph, the gas pressure was very low during the complete test duration. However, between 200- and 340-days test duration, there was a small increase in pressure. The maximum gas pressure registered was approximately 6 kPa.

3.4.3 Power consumption

The power consumption was measured using a simple commercially available meter installed in a wall socket. The reading was done manually, and the accuracy of the measurement was declared by the manufacturer to be ± 1 %. The applied power varied approximately between 49 and 52 W, Figure 3-10, and the total power consumption was 457 kWh after a test duration of 384 days.

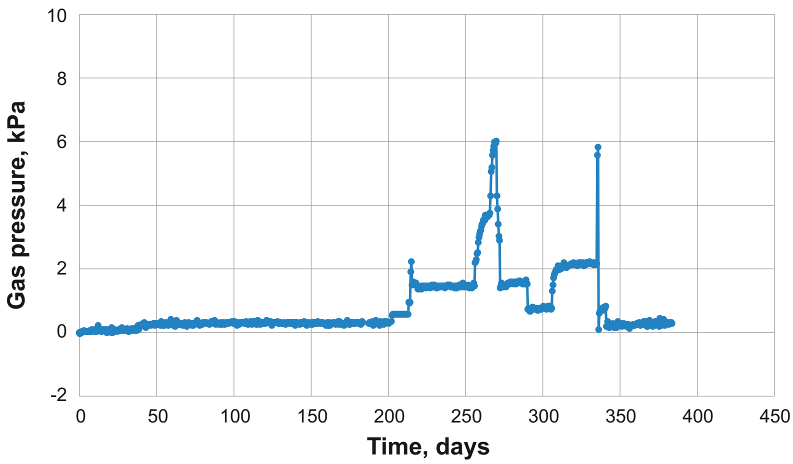


Figure 3-9. *Measured gas pressure at the top of the test setup of Scale test 1.*

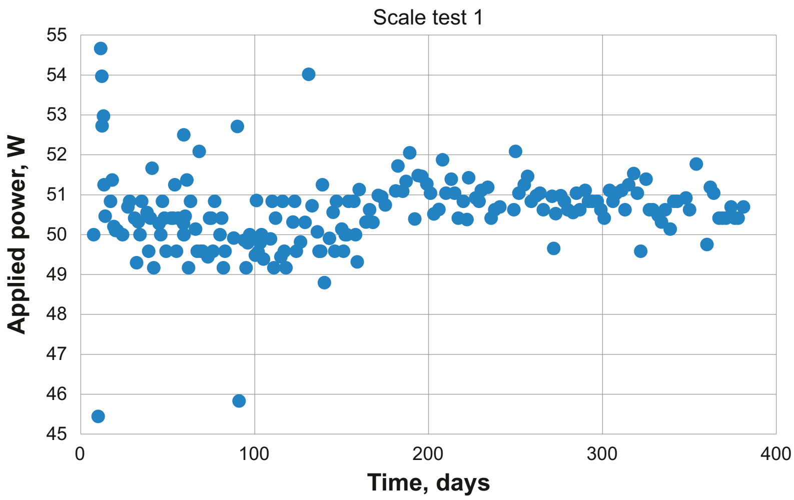


Figure 3-10. *The measured applied power plotted versus time for Scale test 1.*

3.4.4 Dismantling

General

After 384 days, the electrical heater was turned off as planned. Once the temperature had dropped close to room temperature, which took approximately 24 hours, the dismantling of the test started. The dismantling started from the top and the blocks were lifted out one by one. Since the outer PE-tube was divided into four sections, it was possible to lift one tube section when the blocks inside were removed. After removal of one block, samples were cut out and prepared for analyses before the next block was removed.

The water content and bulk density were determined in the blocks at 548 positions. In addition, the water content was determined in the pellet filling at 98 positions.

Water content, density, and degree of saturation

Water content

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

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

$$m_w = m_b - m_s \qquad 3\text{-}1$$

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

$$w = \frac{m_w}{m_s} \qquad 3\text{-}2$$

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:

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

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

$$\rho_b = \frac{m_b}{V} \qquad 3\text{-}4$$

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

$$\rho_d = \frac{\rho_b}{1 + w} \qquad 3\text{-}5$$

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

$$Sr = \frac{w \cdot \rho_b \cdot \rho_s}{\left[\rho_s \cdot [1 + w] - \rho_b\right] \rho_w} \qquad 3\text{-}6$$

In the calculations, a grain density (ρ_s) of 2 780 kg/m^3 have been used.

Sampling

The weight of all individual blocks and the surrounding pellets was determined in conjunction with the installation, see Section 3.4.1. The weight was again determined when the test was dismantled. With this data it was possible to check if the total installed mass still was the same, but also to get a rough estimate regarding the water movements within the test volume during the test time.

An extensive sampling was conducted to determine the water content and the dry density distribution within the test volume. All buffer blocks were sampled in four radial profiles. In addition, a vertical profile was sampled in the cylindrical shaped blocks above the heater. The position of all samples in the ring-shaped blocks is shown in Figure 3-11 and the sampling positions in the cylindrical shaped blocks in Figure 3-12. In addition, samples were also taken from the pellet-filled gap in all four directions (at every block) and at ten levels in the pellet filling at the top to determine the water content. Samples were thus taken at in total 692 positions in the blocks and at in total 98 positions in the pellet filling. With this data it was possible to achieve a good picture of the water content and density distribution within the test volume.

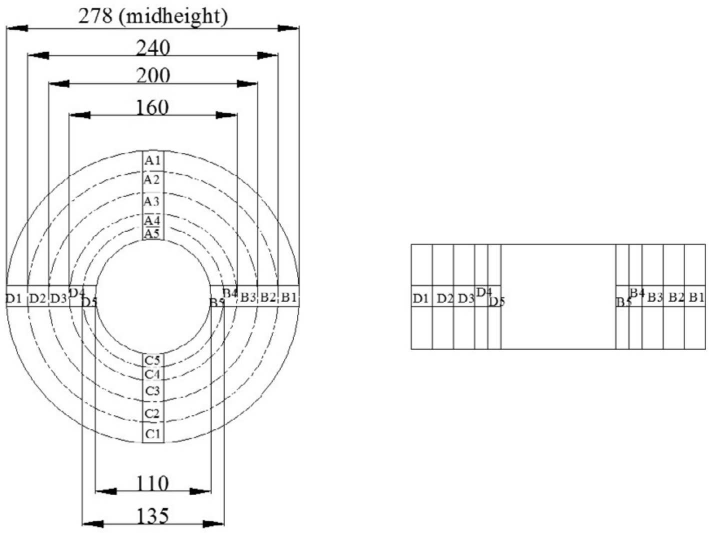


__Figure 3-11.__ Planned sampling of the ring-shaped blocks. The water content and density were determined at in total twenty sampling positions in every ring-shaped block.

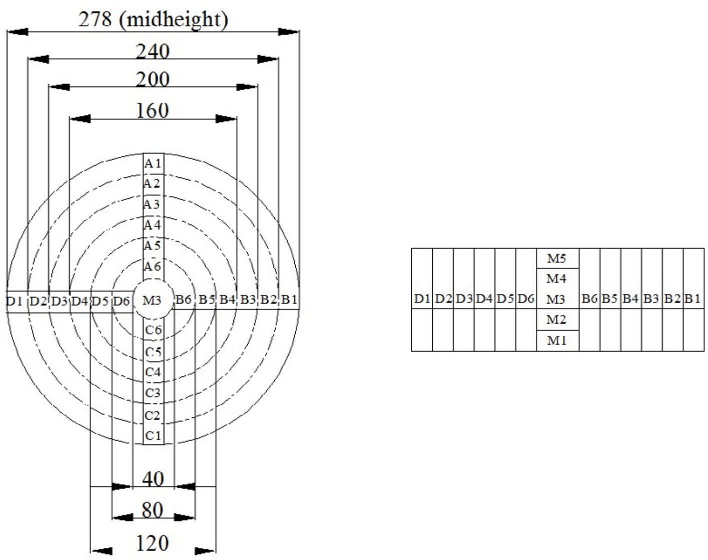


__Figure 3-12.__ Planned sampling of the cylindrical shaped blocks. The water content and density were determined at in total twenty-nine sampling positions in every cylindrical shaped block.

3.4.5 Results from sampling

General

The results from the sampling of the blocks and pellets in direction A is presented in Figure 3-13. The denominations in the graphs, A1 to A6, are the same as the sampling positions, see Figure 3-11 and Figure 3-12. Note that the sampling positions for A4 and A5 differ slightly between the ring-shaped and cylindrical blocks. The test series "Center" is a compilation of all samples taken from the center of the blocks positioned above the heater, denominated M1–M5 in Figure 3-12. The corresponding graphs for sampling directions B, C, and D can be found in Appendix 4, 5, and 6. The vertical black lines in the graphs indicate the initial conditions in the blocks regarding water content, dry density, and degree of saturation.

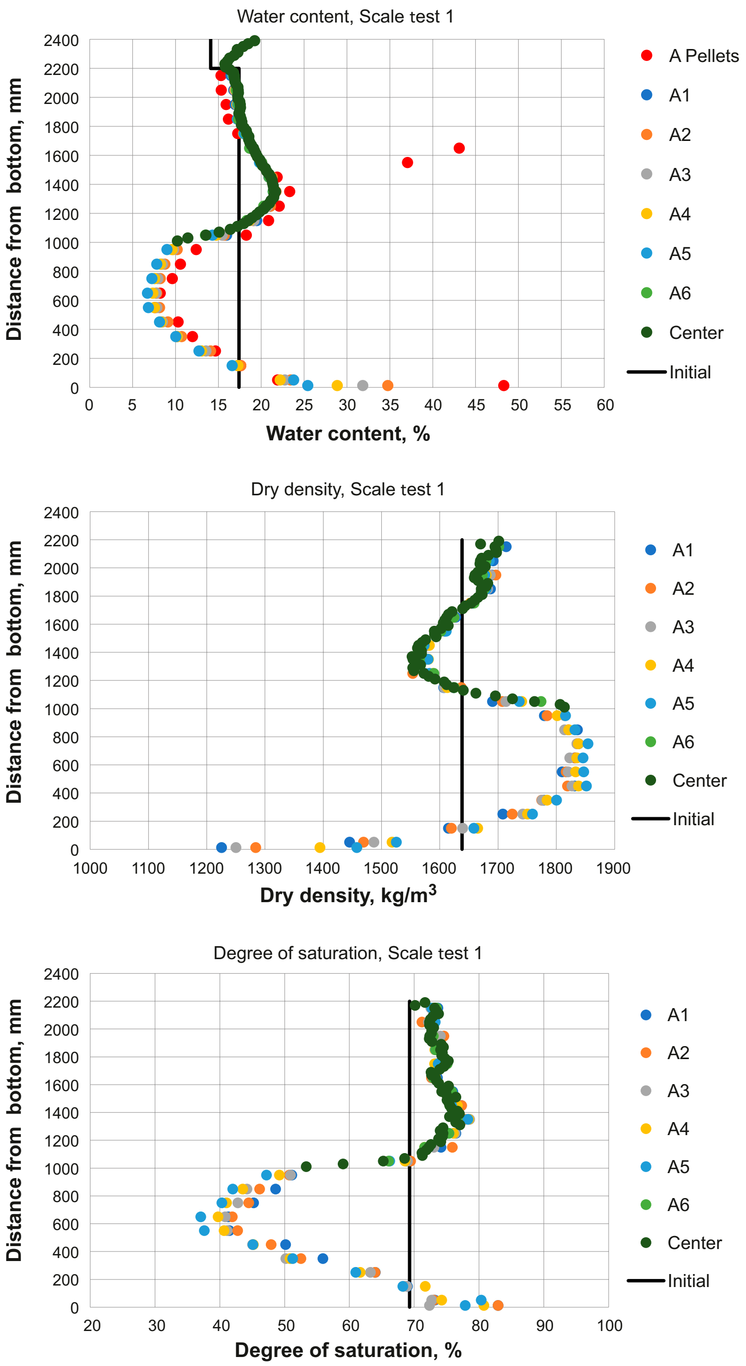


Figure 3-13. *Graphs showing the results from sampling of Scale test 1 in direction A. Upper: Water content distribution at different sampling positions (A1 to A6, see Figure 3-11 and Figure 3-12. Note that the sampling positions for A4 and A5 differ slightly between the ring-shaped and cylindrical blocks). Middle: Dry density distribution. Lower: Degree of saturation distribution.*

Comments on results from blocks around heater

The initial water content of the blocks was 17.4 % and of the pellet filling 14.1 %. The uppermost graph in Figure 3-13 shows that there has been an extensive dehydration of the blocks along the heater, down to a water content of 6 to 7 %. The dehydration of the blocks has resulted in shrinkage and by that an increased density, see middle graph in Figure 3-13. The initial average dry density of the blocks was 1 638 kg/m^3. As shown in the graph the dry density has increased up to 1 850 kg/m^3 between the level 400 to 1 000 mm. The shrinkage has also caused the blocks to crack, see photos provided in Figure 3-14. Radial fractures could be found in block R2–R10.

The bottom block (Block 1, 0–100 mm) had, however, instead taken up water. The bottom plate of the test setup has had a lower temperature, and moisture from the blocks above have condensed here, see photo (lower right) in Figure 3-14. The block had swelled and was stuck in the tube. Extra sampling was made at the level close to the bottom plate (0–25 mm).

Figure 3-14. *Photos taken in conjunction with dismantling of the blocks around the heater, Scale test 1. Upper left: Block 10. Some radial fractures can be seen on the block surface. Note the attachment point for the thermocouple on top of the heater. Upper right: Block 9. Two radial fractures. The block was divided in two pieces when it was removed. Lower left: Block 5. A few radial fractures could be seen. Lower right: The bottom block, Block 1, seen from below. The bottom surface and the lower part of the pellet filling was clearly wetted. The block had swelled and was stuck in the tube.*

Comments on results from blocks above heater

The uppermost graph in Figure 3-13 shows that the water content has increased in the blocks positioned between 1 100 to 1 800 mm. These blocks have also swelled and by that decreased in density. The block positioned just above the heater, 1 000–1 100 mm shows the opposite behavior (decreased water content and increased density). The four uppermost blocks, 1 800–2 200 mm above bottom, were almost unaffected. However, the three uppermost blocks had lost some water, see also Table 3-2, and seems to have shrunk somewhat since they have increased in density. The pellet filling at the top, 2 200–2 400 mm, had an initial water content of 14.1 %. The sampling showed that there had been some water uptake of the pellet filling and that there was a water content gradient from about 15.8 (level 2 200 mm) to 19.2 % (level 2 400). This effect is likely since the pellet filling at the top have had a lower temperature.

Photos taken in conjunction with the dismantling of the blocks above the heater are provided in Figure 3-15. As shown in the photos, several fractures were found in Block 11 (just above the heater), and in the block above, Block 12. Around Block 12, there was a local empty pocket in the pellet filling. Since the blocks around the heater had shrunk, the pellets had moved downwards leaving an empty pocket at this height.

The pellet filling around Block 16, in direction A, had a locally higher water content, upper left photo in Figure 3-15. The pellets stuck together and against the block surface.

Figure 3-15. *Photos taken in conjunction with the dismantling of the blocks above the heater, Scale test 1. Upper left: The pellet filling had locally a higher water content around Block 16 in direction A. Upper right: Block 11. This block had dehydrated, and radial fractures were formed in several directions. Lower left: Block 12. Some fractures were found in the block. There was also a locally empty pocket in the pellet filling. Lower right: Block 12 after sawing. Pieces fell off along the fractures.*

Comparison between installation data and dismantling data of the blocks

The individual blocks used in the test were weighed and measured at the time of installation, see Appendix 1. New measurements of diameter, height, and weight were made in conjunction with the dismantling and the differences between the measurements were calculated, see compilation of data in Appendix 1.

The changes in weight for the blocks and for the surrounding pellets for every block position are compiled in Table 3-2. The changes in mass of the pellets were calculated using the average water content that was determined at dismantling in four directions outside every block. The fourth column in Table 3-2, shows the sum of changes for both blocks and pellets and the last column shows the sum of changes for a certain block interval. The performed measurements give a good picture of what have happened during the test time:

- The two ring-shaped blocks and the surrounding pellets, positioned at the bottom along the heater, block position 1 and 2, have increased their weight within total 1.088 kg. This increase could possibly come from moisture that have been redistributed from blocks and pellets at block position 3 to 5, which in turn have lost 1.351 kg.
- The blocks and pellets at position 6 to 11 have lost in weight, in total 4.282 kg. This loss in weight could probably be caused by redistribution of moisture upwards, primarily to block positions 12 to 20. The increase in weight for block positions 12 to 20 is 2.887 kg.
- The blocks and pellets at position 21 to 22, were almost unaffected.
- The pellet filling positioned at the top of the test (approximately 200 mm high column) had increased in weight by 0.493 kg.
- The last row in Table 3-2 shows the sum of weight changes for both blocks (−3.26 kg) and for the pellets (2.025 kg). This means that there is a discrepancy in water of −1.234 kg. This discrepancy probably comes from problems both to determine the total water content in the pellet filling (large variations), variations in the initial water contents of both blocks and pellets, and possibly through drying during installation and dismantling. An alternative explanation would be leakage from the test volume, but this is not anything that has been detected and it is not considered likely.
- The total amount of water installed in the test was 43.8 kg (35.24 kg in the blocks and 8.55 kg in the pellets), see data provided in Table 5-1. Due to the heat from the simulated canister there have been a redistribution of the water: in total 5.702 kg have been dehydrated from the bentonite blocks and pellets around the heater (block position 3 to 11 and 21 to 22), and 4.468 kg have been taken up by the bentonite blocks and pellets below (block position 1 and 2), and by the blocks and pellets above (block position 12 to 20 and the pellets at the top), Table 3-2. As mentioned in the bullet point above, there are some possible explanations for the discrepancy.

Table 3-2. Discrepancy in weight measured during installation versus dismantling of the blocks and pellets in Scale test 1. Block 1–10: ring-shaped blocks, Block 11–22: cylindrical blocks.

Block no.	Δ mass block kg	Δ mass pellets kg	Sum changes per block position kg	Sum changes per block interval kg
1	0.727	0.288	1.015	
2	−0.011	0.084	0.073	1.088
3	−0.202	0.037	−0.165	
4	−0.496	−0.001	−0.497	
5	−0.665	−0.025	−0.690	−1.351
6	−0.754	−0.080	−0.834	
7	−0.808	−0.086	−0.894	
8	−0.802	−0.079	−0.881	
9	−0.770	−0.064	−0.834	
10	−0.634	−0.012	−0.646	
11	−0.277	0.084	−0.193	−4.282
12	0.091	0.129	0.220	
13	0.338	0.191	0.529	
14	0.397	0.195	0.592	
15	0.339	0.169	0.508	
16	0.235	0.222	0.457	
17	0.152	0.219	0.371	
18	0.046	0.077	0.123	
19	0.017	0.062	0.079	
20	−0.042	0.050	0.008	2.887
21	−0.077	0.039	−0.038	
22	−0.064	0.033	−0.031	−0.069
Pellets at top	na	0.493	0.493	0.493
Sum	−3.260	2.025	−1.234	−1.234

Comments

To give a good picture of the status of the bentonite at the end of the test, contour plots were made using an interpolation program. The plots, see Figure 3-16, Figure 3-17, and Figure 3-18, shows the water content, dry density, and degree of saturation distribution in two different cross sections: directions AC (left plots) and BD (right plots). In the contour plots with the dry density and degree of saturation distribution, the pellet filling is excluded (white fields) since the density was not determined there in conjunction with the dismantling.

As shown in the contour plots, the differences in water content and density were in general small in the radial direction while the differences in axial direction were rather large, Figure 3-16 and Figure 3-17. In general, the blocks around the heater have dried and the blocks above the heater have increased their water content. Moisture, in the form of vapor, has been redistributed downwards to the bottom plate where it has condensed and been taken up by the bottom block, Ring 1, and the surrounding pellets. Above the heater, there are also two points where water clearly has condensed more than in the surroundings. One of the points is at height 1 500–1 700 mm (Block 16 and Block 17). The vapor has condensed in the pellet filling in direction A, outside these blocks, see also photo provided in Figure 3-15 (upper left). Similar condensation behavior could be seen at level 1 200–1 300 mm (Block 13) in direction C.

The average installed dry density of the blocks was 1 638 kg/m^3. As shown in Figure 3-17, the density of the blocks around the heater and at the top of the heater, level 200 to 1 100 mm, was considerably higher, mainly between 1 700 and 1 850 kg/m^3. This increase in dry density depends on the fact that the blocks around the heater have dehydrated and shrunk. The opposite behavior could be seen in the blocks above the heater, level between 1 100 to 1 700 mm, where the blocks instead have swelled, due to moisture uptake, and decreased in density.

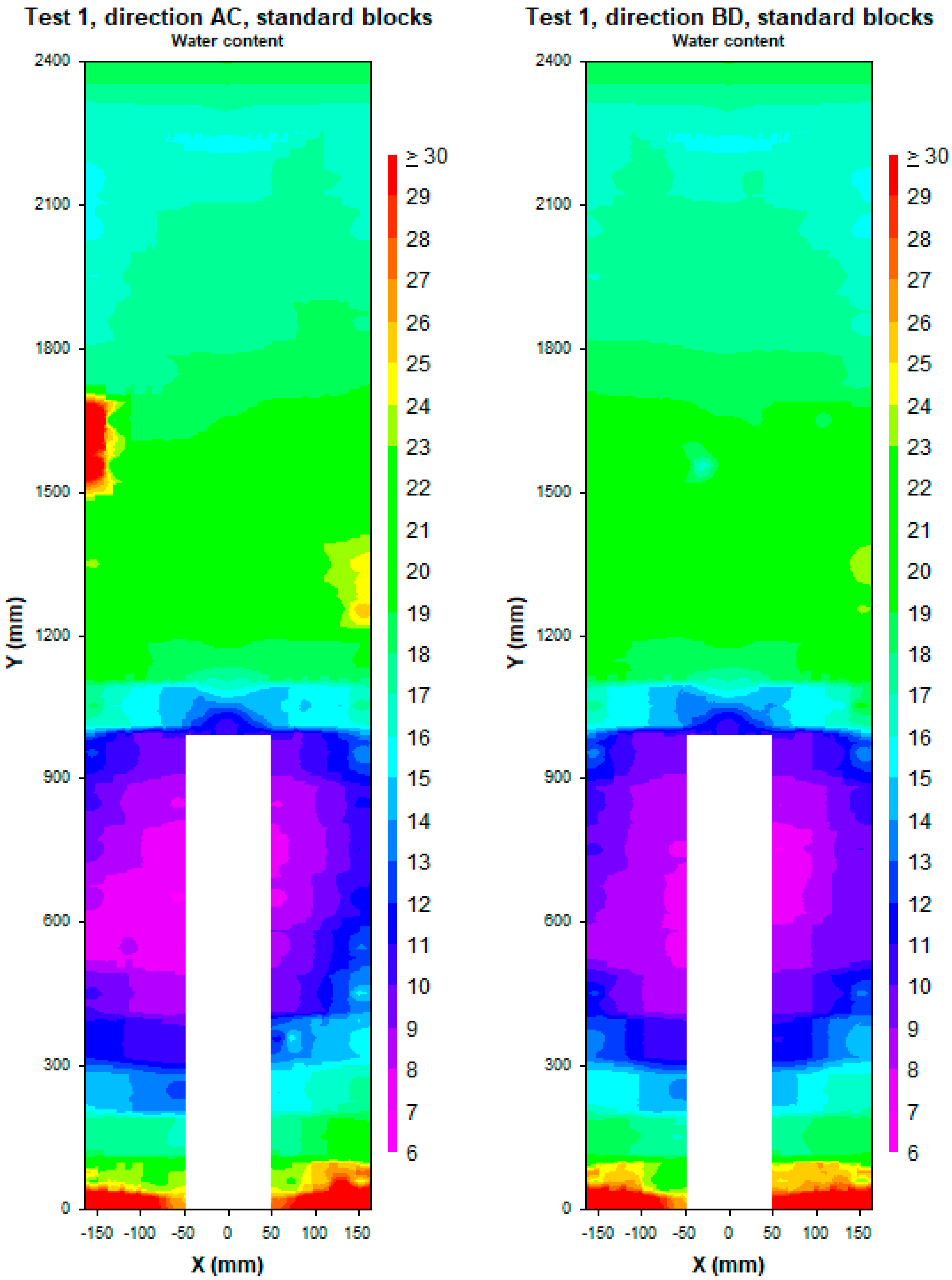


Figure 3-16. *Scale test 1. Contour plots showing the water content distribution (%) in the A and C sections (left) and the B and D sections (right).*

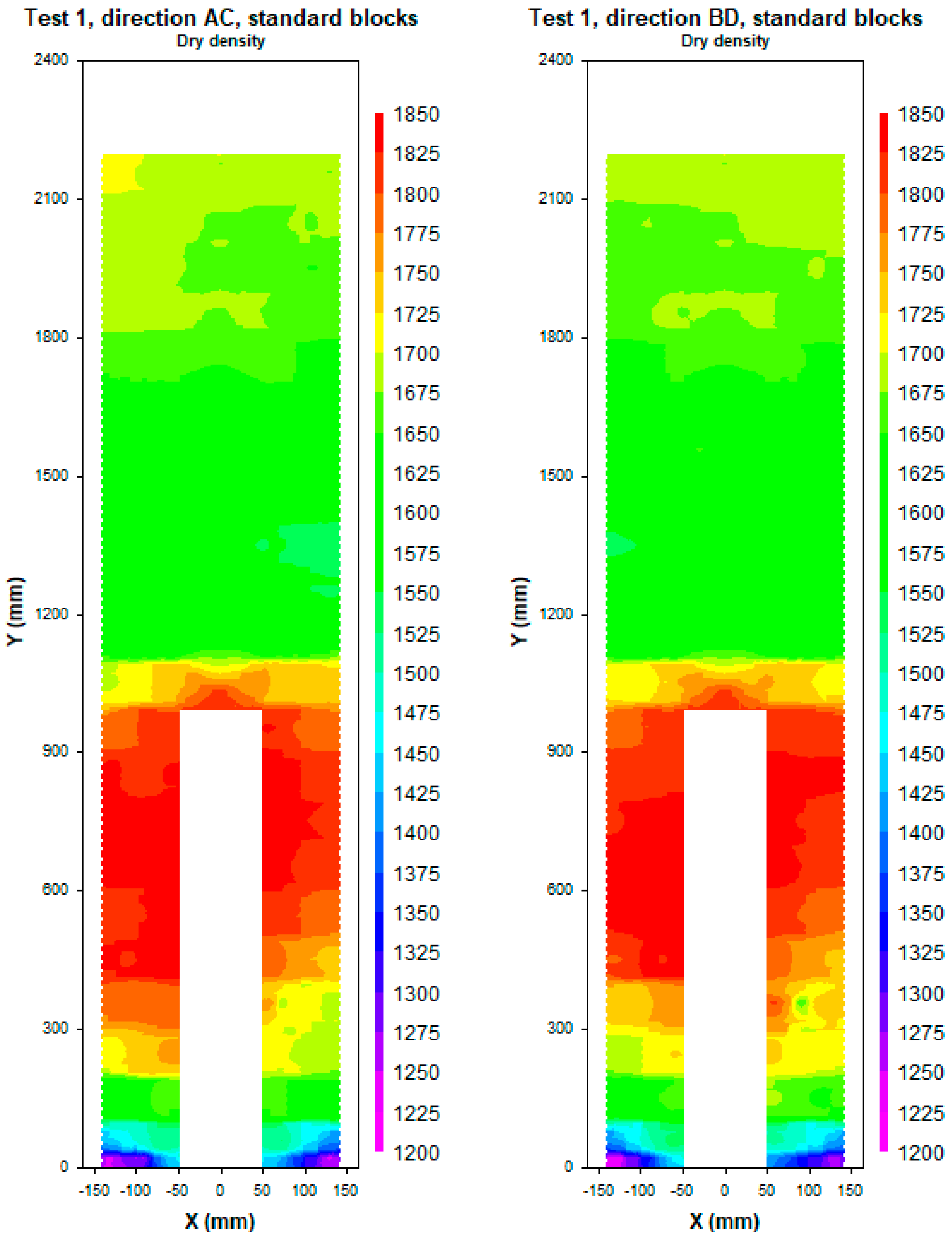


Figure 3-17. *Scale test 1. Contour plots showing the dry density distribution (kg/m³) in the A and C sections (left) and the B and D sections (right).*

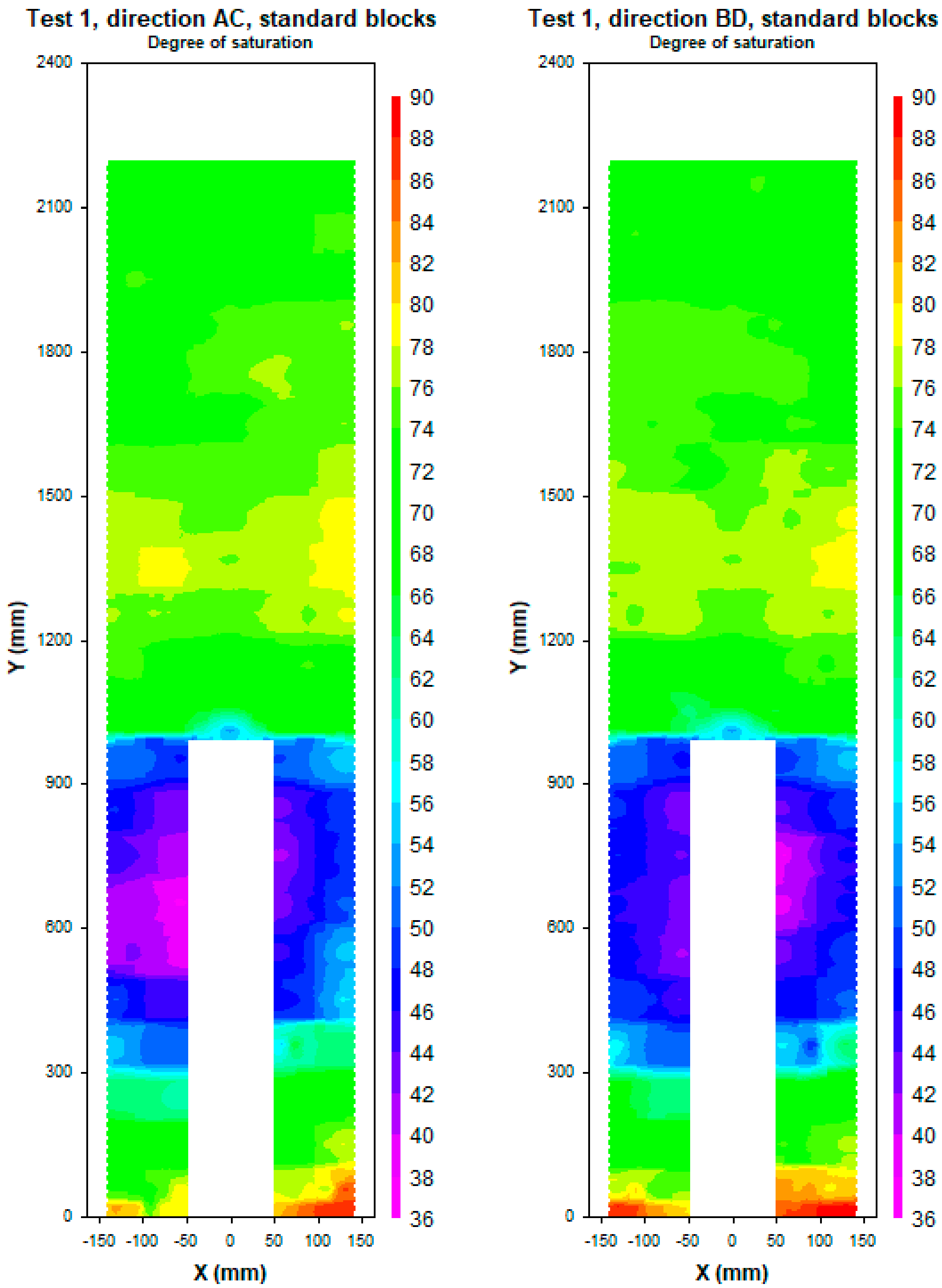


Figure 3-18. *Scale test 1. Contour plots showing the degree of saturation distribution (%) in the A and C sections (left) and the B and D sections (right).*

3.5 Scale test 2: Segmented buffer blocks

3.5.1 Test preparation

Bentonite blocks

This test was performed using so-called segmented blocks. By using segmented blocks instead of full-size blocks, the pressing force can be reduced, which means that smaller and cheaper presses can be used for the block manufacturing. In the technical development process, SKB has evaluated the use of segmented blocks e.g., by performing a full-scale test (Nord et al. 2020).

The segmented blocks positioned along the heater were manufactured using the same type of ring-shaped blocks as in Scale test 1, but every block was sawed into four pieces after manufacturing. The segmented blocks above the heater were also manufactured in the same way. Here, ring-shaped blocks were used together with smaller inner cylindrical block with a diameter of 108 mm filling up the inner space, Figure 3-19. The four outer pieces were positioned as a masonry bond to avoid vertical channels here. There will, however, be a cylindrical vertical channel along the heater and further upwards around the inner cylindrical block, which extends from the top of the heater and all the way up to the top of the uppermost block.

All block parts were measured and weighed before installation, see data provided in Appendix 2.

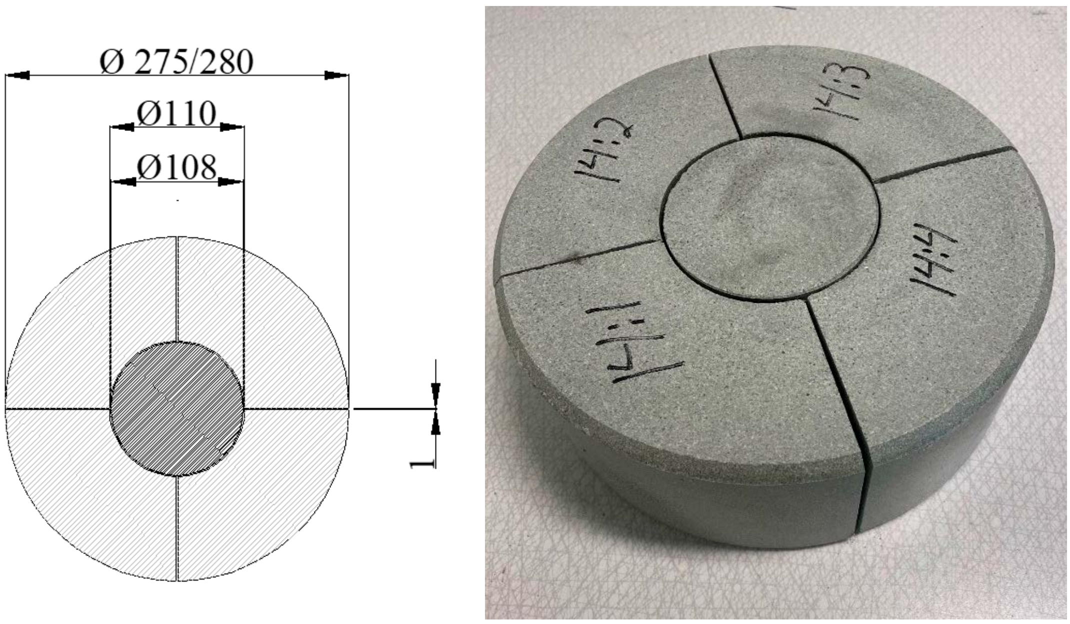


Figure 3-19. *Left: Figure showing the design of the segmented blocks including the dimensions. Right: Photo showing a segmented block (no. 14) from a position above the heater.*

Bentonite pellets

Pellets were installed in the gap between the blocks and the PE-tube. After installation of between one to three blocks (consisting of four or five pieces in this test), pellets were filled up in the outer gap. The weight of the pellets was determined for every single block, see data provided in Appendix 2.

Assembly

The installation procedure was almost the same as for Scale test 1, see description in Section 3.4.1. The exception was the installation of the segmented block parts that was done very carefully to achieve similar gaps between all parts, see left photo in Figure 3-20. Special spacers were used to achieve the same distance of 1 mm between the different block parts. The spacers were removed after positioning of the blocks. The four outer pieces were positioned as a masonry bond to avoid vertical channels i.e., the position of the four block parts above the first installed block were moved 45°, see right photo in Figure 3-20.

Installation data

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

Blocks

The average bulk density of the blocks was 1 914 kg/m^3. The bentonite had a water content of 17.4 % which means that the average dry density of the blocks was 1 630 kg/m^3. These figures were determined before dividing the blocks into segments.

Pellets

The average bulk density of the installed pellet filling was 963 kg/m^3. The pellets had a water content of 14.1 % which means that the average dry density of the pellet filling was 844 kg/m^3.

Test volume

The total test volume was 0.1937 m^3. In total 260.1 kg dry mass bentonite was installed in the test volume (blocks = 199.99 kg and pellets = 60.12 kg). This resulted in an installed average dry density in the test volume of 1 343 kg/m^3.

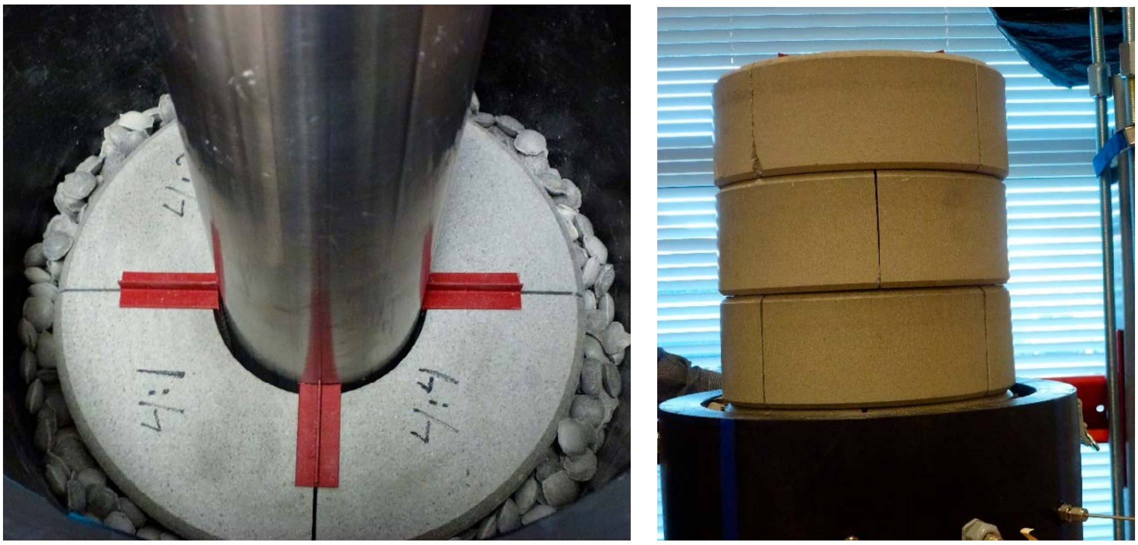


Figure 3-20. *Left: Special spacers were used to achieve the same distances between the different block parts. Right: The blocks were positioned as a masonry bond to avoid vertical channels.*

3.5.2 Registered data during test time

Temperature

The total test duration was 378 days. The graphs provided in Figure 3-21 and Figure 3-22 show the temperature development during Scale test 2.

Some comments on the temperature measurements:

- The temperature on the central heater varied between 69–70 °C at the upper half (thermocouples positioned at 0.5 and 0.9 meters) and 47–48 °C at the bottom (thermocouple positioned at 0.1 meter).
- The temperature on the inner gap on the block side (4.3 mm from the heater surface), was somewhat lower than the heater temperature at the two upper measuring positions (0.5 and 0.9 meters), between 68 and 69 °C. However, at the lower measuring point, 0.1 meter, the temperature was almost the same as on the heater surface, approximately 47 °C.
- The temperature at the outer gap, at the simulated rock surface, was between 41 °C (at 0.1 meter) and 52–53 °C (at 0.5 and 0.9 meters).
- The temperature above the heater, at 1.1-meter level, varied between 48 °C (at the outer gap) and 56 °C (at the center of the block stack).
- The temperature at the top, at 2.2-meter level, was the same at the outer gap and at the center of the block, approximately 32 °C.

The registered variation in temperature on the heater at level 0.5 and 0.9 meters was much smaller compared to Scale test 1, see Section 3.4.

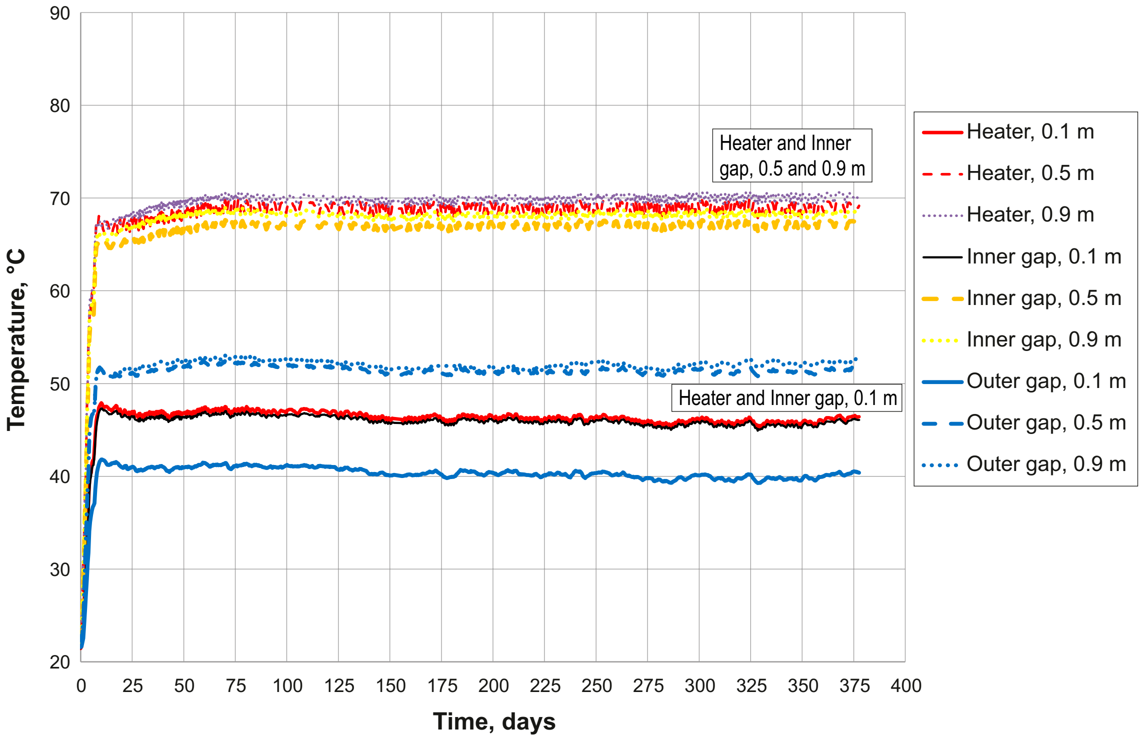


Figure 3-21. *Temperature development for the thermocouples in Scale test 2 placed at levels 0.1, 0.5 and 0.9 meters from the bottom.*

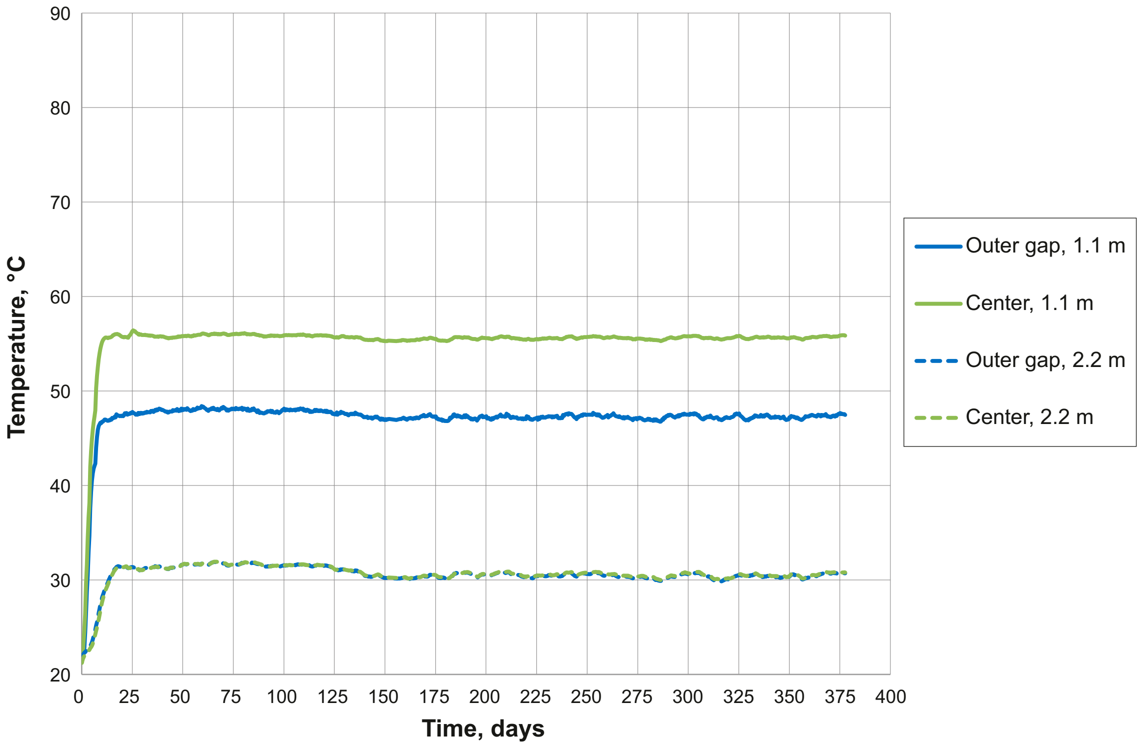


***Figure 3-22.** Temperature development for the thermocouples in Scale test 2 placed at levels 1.1 and 2.2 meters from the bottom.*

Relative Humidity

The graph provided in Figure 3-23 shows the development of the measured relative humidity in Scale test 2.

Some comments on the relative humidity measurements:

- The starting value of the relative humidity was between 60–67 % for all three sensors. The lower value was registered for the sensor positioned at the 2.2 m level. The corresponding value for the sensor at this level in Scale test 1 was 65 %. The reason for this difference is not known but may be due to variations in the water content of the pellets.
- The RH-sensor positioned 0.5 meters from the bottom reacted immediately as the temperature increased. The registered relative humidity reached 100 % after approximately seven days which indicated thermally induced vapor transport horizontally from the heater and outwards against the simulated rock wall. After seven days, the sensor stopped delivering any values. One explanation may be that liquid water had reached the sensor which resulted in failure.
- The RH-sensor positioned 1.1 meters from the bottom also reacted early after the heating had started. The registered relative humidity reached 100 % after about eight days. This indicated horizontal vapor transport from the heater and outwards against the simulated rock wall. After eight days, the sensor stopped delivering any values. One explanation may be that liquid water had reached the sensor which will result in failure.
- The RH-sensor positioned 2.2 meters from the bottom reacted very slowly after the heating was started. The registered relative humidity increased slowly with time indicating vertical vapor transport from the bentonite around the heater. This sensor has, however, continued to deliver data, and the registered relative humidity at the time of dismantling was 73.9 %.

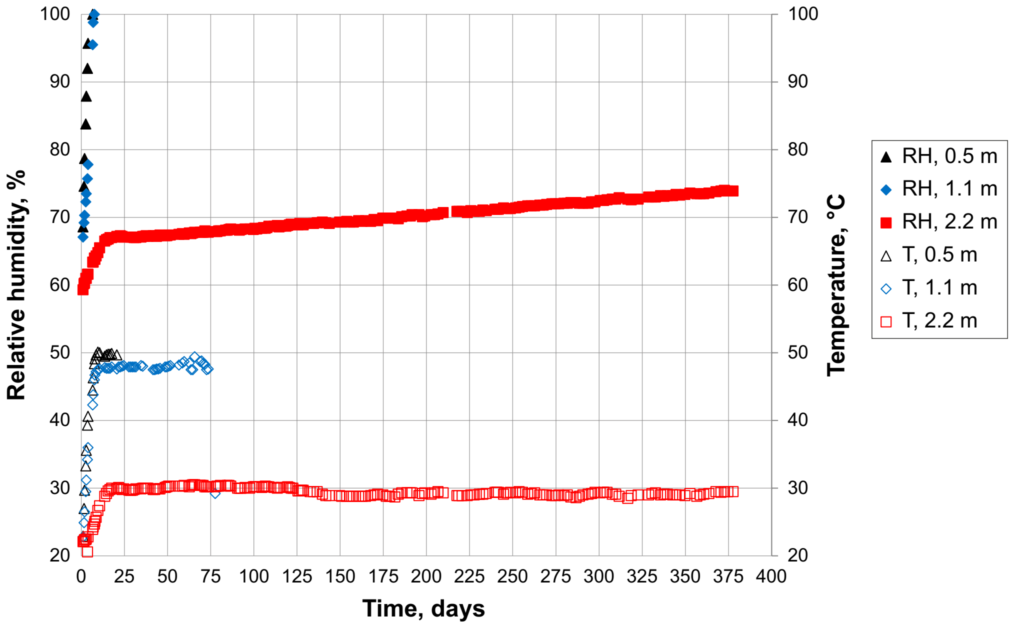


Figure 3-23. *Measured relative humidity in Scale test 2 at three levels (0.5, 1.1 and 2.2 meters from the bottom). The graph also shows the temperature measured with the same sensors at the same positions.*

Gas pressure

The gas pressure was measured at the top of the test cell. In Scale test 2, no pressure higher than 1 kPa was registered. The very low gas pressures registered in both Scale test 1 and Scale test 2 indicate that the test equipment has not been completely gas-tight.

3.5.3 Power consumption

The power consumption was measured by use of a simple commercially available meter installed in a wall socket. The reading was done manually, and the accuracy of the measurement was declared by the manufacturer to be ± 1 %. The applied power varied between approximately 51 and 54 W, Figure 3-24, and the total power consumption was 464 kWh after a test duration of 378 days.

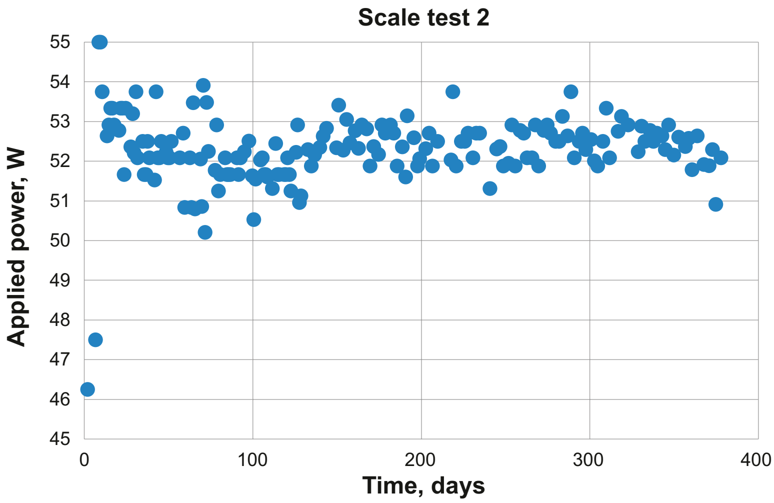


Figure 3-24. *The applied power plotted versus time for Scale test 2.*

3.5.4 Dismantling

After 378 days, the electrical heater was turned off as planned. Once the temperature had dropped close to room temperature, which took approximately 24 hours, the dismantling of the test started.

The weight of all individual blocks was determined in conjunction with the installation, see Section 3.4.1. In this test, the blocks were divided into four pieces and the weight of every piece was determined. The weight of the block pieces was again determined when the test was dismantled. With this data it was possible to achieve a rough estimate of the water movements within the test volume that occurred during the test time.

The blocks in Scale test 2 consisted of a ring-shaped block and a central cylinder (the blocks above the heater), Figure 3-19. The sampling of the ring-shaped blocks was made in the same way as described in Section 3.4.4, Figure 3-11. The sampling positions of the central cylinder is shown in Figure 3-25. The sampling was made in the same four directions (A, B, C, and D) as the ring-shaped blocks outside.

3.5.5 Results from sampling

General

The results from the sampling of the block parts positioned along the heater are provided in three graphs, Figure 3-26. The denominations in the graphs, A1 to A5, are the same as the sampling positions, see Figure 3-11 and Figure 3-12. Note that the sampling positions for A4 and A5 differ slightly between the ring-shaped and cylindrical blocks. The sampling positions for A6 and the test series "Center" (M1–M5 in Figure 3-12 and in Figure 3-25) are also somewhat different between Scale test 1 and Scale test 2. The corresponding graphs for sampling directions B, C, and D can be found in Appendix 7, 8, and 9. The vertical black lines in the graphs indicate the initial conditions in the blocks regarding water content, dry density, and degree of saturation.

It should be noted that four sampling points in the pellets-filled slot have been excluded in the graphs showing water content distribution in Scale test 2. The reason for this was to keep the resolution of the x-axis as high as possible. The four sampling points were positioned in direction A (62.5 % at level 50 mm), in direction B (70.3 % at level 12.5 mm), in direction C (69.3 % at level 12.5 mm), and in direction D (61.3 % at level 50 mm).

Comments on results from blocks along heater

The initial water content of the blocks was 17.4 % and of the pellet filling 14.1 %. The uppermost graph in Figure 3-26 shows that there has been an extensive dehydration of the blocks along the heater, down to a water content below 5 %. The dehydration of the blocks has resulted in shrinkage and by that an increased density, see middle graph in Figure 3-26. The initial average dry density of the blocks was 1 638 kg/m^3. As shown in the graph the dry density has increased up to between 1 800 and 1 900 kg/m^3 between level 400 to 1 000 mm.

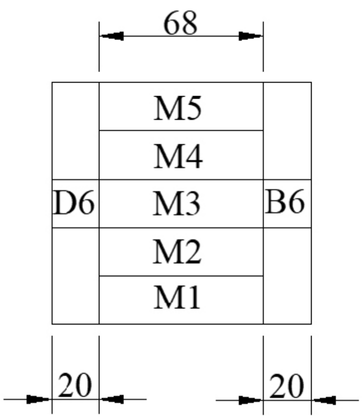


Figure 3-25. Sampling positions in the central cylinder positioned at the center of the ring-shaped blocks above the heater. The sampling was made in the same four directions (A, B, C and D) as the ring-shaped blocks outside.

The shrinkage of the blocks along the heater caused a lot of fractures in the corresponding blocks in Scale test 1. However, in this test, only a few fractures were identified. The difference between the two tests probably depends on that the blocks in this test were divided from the start, which means that high internal tensions did not build up inside the blocks.

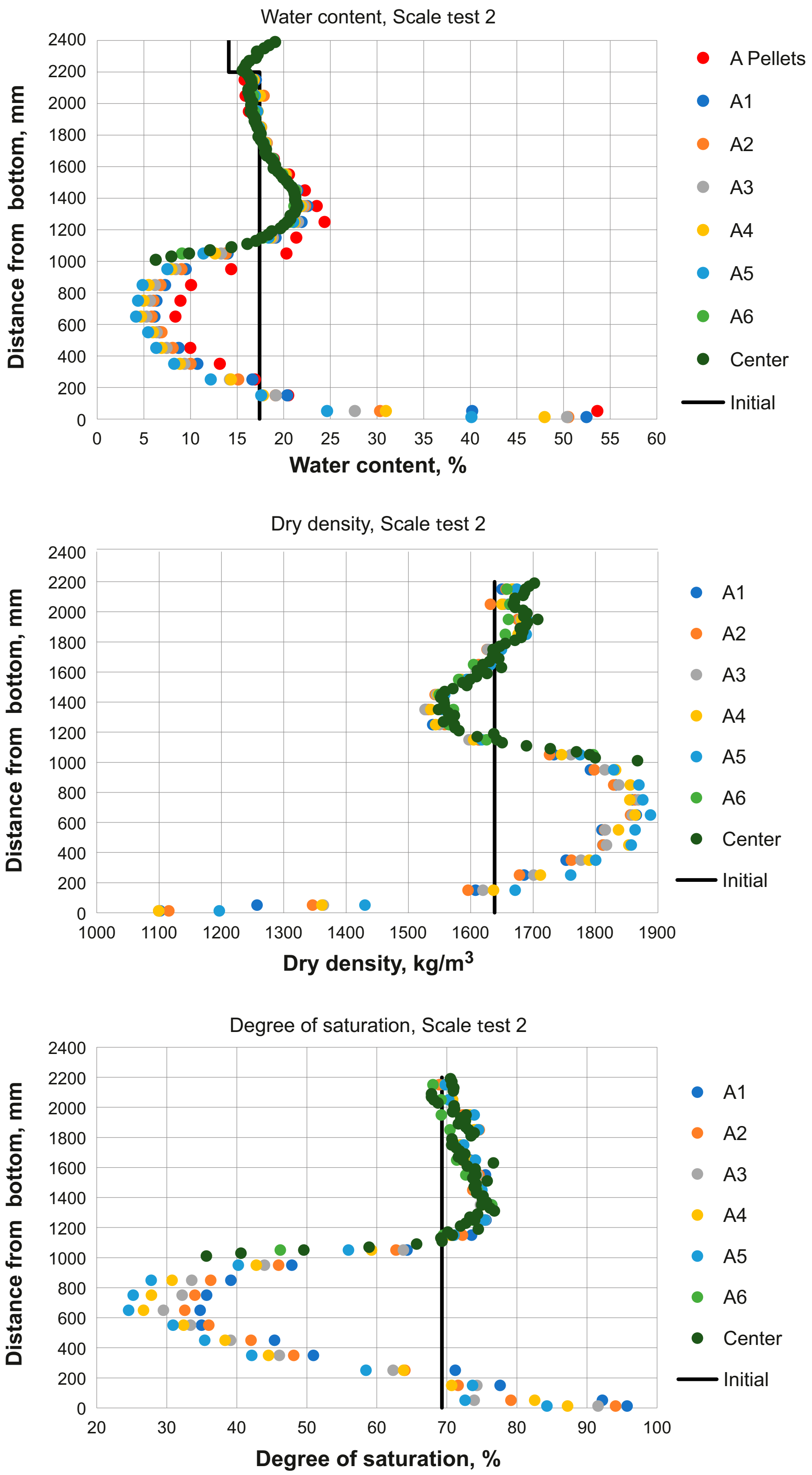


Figure 3-26. *Graphs showing the results from sampling of Scale test 2 in direction A. Upper: Water content distribution at different sampling positions (A1 to A6, see Figure 3-11 and Figure 3-12. Note that the sampling positions for A5 and A6 are not the same for the blocks around the heater and the blocks above the heater). Middle: Dry density distribution. Lower: Degree of saturation distribution.*

It was noted that the radial gaps between the block parts had almost disappeared, especially for Block 3 to Block 6, see also photo provided in Figure 3-27 (upper left). The block parts had moved somewhat towards the heater, probably due to radial moisture redistribution, and this movement may be one explanation for the closing of the radial gaps. There had also been upward movements within the test volume, mainly depending on swelling of the bottom blocks that have pushed the blocks above upwards approximately 18 mm, see measurements of the block heights provided in Appendix 2. This movement upwards possibly also contributed to a movement of the block parts closer to each other.

The two bottom blocks (Block 1 and Block 2) had clearly taken up water. The bottom plate of the test setup has had a lower temperature, and water from the blocks above has condensed here, see photo (lower left and right) in Figure 3-27. The blocks had swelled and were stuck in the tube. Extra sampling was made at the level closest to the bottom plate (0–25 mm).

Figure 3-27. *Photos taken in conjunction with dismantling of the blocks around the heater, Scale test 2. Upper left: Block 4. The block parts had moved closer to each other, and the radial gaps between the block parts had almost disappeared. Upper right: The pellet filling around Block 2 was partly wetted and some of the individual pellets had glued together. Lower left: The bottom block seen from below. The bottom surface and the lower part of the pellet filling was clearly wetted. The block had swelled and was stuck in the tube. Lower right: Dismantling of the bottom block. The block and the pellet filling have swelled together.*

Comments on results from blocks above heater

The uppermost graph in Figure 3-26 shows that the blocks positioned between 1 100 to 1 800 mm (block 11–18) above bottom have increased in water content. These blocks have also swelled and by that decreased in density. The block positioned just above the heater, 1 000–1 100 mm, (block 11) has decreased in water content and shrunk and by that increased in density. The four uppermost blocks, 1 800–2 200 mm above bottom, (block 18–22) were almost unaffected. However, the three uppermost blocks had lost some minor amount of water, see also Table 3-3, and seems to have shrunk since they have increased somewhat in density. The pellet filling at the top, 2 200–2 400 mm, had an initial water content of 14.1 %. The sampling showed that there had been a certain water uptake of the pellet filling and that there was a water content gradient from about 15.6 (level 2 200 mm) to 19.1 % (level 2 400 mm). This is probably caused by the lower temperatures at the top of the test.

Photos taken in conjunction with the dismantling of the blocks above the heater are provided in Figure 3-28. As shown in the photos, some minor fractures were found in Block 11 (just above the heater), and in the block above, Block12, upper left and right in Figure 3-28. In the photo of Block 12 it can also be seen that some of the pellets had almost glued against the block surface, see dark spots on the block surface. This was due to a significant increase of the water content of the pellets at this level.

Figure 3-28. *Photos taken in conjunction with the dismantling of the blocks above the heater, Scale test 2. Upper left: Some minor fractures could be seen in the parts of Block 11. Upper right: Block 12. Fracture in one of the block parts. Some of the pellets were almost glued against the block surface, see dark spots on the surface. Lower left: Block 15. The block parts have swelled, and the initial radial gaps have almost disappeared. Lower right: Block 22. The block was almost unaffected.*

The swelling of the blocks above the heater, Block 12 to Block 18, and of the surrounding pellets, resulted in that the initial radial gaps had almost disappeared, see lower left photo in Figure 3-28. The four uppermost blocks, Block 19 to Block 22, were almost unaffected, lower right photo in Figure 3-28.

Comparison between installation data and dismantling data of the blocks

The individual blocks used in the test were weighed and measured at the time of installation, see Appendix 2. New measurements of diameter, height, and weight were made in conjunction with the dismantling and the differences between the measurements were calculated, see compilation of data in Appendix 2.

The changes in weight for the block parts and for the surrounding pellets at every block position are compiled in Table 3-3. The changes in mass of the pellets were calculated using the average water content that was determined at dismantling in four directions outside every block. The fifth column in Table 3-3, shows the sum of changes for both block parts and pellets, and the last column shows the sum of changes for a certain block interval. The performed measurements give a good picture of what have happened during the test time:

- The two ring-shaped blocks and the surrounding pellets, positioned at the bottom along the heater, block position 1 and 2, have increased their weight within total 2.27 kg. This increase in weight origins probably from water that have been redistributed from blocks and pellets at block position 3 to 6, which in turn have lost 2.444 kg.
- The blocks and pellets at position 7 to 11 have lost in weight, in total 3.967 kg. This loss in weight could probably be caused by redistribution of water upwards, primarily to block positions 12 to 19. The increase in weight for block positions 12 to 19 is 2.532 kg.
- The blocks and pellets at position 20 to 22, were relatively unaffected.
- The pellet filling positioned at the top of the test (approximately 200 mm high column) had increased the weight with 0.511 kg.
- The last row in Table 3-3 shows the sum of weight changes for both blocks (−3.29 kg) and for the pellets (2.183 kg). This means that there is a discrepancy in water of −1.107 kg. This discrepancy probably depends on uncertainties in determining the total water content in the pellet filling, in variations in the initial water contents of both blocks and pellets, and possibly through drying during installation and dismantling. No leakage which could explain this discrepancy was detected during the test and it is considered unlikely that it would be a major factor.
- The total amount of water installed in the test was 43.28 kg (34.80 kg in the blocks and 8.48 kg in the pellets), see data provided in Table 5-1. Due to the heat from the simulated canister there have been a redistribution of the water: in total approximately 6.42 kg have been dehydrated from the bentonite blocks and pellets around the heater (block position 3 to 11 and 20 to 22), and 5.31 kg have been taken up by the bentonite blocks and pellets below (block position 1 and 2), and by the blocks and pellets above (block position 12 to 19 and the pellets at the top), Table 3-3. As mentioned in the bullet above, there are some possible explanations for the discrepancy.

Table 3-3. Discrepancy in weight measured during installation versus dismantling of the block parts and pellets in Scale test 2.

Block no.	Δ mass block parts kg	Δ mass pellets kg	Sum changes per block position kg	Sum changes per block interval kg
1	1.200	0.769	1.969	
2	0.188	0.113	0.301	2.270
3	−0.173	0.055	−0.118	
4	−0.536	−0.009	−0.545	
5	−0.754	−0.065	−0.818	
6	−0.852	−0.110	−0.963	−2.444
7	−0.917	−0.100	−1.017	
8	−0.906	−0.086	−0.992	
9	−0.843	−0.074	−0.917	
10	−0.709	−0.011	−0.719	
11	−0.412	0.090	−0.322	−3.967
12	0.099	0.119	0.218	
13	0.323	0.193	0.516	
14	0.347	0.186	0.534	
15	0.338	0.159	0.497	
16	0.227	0.126	0.353	
17	0.143	0.094	0.237	
18	0.057	0.075	0.132	
19	0.011	0.056	0.046	2.532
20	−0.039	0.035	−0.004	
21	−0.061	0.030	−0.032	
22	−0.000	0.027	0.027	−0.008
Pellets at top	na	0.511	0.511	0.511
Sum	−3.290	2.183	−1.107	−1.107

Comments

To give a good picture of the status of the bentonite at the end of the test, contour plots were made using an interpolation program. The plots, see Figure 3-29, Figure 3-30, and Figure 3-31, shows the water content, the dry density, and the degree of saturation distribution in two different cross sections, directions AC (left plots) and BD (right plots). In the contour plots of the dry density and degree of saturation distribution, the pellet filling is excluded (white fields) since the density was not determined on the pellet filling in conjunction with the dismantling.

As shown in the contour plots, the differences in water content and density were in general small in the radial direction while the differences in the axial direction were rather large, Figure 3-29 and Figure 3-30. In general, the blocks around the heater had dehydrated and the water content in the blocks above the heater had increased. Water, in the form of vapor, has also been transported downwards to the bottom plate where it has condensed and been taken up by the bottom block and the surrounding pellets. Above the heater, there is a tendency that water has condensed locally between about 1 200 and 1 400 mm, particularly in directions C and D.

The average installed dry density of the blocks was 1 638 kg/m^3. As shown in Figure 3-30, the density of the blocks around the heater and at the top of the heater, level 300 to 1 100 mm, is considerably higher, mainly between 1 700 and 1 850 kg/m^3. This increase in dry density depends on the fact that the blocks around the heater have dehydrated and shrunk. The opposite behavior could be seen on the blocks above the heater, between 1 100 and 1 700 mm, where the blocks instead have swelled, and decreased their density.

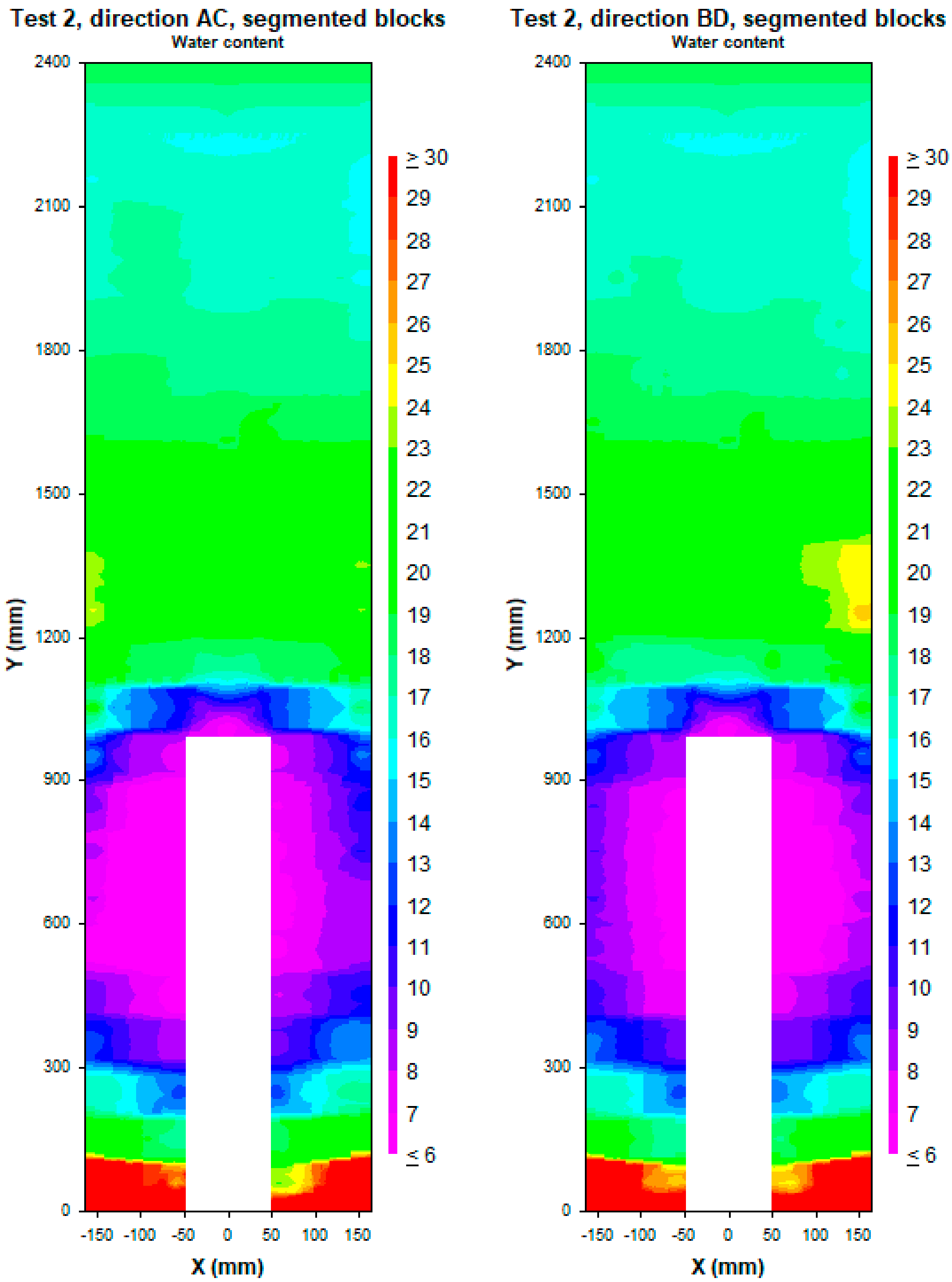


Figure 3-29. *Scale test 2. Contour plots showing the water content distribution (%) in the A and C sections (left) and the B and D sections (right).*

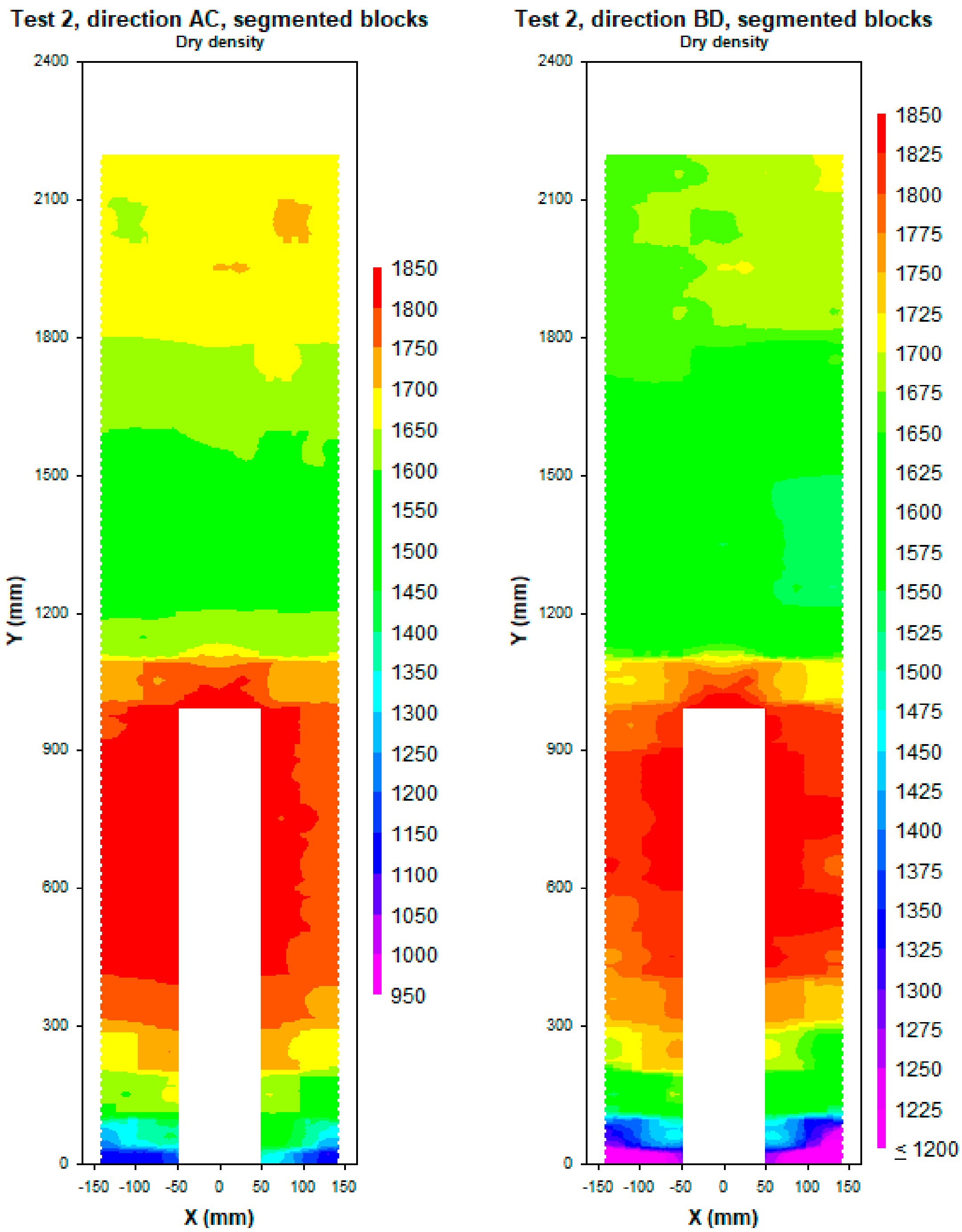


Figure 3-30. *Scale test 2. Contour plots showing the dry density distribution (kg/m³) in the A and C sections (left) and the B and D sections (right).*

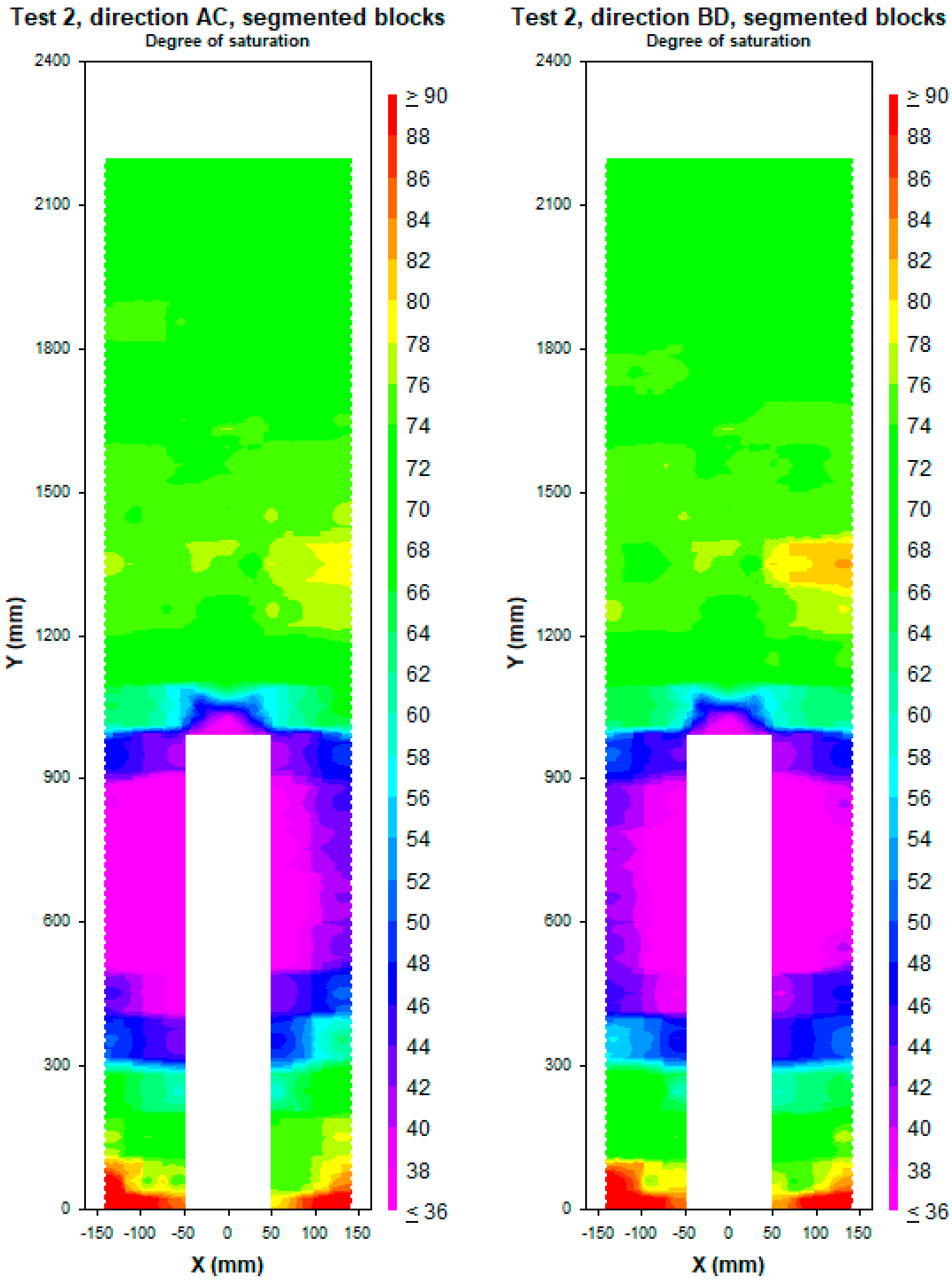


Figure 3-31. *Scale test 2. Contour plots showing the degree of saturation distribution (%) in the A and C sections (left) and the B and D sections (right).*

4 Gap tests with horizontal thermal gradient

4.1 General

The aim of these tests was to obtain basic information on the influence of natural convection on the moisture redistribution within the buffer. The test arrangement was rather like the tests with thermal gradient presented in Åkesson et al. (2020), however, with the important difference that the temperature gradient in the new tests was horizontally oriented, and that the relation between the bottom area and length was considerably larger compared to the earlier tests.

4.2 Test equipment

4.2.1 Test box

The test arrangement consisted of a test box, with a rectangular block-shaped volume. The test box had a height of 1 000 mm, a width of 500 mm and a thickness of 100 mm, see schematic drawing provided in Figure 4-1. Its frame was constructed of four beams made of PVC. This material was chosen to minimize the heat transfer. Sheets made of alumina, with a thickness of four mm, were placed on each side of the box. A heating plate was placed against the alumina sheet on the warm side while the cold side was exposed to the room temperature. The frame of the box i.e., the beams made of PVC, were insulated to minimize the heat losses, see photo provided in Figure 4-1.

4.2.2 Heating

The heating on the warm side was achieved by a large heating plate (500 × 1 000 mm) which was placed against one of the alumina sheets of the box. The applied power was controlled by a regulation system where a thermocouple was used to measure the actual temperature on the plate. No active cooling was made on the cold side. A pretest was made, see Section 4.4, which showed that the desired temperature gradient, which corresponded to a temperature difference of approximately 20 °C between the warm side and the cold side, could be reached.

4.2.3 Instrumentation

The gap tests were sparsely instrumented. In each test, twelve thermocouples and two relative humidity sensors were positioned, see drawing provided in Figure 4-1 showing the positions.

Thermocouples

Thermocouples were positioned at three different heights: 0.1, 0.5 and 0.9 meters from the bottom of the test volume. At all three heights, thermocouples were placed in two sections positioned 0.1 and 0.25 meter respectively from one of the vertical sides. The thermocouples were placed against the alumina sheets with the same configuration at both sides of the test box. The positions of the thermocouples on the test box are shown in Figure 4-1.

Relative Humidity sensors

Relative humidity sensors were positioned on both the upper and lower short side of the test box. The sensors were positioned in-between the warm and the cold side. The positions of the relative humidity sensors are shown in Figure 4-1.

In addition to the measured relative humidity, the sensors also measured the temperature. The results from these sensors were important to judge whether equilibrium had been reached, i.e., when there were no ongoing redistribution of moisture within the test volume and the test therefore was ready for dismantling.

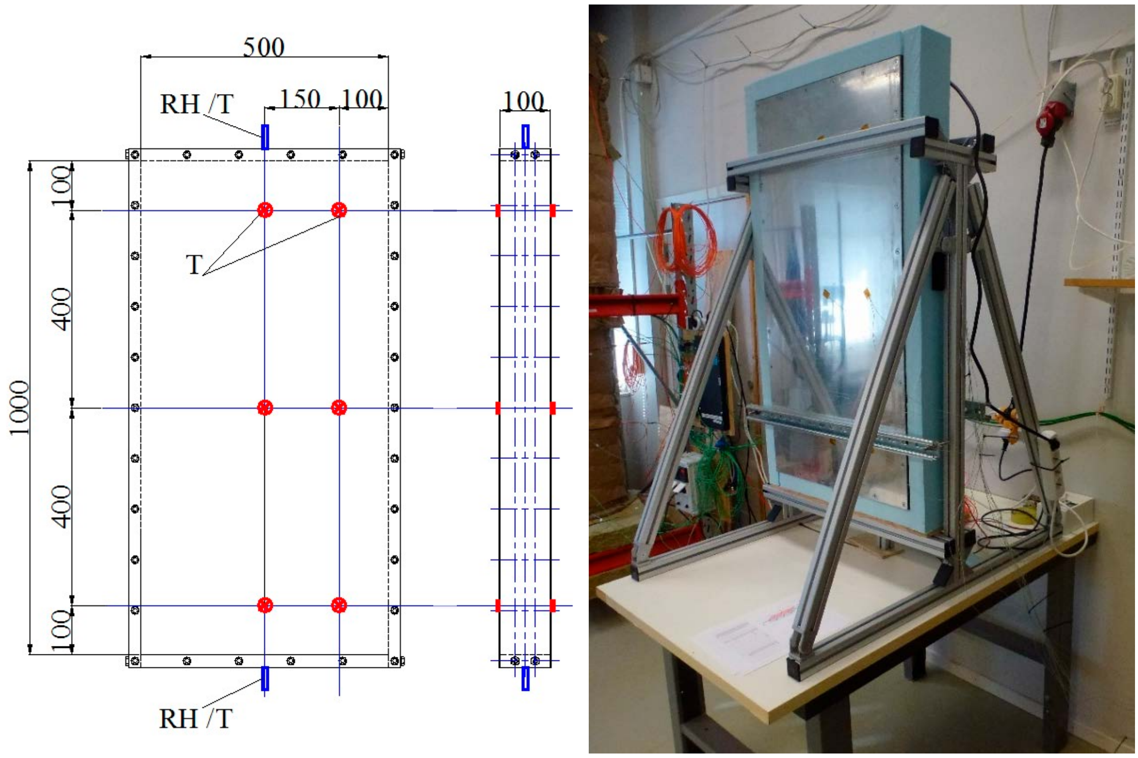


Figure 4-1. Left: Schematic overview of the test equipment. The red dots show the position of the thermocouples. Six thermocouples were positioned on the warm side and six on the cold side. Two relative humidity sensors were positioned on the middle of the upper and lower side (blue boxes). Right: Photo showing the test equipment. The heating plate was positioned on the back of the test equipment. Insulation was placed around the PVC frame (light-blue beams).

4.3 Test matrix

In total three tests were performed. The first test was a pretest to check that the desired temperature gradient could be achieved. Two regular tests were subsequently performed, one test in which a pellet filling was investigated and one test in which a buffer block filling was investigated.

4.4 Pretest

The main objective of this test series was to apply a temperature difference over the bentonite filled gap of approximately 20 °C. A pre-test was made to check if this temperature difference was possible to achieve without having any active cooling on the cold side. The test was made using a gap filling consisting of MX-80 pellets manufactured by extrusion. A graph showing the results from the pre-test is provided in Figure 4-2. In the first step, the temperature on the heated side was set to 40 °C. This resulted in a temperature difference over the gap of approximately 12–15 °C. In the second step the temperature on the heated side was increased to 50 °C which resulted in a temperature difference of between 18–22 °C. The temperature on the heated side varied between 55–58 °C at the mid-height and at the top while the temperature at the lower part was between 52–53 °C. The temperature on the cold side was approximately the same at all positions, about 33–34 °C. It was decided that this temperature setting should be used in the following planned tests.

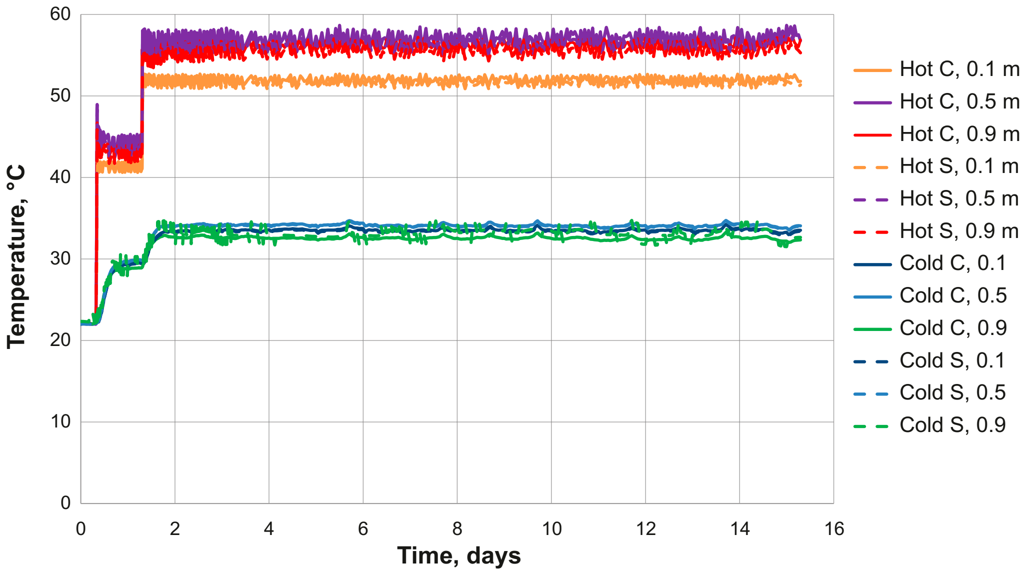


Figure 4-2. *Temperature development registered during the pretest. Thermocouples were placed at three levels (0.1, 0.5 and 0.9 meters from the bottom) on both the hot side and the cold side. (C = Central part of the box, S = Side of the box).*

In conjunction with the dismantling, after fifteen days, it was noted that the bentonite pellets on the cold side were rather "wet", and it was obvious that the pellets in contact with the alumina sheet had swelled. A limited sampling of the pellet filling was made. Samples were taken in the center of the box at three heights (0.1, 0.5 and 0.9 meter) and at three depths (close to the cold side, in the middle of the pellet filling, and close to the warm side). The water content varied between 44–48 % close to the cold side, between 18–19 % in the middle and between 10–13 % close to the warm side. The original water content of these pellets was 17 %. There had thus been a strong redistribution of the moisture present in the pellet filling at installation due to the applied temperature gradient. It was also noted that this redistribution occurred despite the rather short test duration, about fifteen days.

4.5 Gap test 1: Pellets

4.5.1 Test preparation

The gap in the test equipment was filled with bentonite pellets (MX-80 pillows, see Section 2.2). The total installed mass of the pellets was 52.88 kg, and the water content of the pellets was determined to 11.4 % at the time for installation. The installed bulk density of the pellet filling was 1 058 kg/m^3 and the dry density was 949 kg/m^3.

4.5.2 Registered data during test time

Temperature

The graphs provided in Figure 4-3 shows the registered temperature development during the test duration. The temperature on the cold side was between 32 and 34 °C at all six positions. The temperature on the warm side was between 53 and 55 °C at the lower level (0.1 m) while the temperature at the other two levels (0.5 m and 0.9 m) was between 57 and 60 °C. There has thus been some variation in the horizontal gradient between the lower part of the gap (approximately 21–23 °C) and the middle and upper part (approximately 25–26 °C). However, no difference in temperature could be seen between the vertical central part and the peripheral vertical side of the pellet filling, Figure 4-3.

The applied power varied between 82 and 86 W during the test. The total power consumption was 99 kWh after the forty-nine days long test.

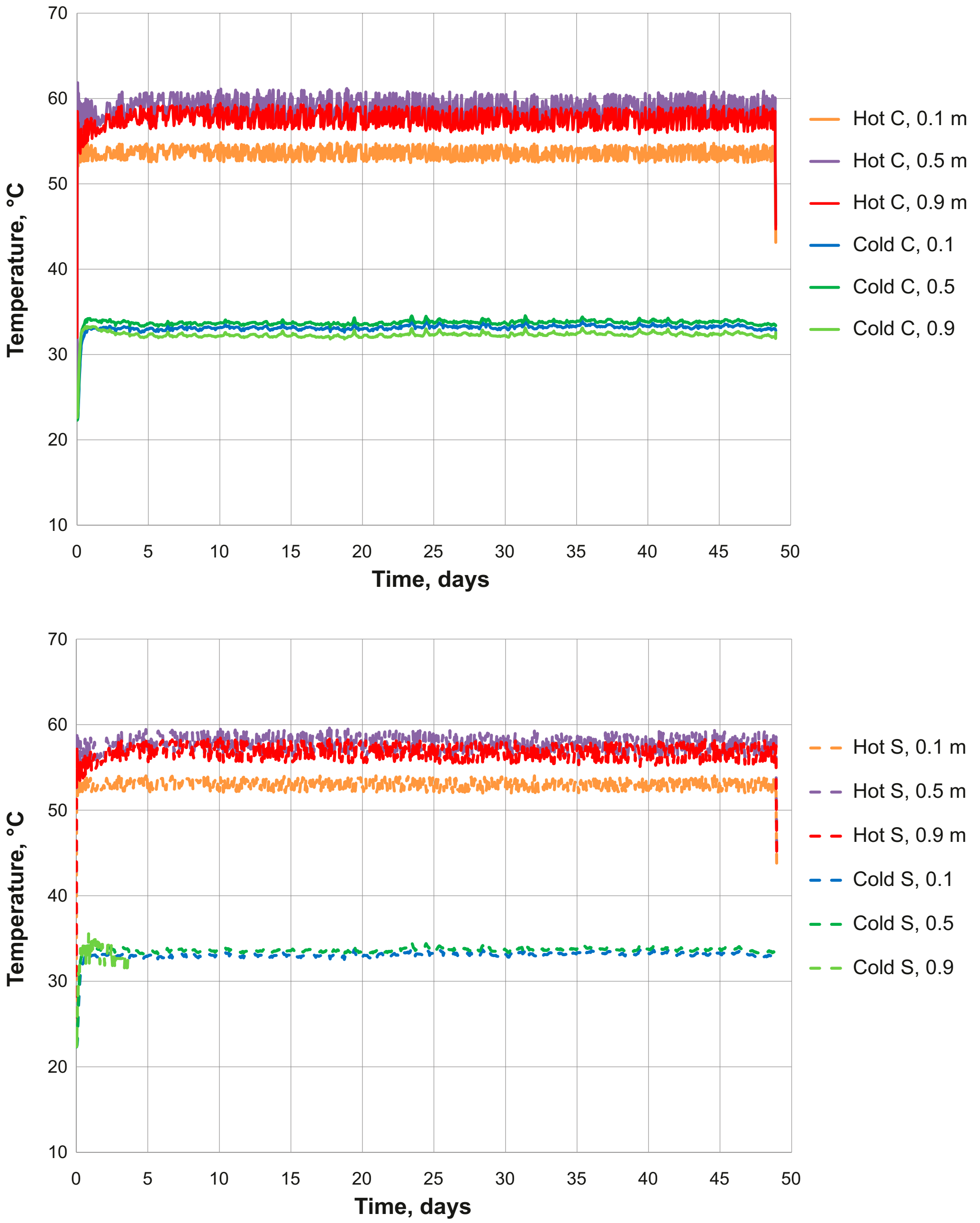


Figure 4-3. *Temperature development during the Gap test 1 with a pellets-filled gap. Thermocouples were placed at three levels (0.1, 0.5 and 0.9 meters from the bottom) on both the hot side and the cold side. Upper graph: Results from thermocouples positioned along the vertical central part of the box (C = Central part of the box). Lower graph: Results from thermocouples positioned along the peripheral vertical side of the box (S = Side of the box).*

Relative humidity

The graph provided in Figure 4-4 shows the development of the measured relative humidity in the test.

Some comments to the relative humidity measurements:

- Immediately after installation of the RH-sensors, the measured relative humidity was 44 % at the top of the box and 54 % at the bottom. The difference may depend on the fact that the sensor at the top probably was situated in an air-filled void (the box was prepared while lying down and when it was later raised to a vertical position the pellets were probably compacted somewhat, which resulted in an airgap at the top) while the sensor at the bottom measured directly against the pellet filling. The measured relative humidity corresponds rather well to the water content of MX-80 pellets which was 11.1 % (Dueck and Nilsson, 2010).

- After starting the test, the relative humidity started to increase very fast. The sensor at the top registered a relative humidity of 90 % after 1.5 hours, whereafter the value slowly decreased with time and after approximately three weeks reached an equilibrium at 80 %. The RH-sensor positioned at the bottom also reacted immediately as the temperature increased. The registered relative humidity at this position increased with time and reached an equilibrium of approximately 72 % after three to four weeks.
- After the first increase in temperature, the temperature registered by the two relative humidity sensors stayed at an almost constant level of 38–39 °C.

4.5.3 Power consumption

The power consumption was measured by use of a simple commercially available meter installed in a wall socket. The reading was done manually, and the accuracy of the measurement was declared by the manufacturer to be ± 1 %. The applied power varied mainly between 82 and 84 W, Figure 4-5, and the total power consumption was 98.8 kWh after 50 days test duration.

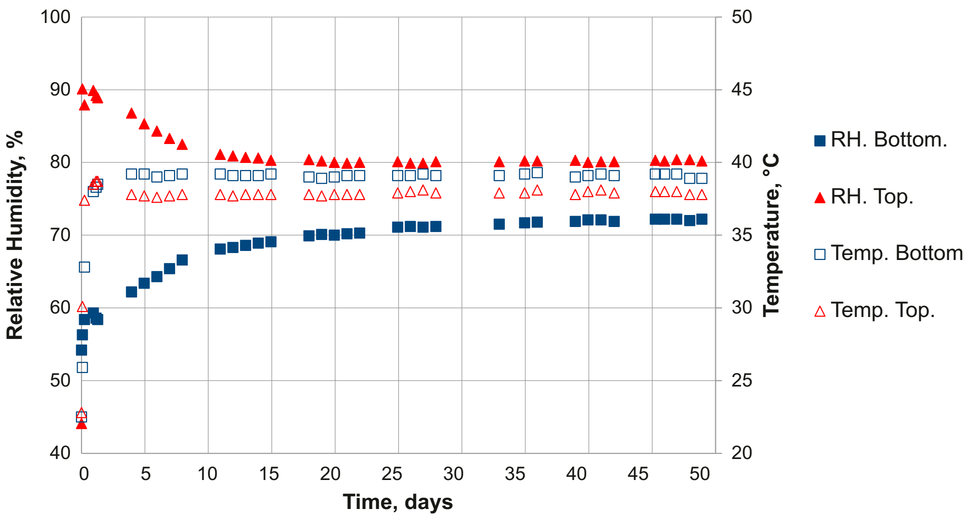


Figure 4-4. *Measured relative humidity in Gap test 1 at two positions, on the top and at the bottom respectively. The graph also shows the temperature measured with the same sensors.*

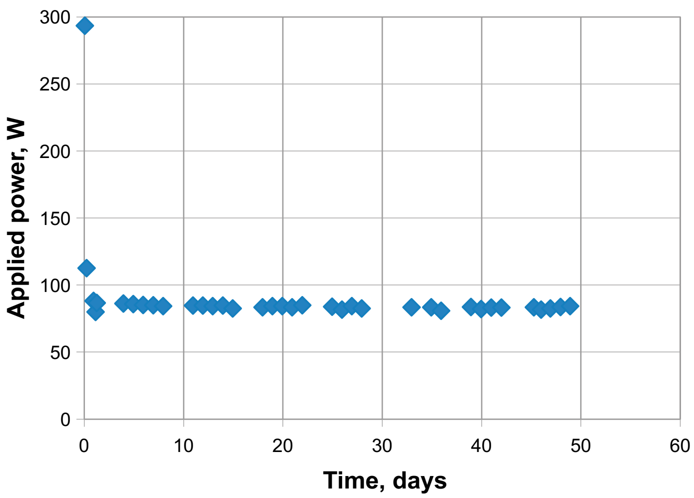


Figure 4-5. *The applied power plotted versus time for Gap test 1 with pellets.*

4.5.4 Dismantling and sampling

After almost fifty days it was judged that the test had reached equilibrium, i.e., the relative humidity sensors indicated that there were no additional redistribution of moisture going on within the test volume, and it was decided to turn off the electrical heater. After approximately two hours of cooling (in room temperature), the dismantling started. The aluminum plate on the cold side was first removed, see Figure 4-6. The pellets at the upper part of the test box were clearly wet and were partly "glued" against the aluminum plate. An extensive sampling was conducted to determine the water content distribution within the pellets filling. Samples were taken in two vertical planes, one in the middle and one peripheral closer to the side, see Figure 4-7. In both planes, samples were taken in eleven profiles. Every profile consisted of five samples. The vertical distance between the profiles was 100 mm. Samples were thus taken at in total 110 positions in the gap tests.

A compilation of the results is provided in Figure 4-8. The graph shows the determined water content at all sampled positions. As shown in the photo provided in Figure 4-6, the pellets have moved somewhat during the handling of the test equipment and no sampling could thus be done in the upper corner on the cold side. The circular dots show the sampling of the section in the middle of the test box and the square dots show the sampling of the section close to the side of the test box. The different colors indicate the sample position in horizontal direction i.e., from the cold side to the warm side. The black vertical line indicates the initial water content of the pellets.

As expected, there was a clear difference in water content between the samples taken closest to the cold side (0–20 mm) and the samples taken closest to the warm side (80–100 mm). There was, however, also some variation in water content in vertical direction, with the lowest values at mid-height and the highest values at the top. There were some samples at the top of the box that had a significantly higher water content, see also the photo provided in Figure 4-6. It was clear that vapor had condensed on the cold side at this level.

Figure 4-6. *The alumina plate on the cold side of Gap test 1 have been removed. Pellets at the upper part of the test box were clearly wet.*

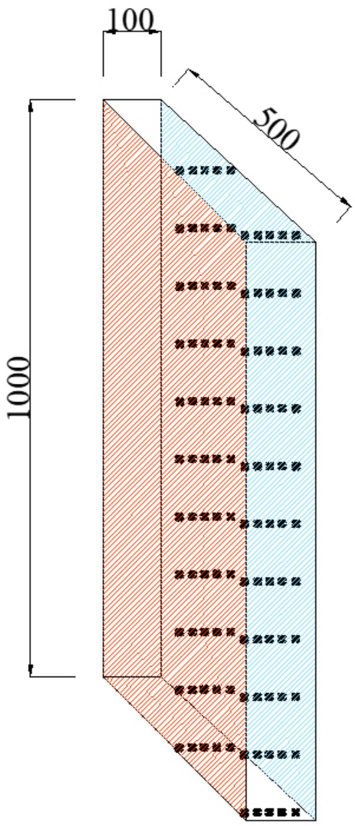


Figure 4-7. *Planned sampling of the gap test. Samples were taken in two vertical planes, one in the middle and one closer to the side. In both planes, samples were taken in eleven profiles. Every profile consisted of five samples.*

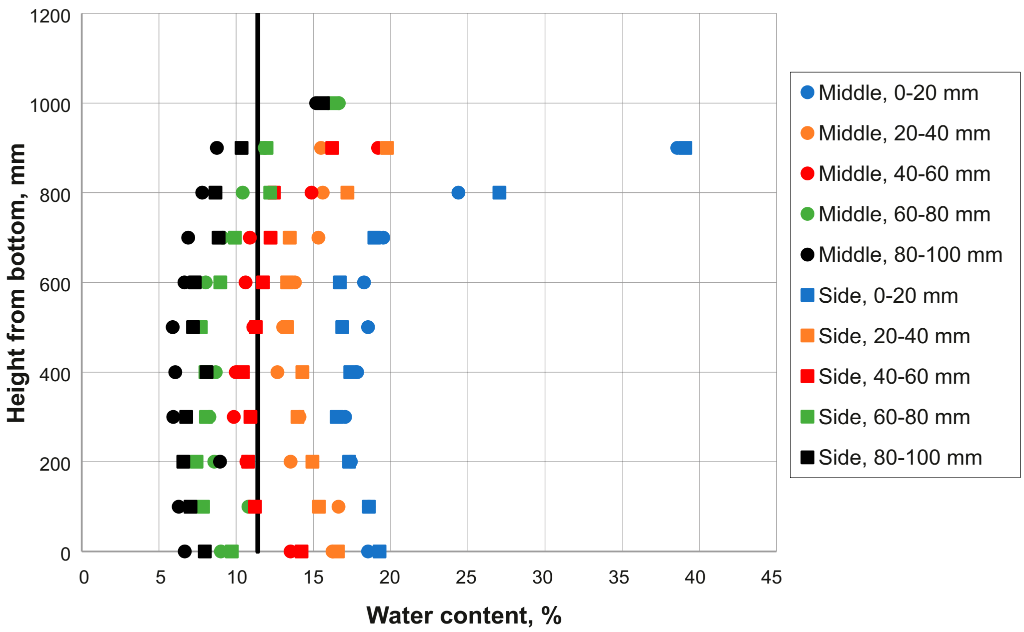


Figure 4-8. *Water content distribution in the pellet filling in Gap test 1. Samples were taken at the middle (circles) and side (squares) of the box at five different depths. The black vertical line indicates the initial water content of the pellets.*

Contour plots were made using an interpolation program, Figure 4-9. The plots show the water content distribution in the two sampled sections. The left contour plot shows the result from the middle section and the right plot shows the result from the side section. The plots clearly show that a redistribution of water within the pellet filling, from the warm side to the cold side has occurred. There was no clear difference between the results from the sampling of the middle section and the peripheral side section.

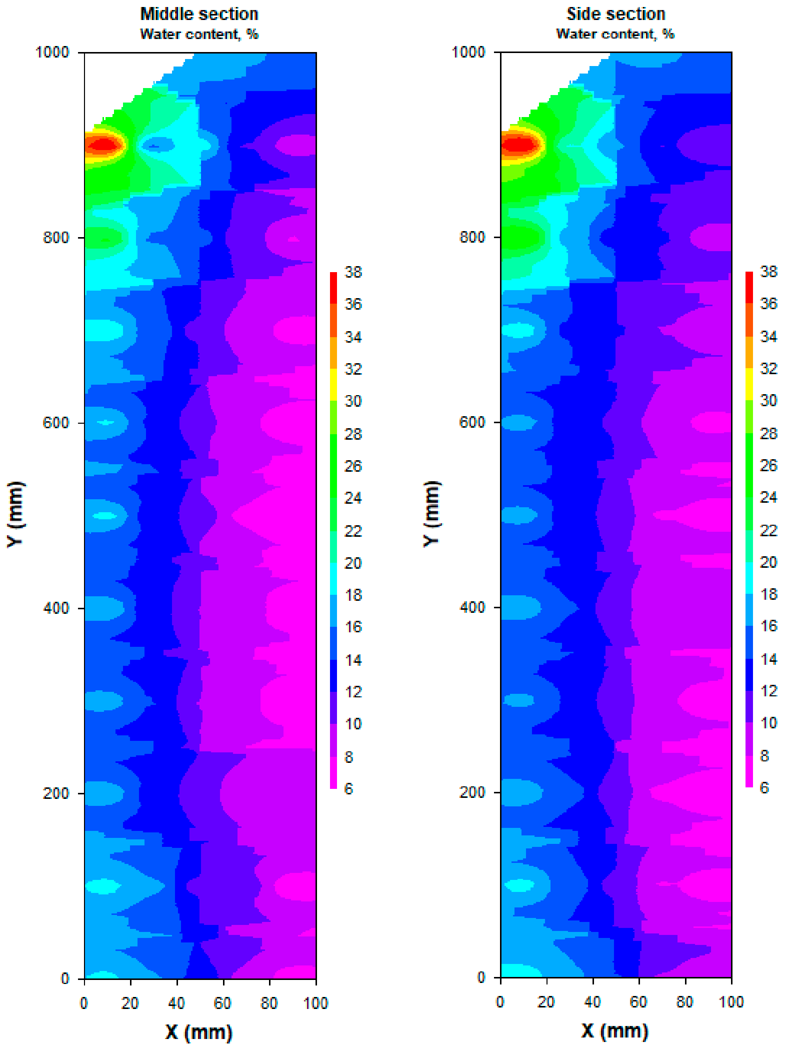


Figure 4-9. *Contour plots showing the water content distribution (%) in the middle section (left) and the side section (right) of Gap test 1.*

4.6 Gap test 2: Blocks

4.6.1 Block manufacturing

The blocks used in these tests were manufactured using the same material as was used in the scale tests, i.e. a material with the trade name Bara-Kade 1002 (sodium bentonite originating from Wyoming, USA).

The blocks were manufactured according to the description provided in Section 2.2. The blocks had a cylindrical shape with a diameter of 275/280 mm and a height of 100 mm. The target water content was 17 % and the target dry density 1 650 kg/m^3 (the block data is provided in Appendix 3). From these cylindrical blocks, bricks with the approximate dimensions 200 x 100 x 98 mm were sawed out using a bandsaw. From every cylindrical block it was possible to saw out two of these brick-sized blocks.

4.6.2 Test preparation

The brick-sized blocks were stacked in the test equipment according to the pattern shown in Figure 4-10. The block stack had a thickness of 98 mm which means that the gap width between the blocks and the temperature-controlled walls was approximately one mm. The block stack was positioned so that there was a gap with a width of approximately one mm between the blocks and the temperature-controlled walls. There were also vertical gaps between the blocks with a width of approximately one mm.

The total installed mass of the blocks was 91.54 kg, and the water content was 17.4 %. The installed average bulk density in the test volume was 1 831 kg/m^3 and the dry density was 1 559 kg/m^3.

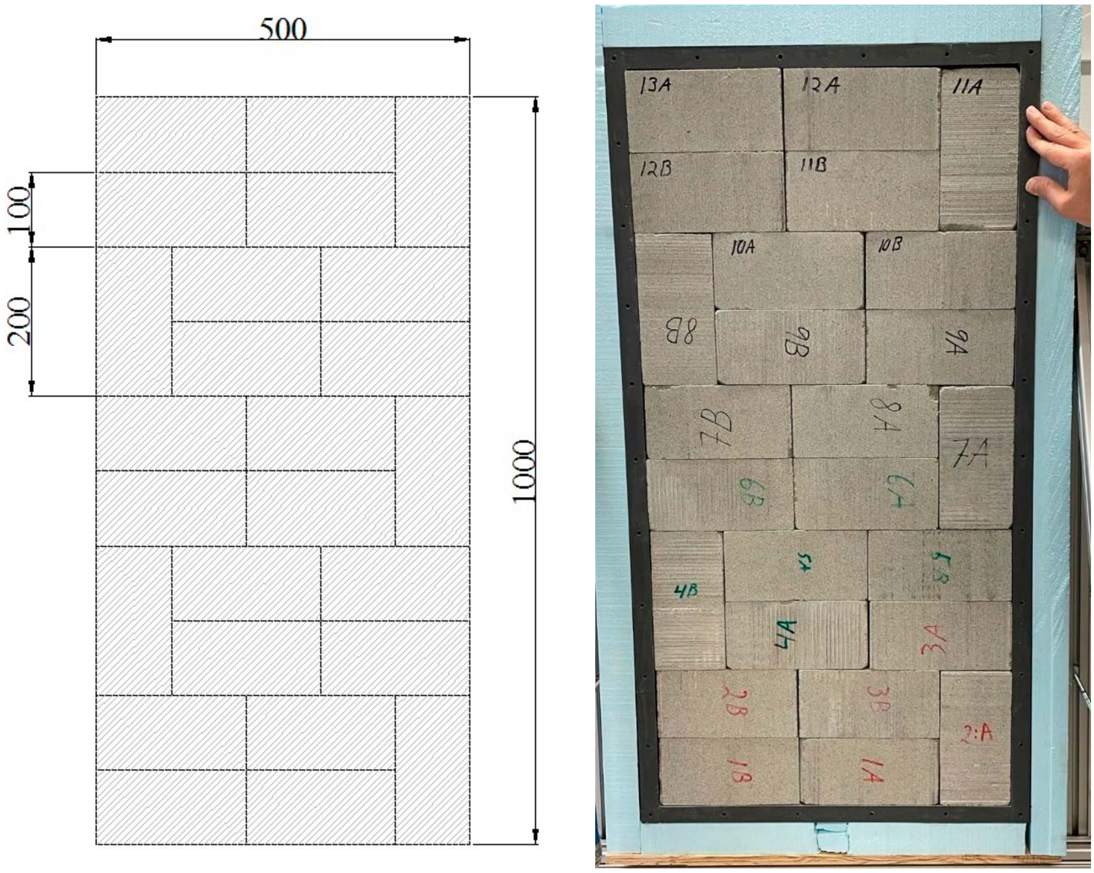


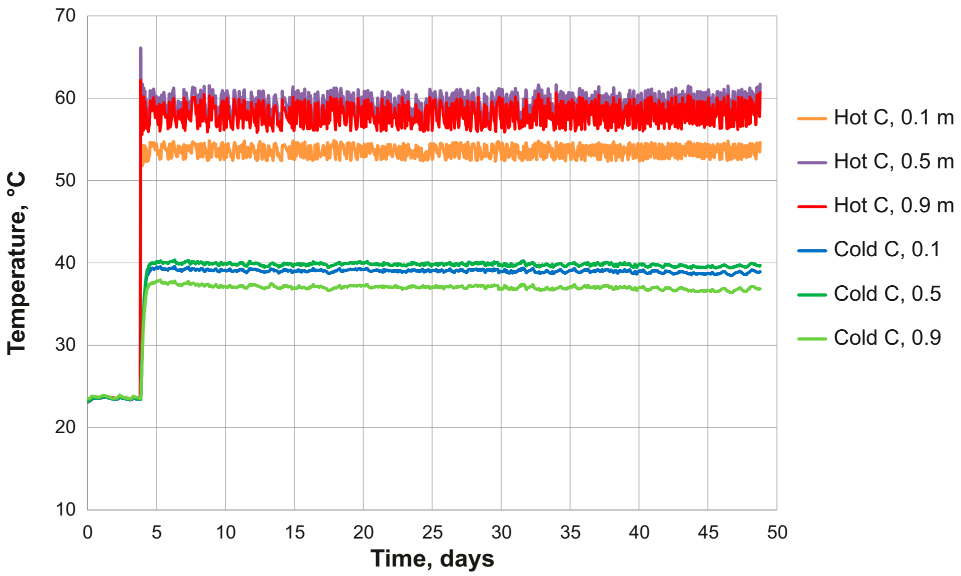
Figure 4-10. *Left: Figure showing how the blocks were stacked in the gap test. Right: Block stack after installation. All blocks were marked with an individual number.*

4.6.3 Registered data during test time

Temperature

The graphs provided in Figure 4-11 shows the registered temperature development during the test time. The temperature on the cold side was between 37 and 40 °C at all six positions. The temperature on the warm side was between 52 and 55 °C at the lower level (0.1 m) while the temperature at the other two levels (0.5 m and 0.9 m) was between 56 and 61 °C. There have thus been some variations in the horizontal gradient between the lower part of the gap (with approximately 13–16 °C difference) and the middle and upper part (with approximately 15–24 °C difference). However, no difference in temperature could be seen between the vertical central part and the peripheral vertical side of the block filling, Figure 4-11.

The applied power varied between 195 to 203 W during the test. The total power consumption was 213.4 kWh after forty-nine days test.



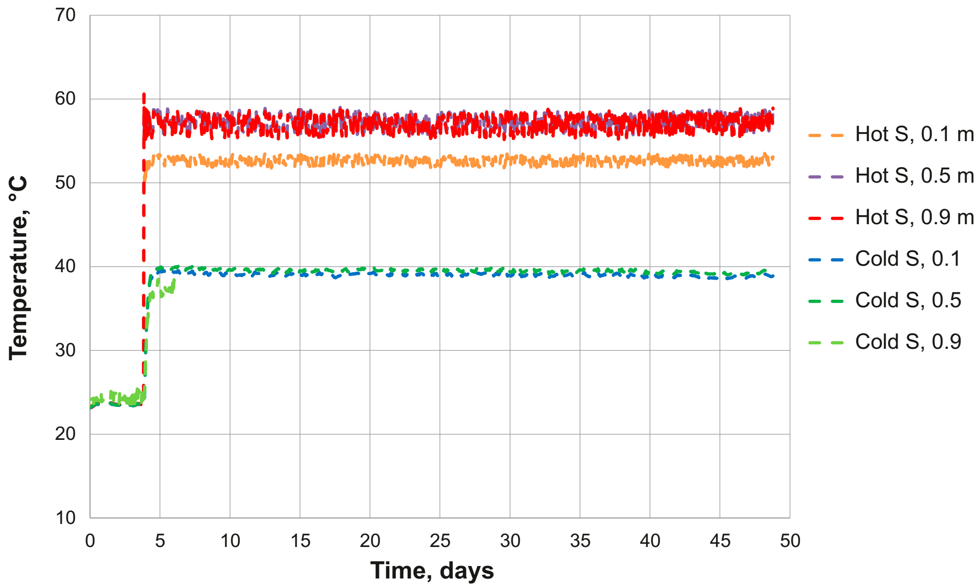


Figure 4-11. *Temperature development during Gap test 2 with a block-filled gap. Thermocouples were placed at three levels (0.1, 0.5 and 0.9 meters from the bottom) on both the hot side and the cold side. Upper graph: Results from thermocouples positioned along the vertical central part of the box (C = Central part of the box). Lower graph: Results from thermocouples positioned along the vertical side of the box (S = Side of the box).*

Relative humidity

The graph provided in Figure 4-12 shows the development of the measured relative humidity in the test.

Some comments on the relative humidity measurements:

- After installation of the RH-sensors, the measured relative humidity was between 65 and 67 % at both the top and bottom of the box. The measured relative humidity corresponds rather well to the water content of the blocks which was 17.4 % (Dueck and Nilsson, 2010).
- After having started the test, the relative humidity started to increase very fast. After 24 hours the sensor at the bottom registered a relative humidity of 92 %. Thereafter this sensor registered a relative humidity between 92 and 93 % for the complete test duration. After 24 hours the sensor at the top registered a relative humidity of approximately 85 %. During the following weeks this value increased to 91 %. After approximately 32 days test duration, this sensor was judged to have stopped working, probably due to water condensing on the electronics.
- After the first increase in temperature, the temperature registered by the two relative humidity sensors stayed at an almost constant level of 38 and 41°C respectively for the duration of the test.

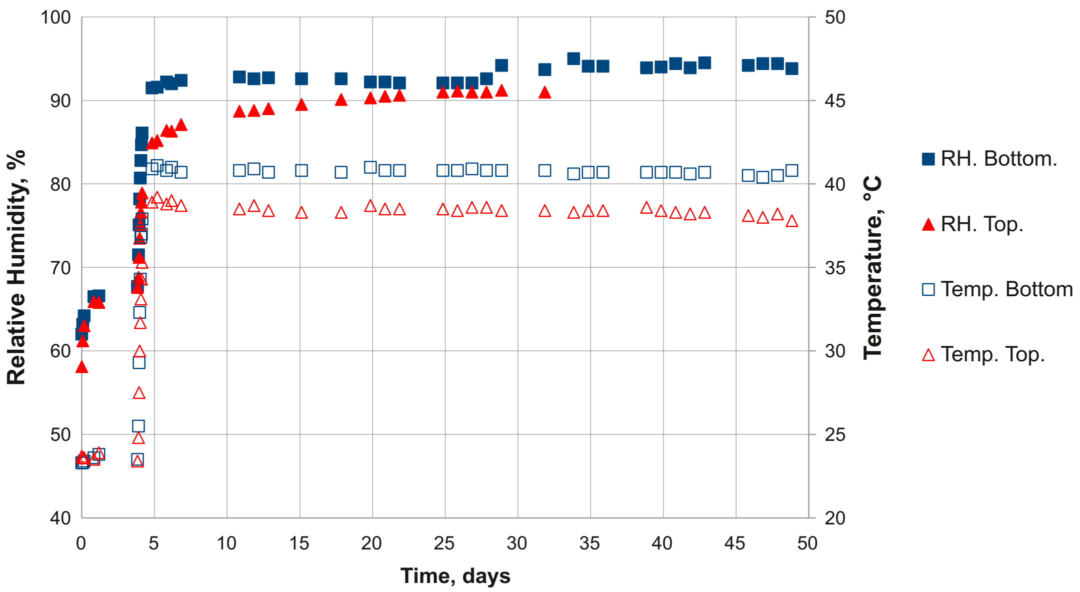


***Figure 4-12.** Measured relative humidity in Gap test 2 at two positions, on the top and at the bottom respectively. The graph also shows the temperature measured with the same sensors.*

4.6.4 Power consumption

The power consumption was measured by use of a simple commercially available meter installed in a wall socket. The reading was done manually, and the accuracy of the measurement was declared by the manufacturer to be ± 1 %. The applied power varied mainly between 196 and 203 W, Figure 4-13, and the total power consumption was 213 kWh after 50 days test duration.

4.6.5 Dismantling and sampling

After almost fifty days test duration it was judged that the test had reached equilibrium i.e., the relative humidity sensors (one of them stopped working after 32 days test duration) indicated that there were no additional redistribution of moisture going on within the test volume, and it was decided to turn off the electrical heater. After approximately three hours of cooling (at room temperature), the dismantling started. The aluminum plate on the cold side was first removed, Figure 4-14. The exposed blocks looked almost like when they were placed. Some small wet points could be seen on one of the blocks positioned at the top, see upper left corner in photo provided in Figure 4-14.

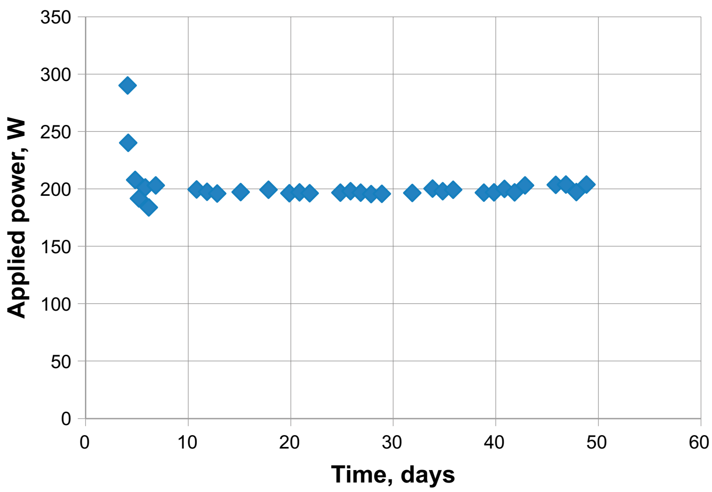


Figure 4-13. *The applied power plotted versus time for Gap test 2 with blocks.*

Figure 4-14. *The alumina plate on the cold side have been removed. Some small wet points could be seen on one of the blocks positioned at the top, see upper left corner in photo.*

An extensive sampling was conducted to determine the water content distribution within the block filling. The sampling positions were the same as described in Section 4.4.4. The only difference was that every sample was cut out from the blocks using a bandsaw.

A compilation of the results from the sampling is provided in Figure 4-15. The graph shows the measured water content for all sampled positions. The circular dots show the sampling of the section in the middle of the test box and the square dots show the sampling of the peripheral section close to the side of the test box. The different colors indicate the sample position in horizontal direction i.e., from the cold side to the warm side. The black vertical line indicates the initial water content of the blocks. The initial water content of the blocks was determined to 17.4 % in conjunction with the manufacturing, Appendix 3. The blocks seem, however, to have dried in conjunction with the sawing, which may explain that the water content determined in most sampling points was lower than the initial.

As expected, there was a clear difference in water content between the samples taken closest to the cold side (0–20 mm) and the samples taken closest to the warm side (80–100 mm). There is, however, also a difference in water content in the vertical direction. The samples taken from the top of the box have a significantly higher water content compared to those from the bottom.

Contour plots were made using an interpolation program, Figure 4-16. The plots show the water content distribution in the two sampled sections. The left contour plot shows the result from the middle section and the right plot shows the result from the side section. The plots show clearly how there has been a redistribution of moisture within the blocks, from the warm side to the cold side. The graphs also show that the water content at the top of the side section (right plot) was somewhat higher compared to the same position at the middle section. At all other positions, the water content distribution was very similar between the two sections.

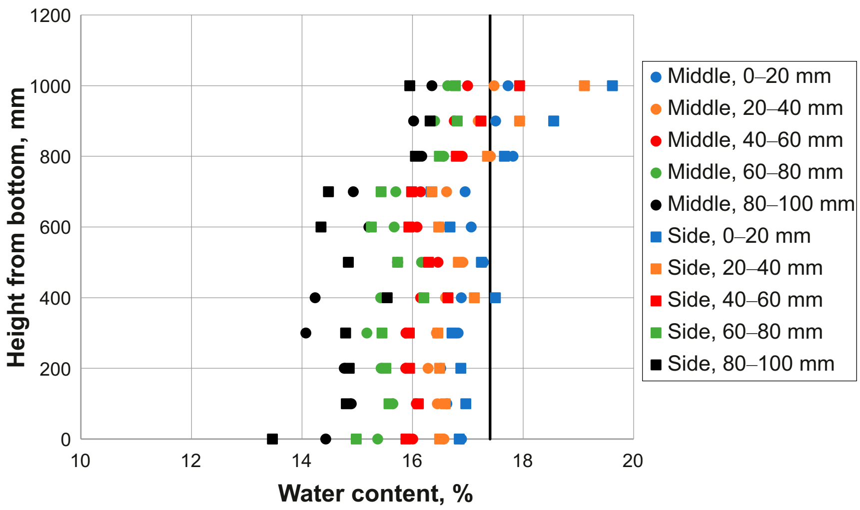


Figure 4-15. *Water content distribution in the bentonite blocks in Gap test 2. Samples were taken along the middle (circles) and side (squares) of the box at five different depths. The black vertical line indicates the initial water content of the blocks.*

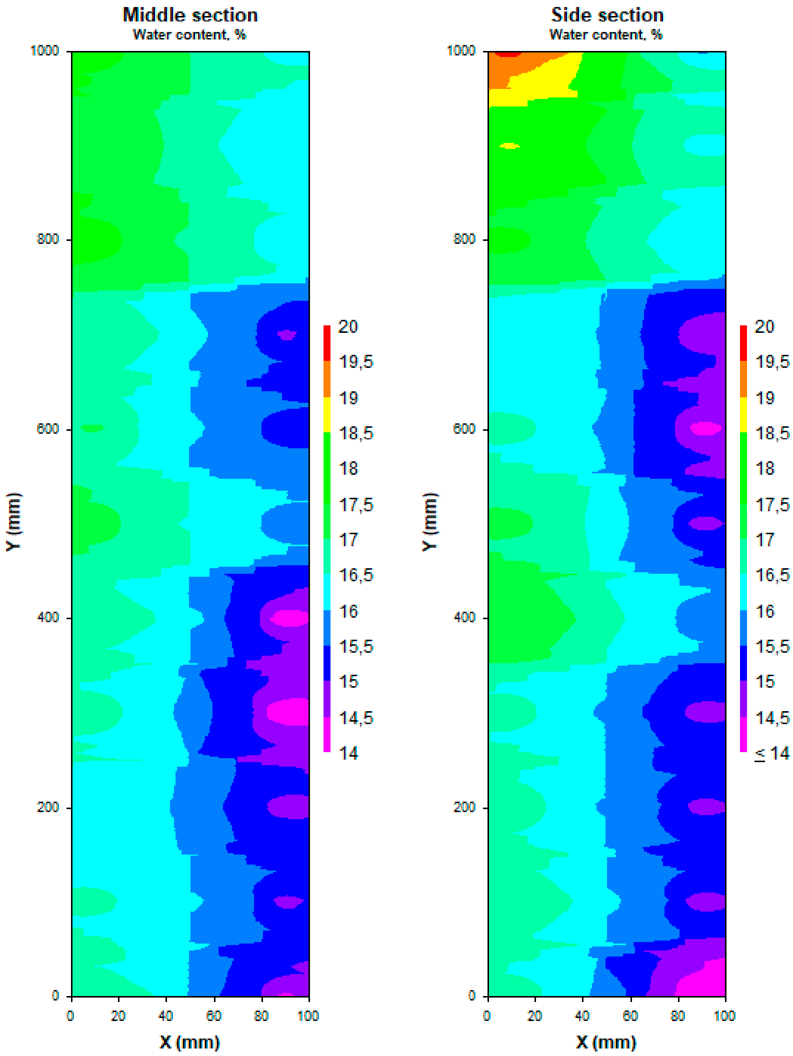


Figure 4-16. *Contour plots showing the water content distribution (%) in the middle section (left) and the side section (right) of Gap test 2.*

5 Comments and discussion

5.1 Tests in scale 1:5

5.1.1 Temperature distribution

The temperature evolutions of the scale tests (Figure 3-6 and Figure 3-7 for Scale test 1, and Figure 3-21 and Figure 3-22 for Scale test 2) show that steady-state conditions were reached after approximately two to three months. To achieve a good picture of the temperature distribution at steady state, graphs showing the test layout, and the registered temperature are provided in Figure 5-1. The graphs show the temperature distribution at day 350. The number of thermocouples installed in these tests was limited (13 pcs in each test, see Figure 3-2) and the graphs therefore show a rather rough picture of the temperature distribution. The thermocouples were mainly positioned in the sampling direction C, ± 45° (see Figure 3-11).

The temperature distribution was in general very similar for the two tests. A small difference was the temperature at the warmest part of the heater that was somewhat higher in Scale test 1, between 70 and 71 °C, as compared to a temperature between 67 and 70 °C in Scale test 2.

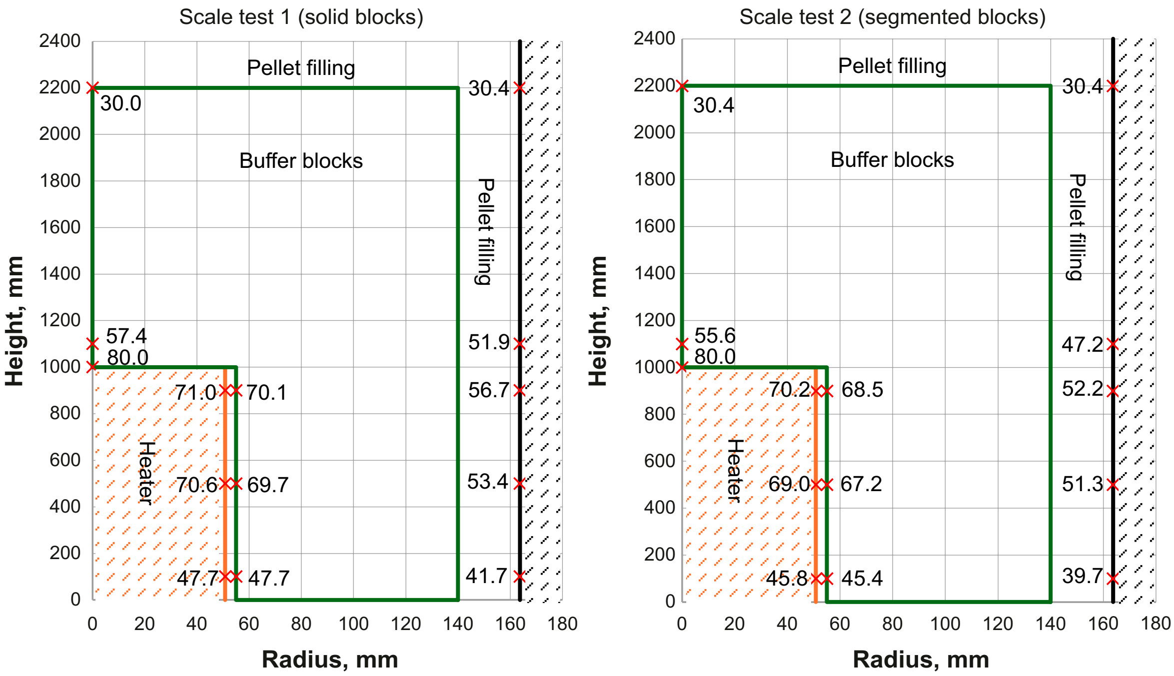


Figure 5-1. *Graphs showing the temperature distribution in Scale test 1 (left) and Scale test 2 (right) at day 350.*

5.1.2 RH evolution

Comments on the registered RH values in both scale tests:

- The registered RH values after installation varied between 60 and 67 % in both tests. This corresponds rather well with the water content of the installed MX-80 pellets (14.1 %).
- The two sensors positioned at the inner surface of the two test cells at levels 0.5 and 1.1 meter from bottom reacted very fast after the heating was started; the sensors reached 100 % in less than one week. The vapor transport in the radial direction was thus rather fast.
- The RH-sensors positioned 2.2 meters from the bottom plate reacted very slowly after heating was started and continued to show a slow increase in the registered RH thereafter. At the time of dismantling, the sensors showed RH-values of approximately 79 % (Scale test 1) and 74 % (Scale test 2). The measured water contents of the pellets at this level were 15.8 % and 15.6 % respectively. A comparison of these results with retention curves for MX-80 (Dueck and Nilsson, 2010) suggests that the sensor used in Test 2 underestimated the RH value.

5.1.3 Water content distribution

The total amount of installed water in the two tests was 43.8 kg and 43.28 kg respectively, see compilation of installation data in Table 5-1.

Table 5-1. Installation data from Scale Test 1 and Scale Test 2.

Installation data		
	Test 1	**Test 2**
Installed block mass, kg	237.80	234.79
Water content, %	17.4	17.4
Dry mass, kg	202.56	199.99
Water mass, kg	35.24	34.80
Installed pellets mass, kg	69.2	68.6
Water content, %	14.1	14.1
Dry mass, kg	60.65	60.12
Water mass, kg	8.55	8.48
Total installed mass of water, kg	**43.80**	**43.28**

The results from the sampling showed that a significant moisture redistribution had taken place during the test period. Contour plots showing the measured water content distribution in the two tests are provided in Figure 5-2. For each of the tests, the water content distribution is shown in four directions (A, B, C and D).

Some comments to the results:

- In general, the sampling showed that moisture has been transported from the blocks and pellets in block positions 3 to 11 (around and at the top of the heater) upwards to block positions 12 to 19, but also downwards to block positions 1 and 2.
- The individual blocks used in the test were weighed and measured at time for installation. New measurements were made in conjunction with the dismantling and the differences between the measurements were calculated. Corresponding calculations of the changes in mass of the pellets surrounding every block were made using the average water content that was determined at dismantling in four directions outside every block and comparing this with the initial water content of the pellets. The results from these measurements showed that the sum of weight changes for the blocks in Scale test 1 was −3.26 kg and for the pellets 2.03 kg, Table 3-2. This means that there was a discrepancy of −1.23 kg. Corresponding figures for Scale test 2 were −3.29 kg for the blocks, 2.18 kg for the pellets and a discrepancy of −1.11 kg, Table 3-3. These figures for the two tests were thus very similar. The discrepancy probably depends on in problems to determine the average water content in the pellet filling (large variations) and/or variations in the initial water contents of both blocks and pellets. A third explanation could be leakages from the test volume, but no signs of this was detected.

- The sum of redistributed moisture in the two tests was somewhat higher in Scale test 2 (6.42 kg dehydrated and 5.313 kg taken up) than in Scale test 1 (5.702 kg dehydrated and 4.468 kg taken up), Table 3-2 and Table 3-3. This difference may be due to the segmented blocks used in Scale test 2 which increases the number of gaps between the blocks. This is believed to facilitate vapor transport due to natural convection. For example, the dehydration of the bentonite blocks around the heater seems to have been more extensive in Scale test 2, see contour plots provided in Figure 3-16 (Scale test 1) and in Figure 3-29 (Scale test 2).
- In both scale tests, specific condensation points were identified in the pellet filling above the heater. In Scale test 1 there were higher water contents at the level of block 13 and 14 (direction C) and at the level of block 16 and 17 (direction A), see Figure 5-2. Corresponding condensation points were found in Scale test 2 at the level of block 13 and 14 (direction A and D), Figure 5-2.
- The rotational symmetry of the sampling results was not perfect. Except for the condensation points in the pellet filling, see bullet above, it was also clear that the dehydration of the bentonite blocks around the heater in Scale test 2 was more extensive in direction A and D, Figure 5-2. In Scale test 1, there was also a tendency that the dehydration was more extensive in direction A, but this was not as pronounced as for Scale test 2.

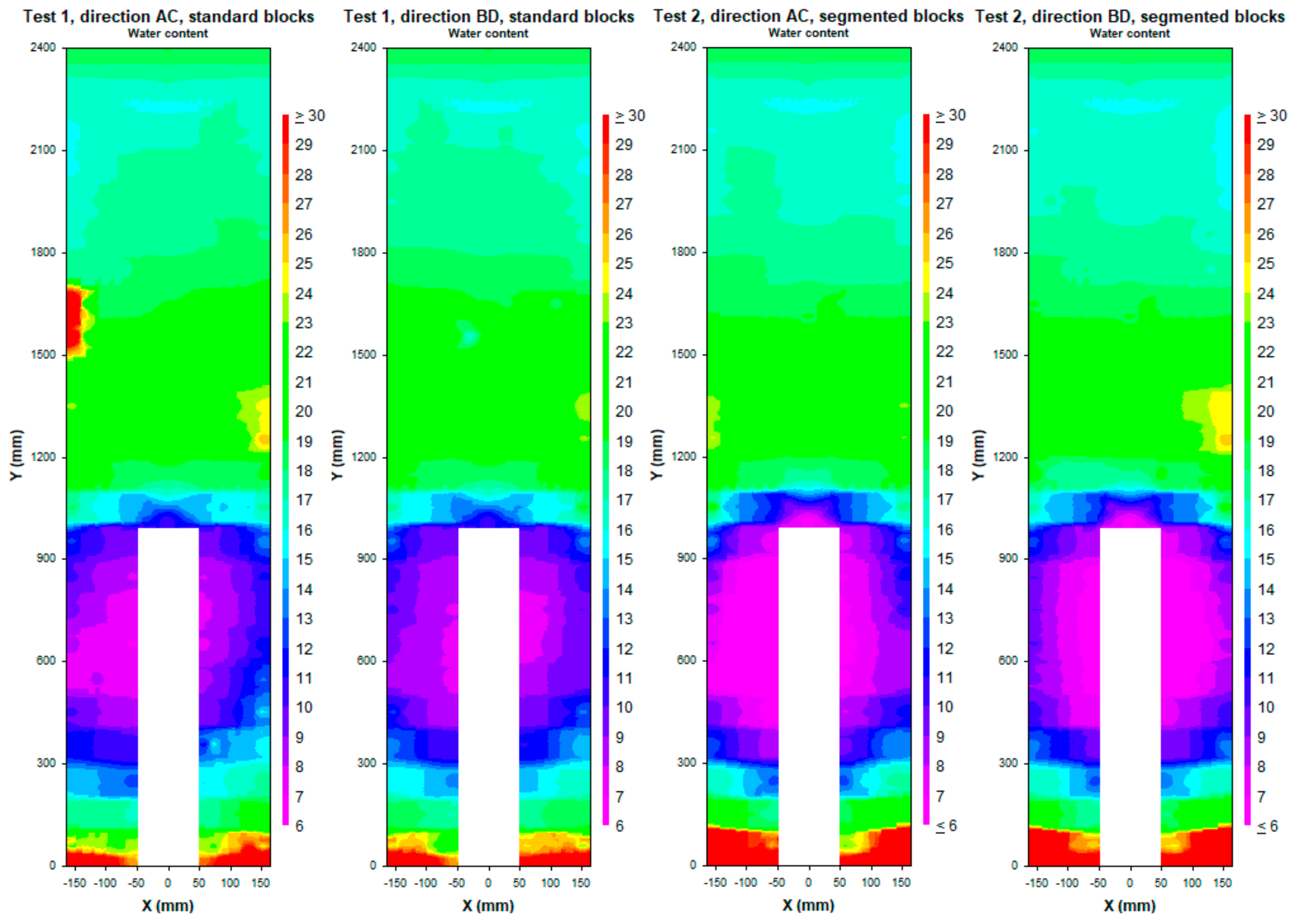


Figure 5-2. *Contour plots showing the water content distribution (%) in four directions for each of the two scale tests. The two contour plots to the left show the results from Scale test 1 and the two contour plots to the right show the results from Scale test 2.*

5.2 Gap tests with horizontal thermal gradient

5.2.1 Gap test 1: Pellets

Temperature evolution

The temperature evolutions in Figure 4-3 show that steady-state conditions were reached during the first day. The temperature on the cold side was between 32 and 34 °C and between 53 and 60 °C at the warm side. The lower temperature on the warm side was at the lower part of the box. There has thus been some variation in radial gradient between the lower part of the gap (approximately 21–23 °C) and the middle and upper part (approximately 25–26 °C). After steady-state conditions were reached, there were no noticeable changes in the temperature evolutions (only small variations depending on the temperature controlling system). Also, the applied power was rather constant, Figure 4-5. This implies that there wasn´t any noticeable change in thermal conductivity, even though the moisture content was redistributed.

RH evolution

The RH values started at an initial level of between 44 % (at the top of the box) and 54 % (at the bottom of the box). The difference may depend on the fact that the sensor at the top probably was situated in an air-filled void. After approximately three weeks test duration, the RH values had reached an equilibrium of between 72 % at the bottom and 80 % at the top.

Water content distribution

The results show that a significant moisture redistribution took place during the test period. The initial water content of the pellet filling was 11.4 %. At time for dismantling, the water content distribution varied between 5.9 and 39.1 %, Figure 4-8. The differences in water content between the central parts of the box and the side parts were small, Figure 4-9.

5.2.2 Gap test 2: Blocks

Temperature evolution

The temperature evolutions in Figure 4-11 show that steady-state conditions were reached during the first day. The temperature on the cold side was between 37 and 40 °C and between 52 and 61 °C at the warm side. The lower temperature on the warm side was at the lower part of the box. There has thus been some variation in radial gradient between the lower part of the gap (approximately 13–16 °C) and the middle and upper part (approximately 15–24 °C). After steady-state conditions were reached, there were no noticeable changes in the temperature evolutions (only small variations depending on the temperature controlling system). Also, the applied power was rather constant, Figure 4-13. This implies that there wasn´t any noticeable change in thermal conductivity, even though the moisture content was redistributed.

RH evolution

The RH values started at an initial level of between 65 % (at the top of the box) and 67 % (at the bottom of the box). After having started the heating, the RH increased very fast. After approximately four weeks test duration, both sensors registered RH values above 90 % (between 90 and 93 %). However, after 32 days test duration the sensor at the top stopped working.

Water content distribution

The results show that a moisture redistribution took place during the test period. The initial water content of the blocks was 17.4 %. At time for dismantling, the water content distribution varied between 13.5 and 19.6 %, Figure 4-8. The differences in water content between the central parts of the box and the side parts were, however, small, Figure 4-9.

5.3 Evaluation of water content vs temperature relations

The final state regarding water content and temperature can be used to assess how far the vapor pressure had equilibrated at the end of each test. The final temperature measurement from each sensor was with this approach plotted against the water content measured in bentonite samples taken as close as possible to the corresponding sensor position (Figure 5-3).

For the sensors around the heater and in the pellets-filled slot in the scale tests, which were all positioned in the C direction (± 45°), this generally meant average water content values from bentonite samples taken in the same direction, but at 50 mm above and 50 mm below the sensor position. The sensors at the lateral side of the heaters were not included due to the presence of the inner slot. For the central sensors at 1.1 and 2.2 m above the bottom plate, it meant average water content values from two adjacent bentonite samples. Finally, for the sensor at the top of the heater in each scale tests, and for all the temperature sensors in the slot tests, all sensor positions coincided with one adjacent bentonite sample.

In addition to this data, lines representing different constant vapor pressures were included. These were based on the simple relation $p_v = RH(w) \cdot p_v^{sat}(T)$, where $RH(w)$ is a water retention curve for free swelling condition, and $p_v^{sat}(T)$ is saturation vapor pressure as a function of temperature.

For the scale tests, this shows that the final state in the lower part of the test setup (up to 1.1 m above the bottom plate) generally corresponded to a vapor pressure of approximately 70 mbar, albeit with a quite significant margin, whereas the corresponding vapor pressure at the upper part was approximately 25 mbar (Figure 5-3, left diagram). The final state of the gap test with pellets material likewise corresponded to vapor pressure of approximately 45 mbar. For the gap test with blocks, however, there appeared to be a quite significant divide, with which the vapor pressure varied between 45 and 90 mbar at the cool and warm side, respectively.

This indicates that the conditions in the lower part of the scale tests, and in the gap test with pellets had proceeded quite far towards an equilibrated vapor pressure. For the entire scale tests including also the upper part, and for the gap test with bentonite blocks, however, there were apparently a remaining potential for further moisture redistribution.

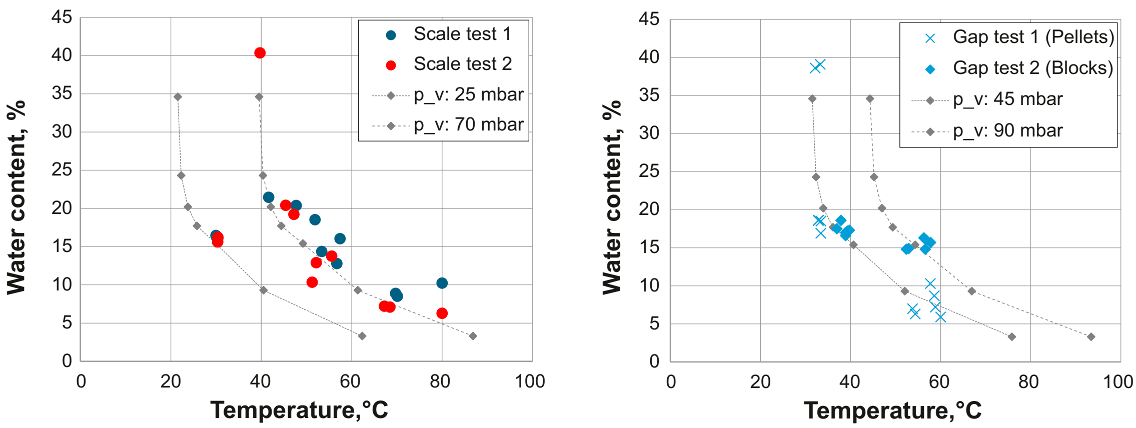


Figure 5-3. Compilations of the final state regarding water content and temperature at the sensor positions. Dashed gray lines are based on water retention data for MX-80 and free swelling conditions and for an initial water content of 17 % (Dueck, 2004).

6 Concluding remarks

The presented tests were performed with the overall objective to improve the understanding of the role of natural convection for the moisture redistribution from hot to cold parts of the bentonite buffer and the backfill.

Scale tests

The scale tests were designed to mimic the conditions in a dry deposition hole and a dry tunnel section as far as possible with a simplified test geometry, approximately in scale 1:5, and were run with constant heater temperature (80 °C) during one year, after which the water content distribution was determined. The test setup was not an exact physical model of a real deposition hole, but instead a test case which was intended to be used for model validation. Two tests were performed, one with solid blocks and one with segmented blocks.

The results from the scale tests show that the largest moisture redistribution had occurred from the upper part of the heater (block 6/7 – 11), to the bentonite above the heater (block 12 – upper pellet filling). The redistribution measured as increased water mass in block 12 and above, was approximately the same (~ 3 kg) for both solid and for segmented blocks. The second largest redistribution had occurred from the bentonite in the mid-section of the heater (block 3–5/6) to the bentonite around the lower part of the heater (block 1 and 2). The redistribution measured as increased water mass in block 1 and 2 was significantly higher in the case with segmented blocks (~ 2 kg) as compared with the case with solid blocks (~ 1 kg). This difference was also reflected in the water content values found in the driest part around the heater, which was ~ 4 % for segmented blocks and ~ 6 % for solid blocks.

Taken together, this indicates that the introduction of segmented buffer blocks does not lead to an increased moisture redistribution from the ring-shaped block around the canister to the bentonite installations above, at least not for a modest slot width of 1 mm. A segmented buffer does however seem to lead to a more pronounced redistribution in the buffer around the canister, probably due to natural convection in the slots between the segmented blocks. The absence of an increased redistribution to the installation above may at least partly be an effect of the closing of the slots in Block 12–18 above the heater. However, the radial slots in the ring-shaped blocks around the heater also seemed to have closed, and this did not prevent the redistribution around the heater to be more pronounced. The moisture transport driven by natural convection therefore seems to be most important adjacent to the canister where the gas in the slots is exposed to the radial heat flux from the canister.

Gap tests

The gap tests were designed to give basic information regarding the contribution of the natural convection on the moisture redistribution within the buffer. The test arrangement was rather similar to the tests with thermal gradient presented by Åkesson et al. (2020), but with the important differences that the temperature gradient in the new tests was horizontally oriented, and that the relation between the bottom area and the length was considerably larger compared to the earlier tests. Two tests were performed, one with a pellet filling and one with bentonite blocks. Both tests were performed during a period of 49 days with a maximum temperature difference between the hot and cold side of approximately 25 °C.

The evolution of relative humidity in the pellets displayed an immediate divergence of the trends, with a significantly higher RH level at the top, which indicates a rapid vapor transport driven by natural convection, and also that the gas phase was not in equilibrium with the bentonite during the initial stage. The subsequent evolution with converging RH levels indicates the occurrence of moisture redistribution and equilibration of vapor pressures. The diverging RH evolutions at the top and the bottom were much less pronounced in the test with bentonite blocks, which may indicate that the bentonite and the adjacent gas phase was (locally) closer to equilibrium in this test, possibly due to a lower rate of vapor transfer.

The measured water content distributions showed that the vertical profiles were fairly similar for the two tests with a difference between the top and the bottom positions of approximately 2 %, although the pellets displayed a minimum at mid-height. For the horizontal profiles on the other hand, the general difference in water content between the hot and the cold side were much higher in the test with pellets with approximately 12–13 %, while the corresponding difference in the test with blocks was approximately 2–3 %. This indicates that pellets, at the end of the test, were closer to equilibrium regarding vapor pressure than in the corresponding test with bentonite blocks. The reason for why the condition in the blocks was farther away from equilibrium may be due to a lower rate of vapor transfer in this test.

Final remark

The experimental results display some uncertainty regarding the water mass balance of the scale tests, and the relatively low final water content in the slot test with bentonite blocks, which both indicate that some minor dehydration occurred during some stage of these experiments. Moreover, the heat transport from the lower part of the heaters in the scale tests was not only radial, as initially intended, but to some extent also axial, which meant that the temperature in the lower part was lower than the temperature at the heater mid-section, which in turn seems to have yielded an amplified moisture accumulation at the bottom of the test setup. Still, all the presented tests were performed at well-defined conditions and have resulted in consistent data sets regarding distributions of temperature, water content and dry density, and should therefore be readily applicable for model validation.

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Appendix 1

Scale test 1

Installation data. Blocks and pellets.

No.	Complete block								Pellets installation						
	Dy mm	dy mm	di mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³	Dy mm	di mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³
Block 1	280.3	276.3	110.3	99.8	9.82	1 919	17.4	1 635	327.2	278.3	99.8	2.22	957	14.1	838
Block 2	280.3	276.3	110.3	99.8	9.84	1 923	17.4	1 638	327.2	278.3	99.8	2.22	957	14.1	838
Block 3	280.3	276.3	110.3	99.5	9.82	1 925	17.4	1 640	327.2	278.3	99.5	2.29	990	14.1	867
Block 4	280.3	276.3	110.3	100.0	9.82	1 915	17.4	1 631	327.2	278.3	100.0	2.29	985	14.1	863
Block 5	280.3	276.3	110.3	99.7	9.82	1 921	17.4	1 636	327.2	278.3	99.7	2.18	940	14.1	824
Block 6	280.3	276.3	110.3	99.7	9.80	1 917	17.4	1 633	327.2	278.3	99.7	2.18	940	14.1	824
Block 7	280.3	276.3	110.3	100.0	9.82	1 915	17.4	1 631	327.2	278.3	100.0	2.35	1 012	14.1	887
Block 8	280.3	276.3	110.3	99.8	9.84	1 923	17.4	1 638	327.2	278.3	99.8	2.35	1 014	14.1	889
Block 9	280.3	276.3	110.3	99.7	9.82	1 921	17.4	1 636	327.2	278.3	99.7	2.35	1 015	14.1	890
Block 10	280.3	276.3	110.3	99.6	9.80	1 919	17.4	1 635	327.2	278.3	99.6	2.33	1 005	14.1	880
Block 11	280.3	276.3	-	99.7	11.54	1 903	17.4	1 621	327.2	278.3	99.7	2.33	1 004	14.1	880
Block 12	280.3	276.3	-	99.1	11.64	1 931	17.4	1 645	327.2	278.3	99.1	2.33	1 010	14.1	885
Block 13	280.3	276.3	-	99.7	11.62	1 916	17.4	1 632	327.2	278.3	99.7	2.33	1 003	14.1	879
Block 14	280.3	276.3	-	99.6	11.64	1 921	17.4	1 636	327.2	278.3	99.6	2.33	1 004	14.1	880
Block 15	280.3	276.3	-	99.1	11.60	1 924	17.4	1 639	327.2	278.3	99.1	2.33	1 009	14.1	884
Block 16	280.3	276.3	-	99.6	11.64	1 921	17.4	1 636	327.2	278.3	99.6	2.33	1 004	14.1	880
Block 17	280.3	276.3	-	99.9	11.66	1 919	17.4	1 634	327.2	278.3	99.9	2.18	938	14.1	822
Block 18	280.3	276.3	-	99.2	11.66	1 932	17.4	1 646	327.2	278.3	99.2	2.18	945	14.1	828
Block 19	280.3	276.3	-	99.6	11.62	1 937	17.4	1 650	327.2	278.3	98.6	2.33	1 014	14.1	889
Block 20	280.3	276.3	-	99.2	11.66	1 932	17.4	1 646	327.2	278.3	99.2	2.33	1 008	14.1	883
Block 21	280.3	276.3	-	99.5	11.68	1 930	17.4	1 644	327.2	278.3	99.5	2.33	1 005	14.1	881
Block 22	280.3	276.3	-	99.1	11.64	1 931	17.4	1 645	327.2	278.3	99.1	2.33	1 009	14.1	884
Pellets	-	-	-	-	-	-	-	-	327.2	-	210	18.82	1 066	14.1	934
Sum					237.80							69.20			

Scale test 1

Dismantling data. Blocks.

No.	Installation data				Dismantling data				Differences			
	Dy mm	dy mm	Height mm	Mass kg	Dy mm	dy mm	Height mm	Mass kg	Dy mm	dy mm	Height mm	Mass kg
Block 1	280.3	276.3	99.8	9.82	-	281.4	109.2	10.547	-	5.1	9.4	0.727
Block 2	280.3	276.3	99.8	9.84	-	-	101.6	9.829	-	-	1.8	−0.011
Block 3	280.3	276.3	99.5	9.82	278.1	274.6	99.3	9.618	−2.2	−1.7	−0.2	−0.202
Block 4	280.3	276.3	100	9.82	-	-	98.5	9.324	-	-	−1.5	−0.496
Block 5	280.3	276.3	99.7	9.82	276.0	271.5	97.6	9.155	−4.3	−4.8	−2.1	−0.665
Block 6	280.3	276.3	99.7	9.8	275.0	271.0	97.0	9.046	−5.3	−5.3	−2.7	−0.754
Block 7	280.3	276.3	100	9.82	274.0	269.5	97.0	9.012	−6.3	−6.8	−3.0	−0.808
Block 8	280.3	276.3	99.8	9.84	274.0	270.0	97.0	9.038	−6.3	−6.3	−2.8	−0.802
Block 9	280.3	276.3	99.7	9.82	274.0	270.5	97.0	9.05	−6.3	−5.8	−2.7	−0.77
Block 10	280.3	276.3	99.6	9.8	275.0	272.5	98.0	9.166	−5.3	−3.8	−1.6	−0.634
Block 11	280.3	276.3	99.7	11.54	-	277.5	103.0	11.263	-	1.2	3.3	−0.277
Block 12	280.3	276.3	99.1	11.64	284.0	281.0	102.0	11.731	3.7	4.7	2.9	0.091
Block 13	280.3	276.3	99.7	11.62	285.5	283.0	102.5	11.958	5.2	6.7	2.8	0.338
Block 14	280.3	276.3	99.6	11.64	283.0	283.0	102.0	12.037	2.7	6.7	2.4	0.397
Block 15	280.3	276.3	99.1	11.6	285.8	280.3	102.0	11.939	5.5	4.0	2.9	0.339
Block 16	280.3	276.3	99.6	11.64	-	-	-	**11.876**	-	-	-	**0.235**
Block 17	280.3	276.3	99.9	11.66	-	-	-	11.812	-	-	-	0.152
Block 18	280.3	276.3	99.2	11.66	-	-	-	11.706	-	-	-	0.046
Block 19	280.3	276.3	99.6	11.62	-	-	-	11.637	-	-	-	0.017
Block 20	280.3	276.3	99.2	11.66	-	-	-	11.618	-	-	-	−0.042
Block 21	280.3	276.3	99.5	11.68	-	-	-	11.603	-	-	-	−0.077
Block 22	280.3	276.3	99.1	11.64	-	-	-	11.576	-	-	-	−0.064
Sum				237.80				234.541				−3.260

The weight of block 16 (bold text) was estimated based on the water content determinations.

Appendix 2

Scale test 2

Installation data. Ring-shaped blocks.

No.	Ring-shaped block before division								Block parts after division				
	Dy mm	dy mm	di mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³	Part 1:1 kg	Part 1:2 kg	Part 1:3 kg	Part 1:4 kg	Sum kg
Block 1	280.5	276.4	110.4	100	9.84	1 917	17.4	1 633	2.22411	2.39868	2.43197	2.41468	9.46944
Block 2	280.5	276.4	110.4	99.7	9.80	1 915	17.4	1 631	2.48264	2.36673	2.48439	2.34974	9.68350
Block 3	280.5	276.4	110.4	99.9	9.82	1 915	17.4	1 631	2.45760	2.37189	2.39055	2.51320	9.73324
Block 4	280.5	276.4	110.4	99.9	9.84	1 919	17.4	1 635	2.42216	2.44688	2.37592	2.50014	9.74510
Block 5	280.5	276.4	110.4	100	9.82	1 913	17.4	1 630	2.41679	2.44087	2.48781	2.38727	9.73274
Block 6	280.5	276.4	110.4	99.7	9.84	1 923	17.4	1 638	2.43036	2.43867	2.45830	2.40383	9.73116
Block 7	280.5	276.4	110.4	99.6	9.82	1 921	17.4	1 636	2.39797	2.42161	2.44866	2.46177	9.73001
Block 8	280.5	276.4	110.4	99.7	9.82	1 919	17.4	1 635	2.38355	2.47005	2.47158	2.39862	9.72380
Block 9	280.5	276.4	110.4	99.8	9.80	1 913	17.4	1 630	2.39068	2.39009	2.42835	2.48953	9.69865
Block 10	280.5	276.4	110.4	101	9.84	1 898	17.4	1 617	2.42370	2.48689	2.40009	2.41091	9.72159
Block 11	280.5	276.4	110.4	100.2	9.82	1 910	17.4	1 627	2.39818	2.39937	2.46330	2.45620	9.71705
Block 12	280.5	276.4	110.4	100	9.82	1 913	17.4	1 630	2.47610	2.41757	2.39592	2.43381	9.72340
Block 13	280.5	276.4	110.4	99.7	9.82	1 919	17.4	1 635	2.44959	2.40931	2.39790	2.45937	9.71617
Block 14	280.5	276.4	110.4	99.6	9.80	1 917	17.4	1 633	2.50012	2.44768	2.35175	2.48840	9.78795
Block 15	280.5	276.4	110.4	99.9	9.80	1 911	17.4	1 628	2.45512	2.40765	2.35721	2.49502	9.71500
Block 16	280.5	276.4	110.4	99.8	9.80	1 913	17.4	1 630	2.40308	2.39697	2.45302	2.46666	9.71973
Block 17	280.5	276.4	110.4	100.1	9.80	1 908	17.4	1 625	2.42832	2.49555	2.43418	2.33972	9.69777
Block 18	280.5	276.4	110.4	99.6	9.80	1 917	17.4	1 633	2.41647	2.35670	2.47785	2.45105	9.70207
Block 19	280.5	276.4	110.4	99.9	9.80	1 911	17.4	1 628	2.39753	2.43510	2.46115	2.41461	9.70839
Block 20	280.5	276.4	110.4	99.8	9.80	1 913	17.4	1 630	2.39495	2.48992	2.46414	2.36523	9.71424
Block 21	280.5	276.4	110.4	99.8	9.80	1 913	17.4	1 630	2.46159	2.43338	2.38399	2.42958	9.70854
Block 22	280.5	276.4	110.4	99.8	9.78	1 909	17.4	1 626	2.45101	2.43861	2.38593	2.41454	9.69009
Sum					215.88								213.57

Scale test 2

Installation data. Central blocks and pellets.

No.	Central block part						Pellets installation						
	Dy mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³	Dy mm	di mm	Height mm	Mass kg	Bulk density kg/m³	Water content %	Dry density kg/m³
-	-	-	-	-	-	-	327.4	278.45	100	1.95	837	14.1	734
-	-	-	-	-	-	-	327.4	278.45	99.7	1.95	840	14.1	736
-	-	-	-	-	-	-	327.4	278.45	99.9	2.21	950	14.1	832
-	-	-	-	-	-	-	327.4	278.45	99.9	2.21	950	14.1	832
-	-	-	-	-	-	-	327.4	278.45	100	2.27	975	14.1	854
-	-	-	-	-	-	-	327.4	278.45	99.7	2.27	978	14.1	857
-	-	-	-	-	-	-	327.4	278.45	99.6	2.28	983	14.1	861
-	-	-	-	-	-	-	327.4	278.45	99.7	2.28	982	14.1	860
-	-	-	-	-	-	-	327.4	278.45	99.8	2.43	1045	14.1	916
-	-	-	-	-	-	-	327.4	278.45	101	2.43	1033	14.1	905
Block 11	108.2	99.6	1.74600	1907	17.4	1624	327.4	278.45	100.2	2.03	870	14.1	762
Block 12	108.1	100.8	1.75109	1893	17.4	1612	327.4	278.45	100	2.03	872	14.1	764
Block 13	108.0	100.3	1.76421	1920	17.4	1635	327.4	278.45	99.7	2.29	988	14.1	866
Block 14	108.0	100.1	1.77077	1931	17.4	1645	327.4	278.45	99.6	2.29	989	14.1	866
Block 15	108.0	100.2	1.76853	1927	17.4	1641	327.4	278.45	99.9	2.29	986	14.1	864
Block 16	107.8	100.4	1.77535	1930	17.4	1644	327.4	278.45	99.8	2.25	969	14.1	850
Block 17	108.0	100.5	1.76124	1920	17.4	1636	327.4	278.45	100.1	2.25	966	14.1	847
Block 18	108.0	100.5	1.76503	1917	17.4	1633	327.4	278.45	99.6	2.25	971	14.1	851
Block 19	108.0	100.8	1.77530	1923	17.4	1638	327.4	278.45	99.9	2.32	997	14.1	874
Block 20	108.0	100.2	1.78105	1940	17.4	1653	327.4	278.45	99.8	2.32	998	14.1	875
Block 21	108.0	100.2	1.77465	1914	17.4	1631	327.4	278.45	99.8	2.23	959	14.1	841
Block 22	108.0	100.2	1.78376	1925	17.4	1640	327.4	278.45	99.8	2.23	959	14.1	841
Pellets							327.4	-	202.5	19.52	1145	14.1	1004
Sum			21.217							68.60			

Scale test 2

Dismantling data. Ring-shaped blocks.

Block	Block parts at installation						Block parts after dismantling						Differences	
no.	Part 1:1 kg	Part 1:2 kg	Part 1:3 kg	Part 1:4 kg	Sum kg	Height mm	Part 1:1 kg	Part 1:2 kg	Part 1:3 kg	Part 1:4 kg	Sum kg	Height mm	Sum kg	Height mm
Block 1	2.224	2.399	2.432	2.415	9.469	100	**2.52**	**2.70**	**2.73**	**2.71**	**10.669**	115.500	**1.200**	15.500
Block 2	2.483	2.367	2.484	2.350	9.684	99.7	2.546	2.414	2.520	2.392	9.872	102.170	0.188	2.470
Block 3	2.458	2.372	2.391	2.513	9.733	99.9	2.419	2.334	2.340	2.467	9.560	99.720	−0.173	−0.180
Block 4	2.422	2.447	2.376	2.500	9.745	99.9	2.239	2.373	2.301	2.296	9.209	97.938	−0.536	−1.963
Block 5	2.417	2.441	2.488	2.387	9.733	100	2.280	2.206	2.245	2.248	8.979	97.200	−0.754	−2.800
Block 6	2.430	2.439	2.458	2.404	9.731	99.7	2.239	2.208	2.224	2.208	8.879	96.838	−0.852	−2.863
Block 7	2.398	2.422	2.449	2.462	9.730	99.6	2.196	2.242	2.194	2.181	8.813	96.413	−0.917	−3.187
Block 8	2.384	2.470	2.472	2.399	9.724	99.7	2.171	2.216	2.234	2.197	8.818	96.650	−0.906	−3.050
Block 9	2.391	2.390	2.428	2.490	9.399	99.8	2.200	2.282	2.198	2.176	8.856	96.850	−0.843	−2.950
Block 10	2.424	2.487	2.400	2.411	9.722	101	2.223	2.245	2.249	2.296	9.013	98.625	−0.709	−2.375
Block 11	2.398	2.399	2.463	2.456	9.717	100.2	2.380	2.379	2.327	2.318	9.404	99.798	−0.313	−0.403
Block 12	2.476	2.418	2.396	2.434	9.723	100	2.412	2.442	2.507	2.444	9.805	101.800	0.082	1.800
Block 13	2.450	2.409	2.398	2.459	9.716	99.7	2.466	2.508	2.517	2.500	9.991	102.875	0.275	3.175
Block 14	2.500	2.448	2.352	2.488	9.788	99.6	2.608	2.558	2.424	2.481	10.071	103.675	0.283	4.075
Block 15	2.455	2.408	2.357	2.495	9.715	99.9	2.494	2.429	2.550	2.528	10.001	103.250	0.286	3.350
Block 16	2.403	2.397	2.453	2.467	9.720	99.8	2.501	2.494	2.459	2.454	9.908	102.150	0.188	2.350
Block 17	2.428	2.496	2.434	2.340	9.698	100.1	2.463	2.525	2.457	2.369	9.814	101.075	0.116	0.975
Block 18	2.416	2.357	2.478	2.451	9.702	99.6	2.426	2.365	2.494	2.463	9.748	100.500	0.046	0.900
Block 19	2.398	2.435	2.461	2.415	9.708	99.9	2.463	2.417	2.393	2.430	9.703	99.938	−0.005	0.037
Block 20	2.395	2.490	2.464	2.365	9.714	99.8	2.462	2.356	2.383	2.480	9.681	100.055	−0.033	0.255
Block 21	2.462	2.433	2.384	2.430	9.709	99.8	2.373	2.420	2.445	2.417	9.655	99.463	−0.054	−0.338
Block 22	2.451	2.439	2.386	2.415	9.690	99.8	**2.451**	**2.439**	**2.386**	**2.415**	**9.690**	99.343	**0.000**	−0.457
Sum					213.570						210.140		−3.430	

Note that the weight of the block parts of Block1 and Block 22 (bold text) was estimated based on the water content determinations.

Scale test 2

Dismantling data. Central blocks.

Central block part									
No.	At installation			After dismantling			Differences		
	Dy mm	Height mm	Mass kg	Dy mm	Height mm	Mass kg	Dy mm	Height mm	Mass kg
Block 11	108.2	99.6	1.746	107.7	96.8	1.647	−0.5	−2.8	−0.099
Block 12	108.1	100.8	1.751	110.0	101.6	1.768	1.9	0.8	0.017
Block 13	108.0	100.3	1.764	110.6	102.7	1.812	2.6	2.4	0.048
Block 14	108.0	100.1	1.771	111.2	103.1	1.835	3.2	3.0	0.064
Block 15	108.0	100.2	1.769	110.6	103.0	1.821	2.6	2.8	0.052
Block 16	108.0	100.4	1.775	109.7	102.1	1.814	1.7	1.7	0.039
Block 17	107.8	100.5	1.761	108.7	102.4	1.788	0.9	1.9	0.027
Block 18	108.0	100.5	1.765	108.5	101.7	1.776	0.5	1.2	0.011
Block 19	108.0	100.8	1.775	108.0	101.1	1.770	0.0	0.3	−0.005
Block 20	108.0	100.2	1.781	108.0	100.6	1.775	0.0	0.4	−0.006
Block 21	108.0	100.2	1.775	108.0	101.5	1.767	0.0	0.3	−0.008
Block 22	108.0	100.2	1.784	-	100.6	**1.784**	-	−0.5	**0.000**
Sum			21.217			21.357			0.040

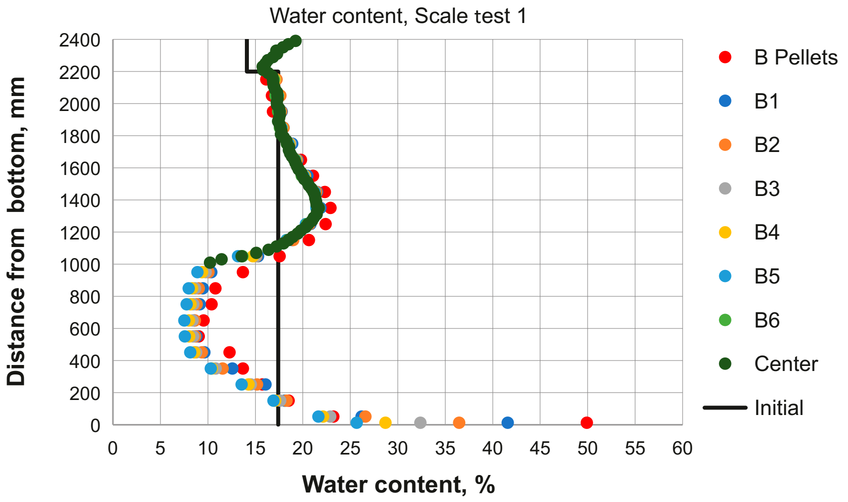
The weight of the central block part of Block 22 (bold text) was estimated based on the water content determinations.

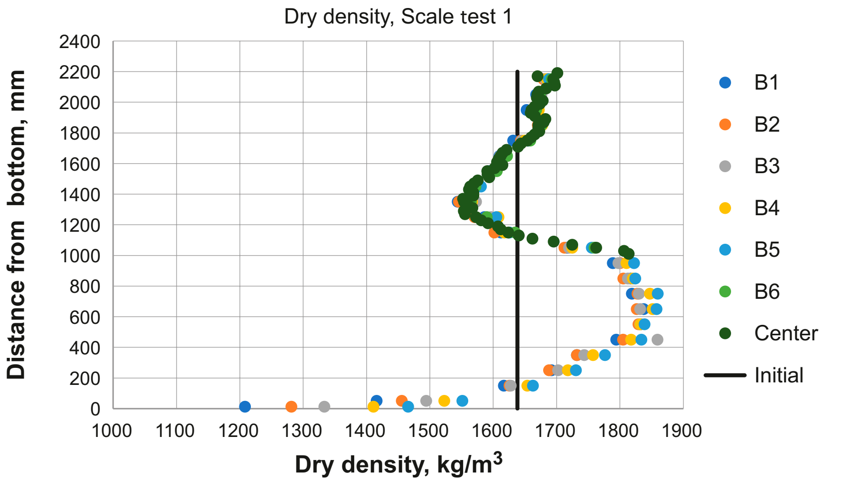
Appendix 3

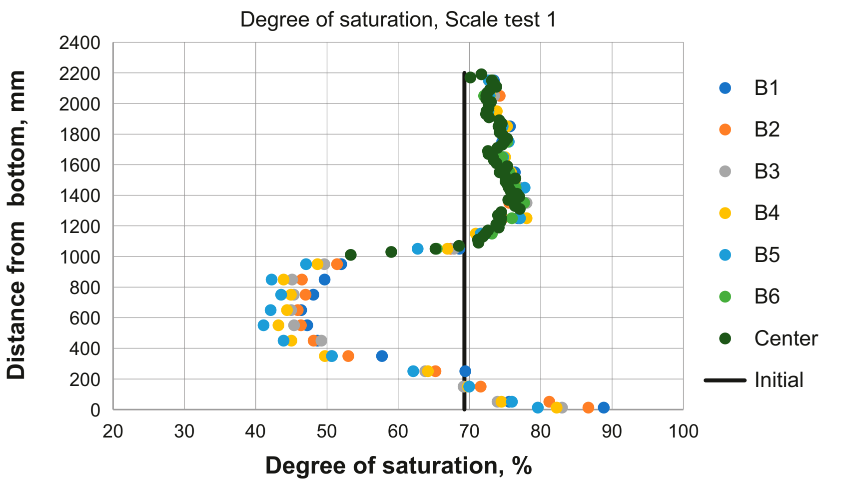
Gap test with blocks, (blocks with brick size were sawed out from the blocks below).

No.	Type	Complete block						
		Dy mm	**dy mm**	**Height mm**	**Mass kg**	**Bulk density kg/m³**	**Water content %**	**Dry density kg/m³**
Block 1	Cylinder	280.3	276.4	100.0	11.66	1916	17.4	1632
Block 2	Cylinder	280.3	276.4	99.8	11.64	1917	17.4	1633
Block 3	Cylinder	280.3	276.4	100.0	11.62	1910	17.4	1627
Block 4	Cylinder	280.3	276.4	99.8	11.68	1923	17.4	1638
Block 5	Cylinder	280.3	276.4	99.8	11.66	1920	17.4	1635
Block 6	Cylinder	280.3	276.4	99.8	11.64	1917	17.4	1633
Block 7	Cylinder	280.3	276.4	100.4	11.66	1909	17.4	1626
Block 8	Cylinder	280.3	276.4	99.8	11.66	1920	17.4	1635
Block 9	Cylinder	280.3	276.4	100.3	11.68	1914	17.4	1630
Block 10	Cylinder	280.3	276.4	99.4	11.64	1924	17.4	1639
Block 11	Cylinder	280.3	276.4	99.8	11.66	1920	17.4	1635
Block 12	Cylinder	280.3	276.4	100.5	11.64	1903	17.4	1621
Block 13	Cylinder	280.3	276.4	99.4	11.64	1924	17.4	1639
Block 14	Cylinder	280.3	276.4	99.5	11.66	1926	17.4	1640

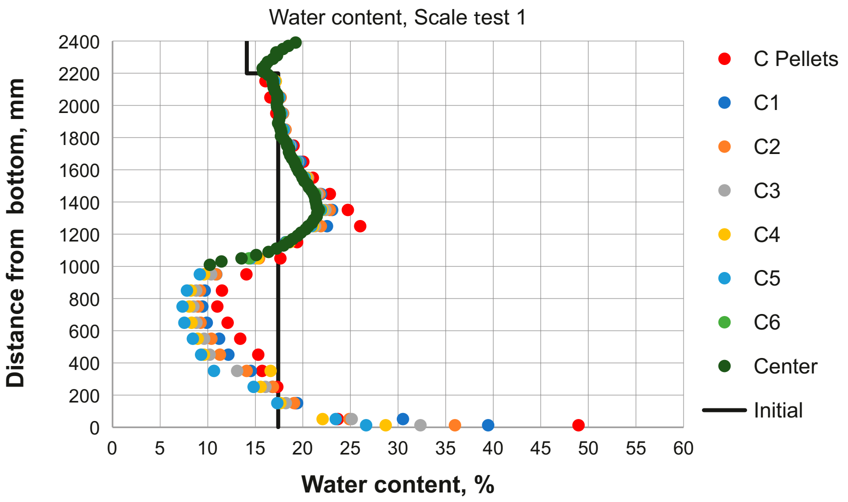
Results from Scale test 1, direction B

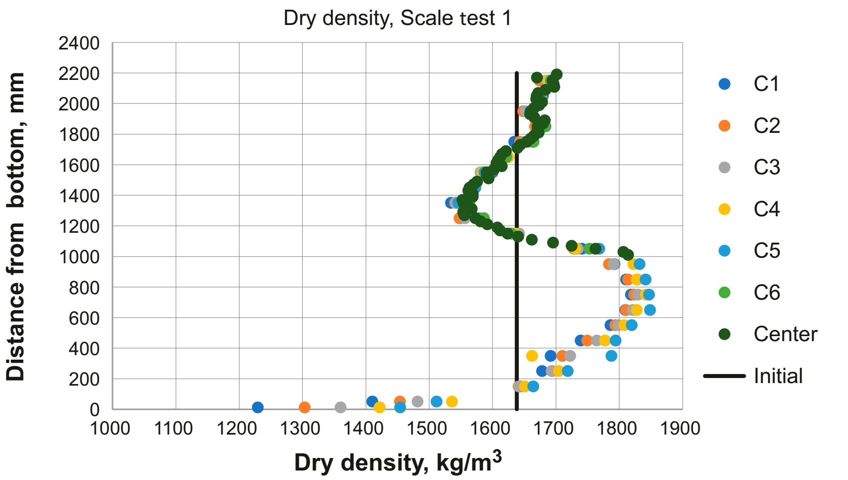


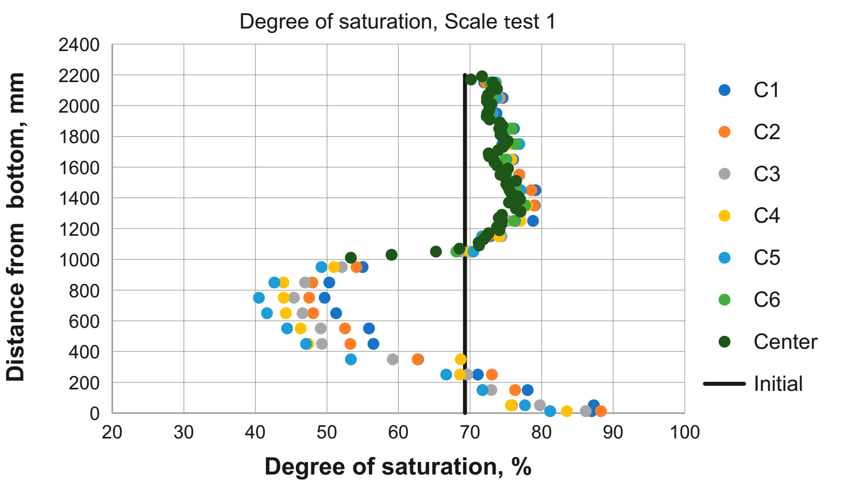




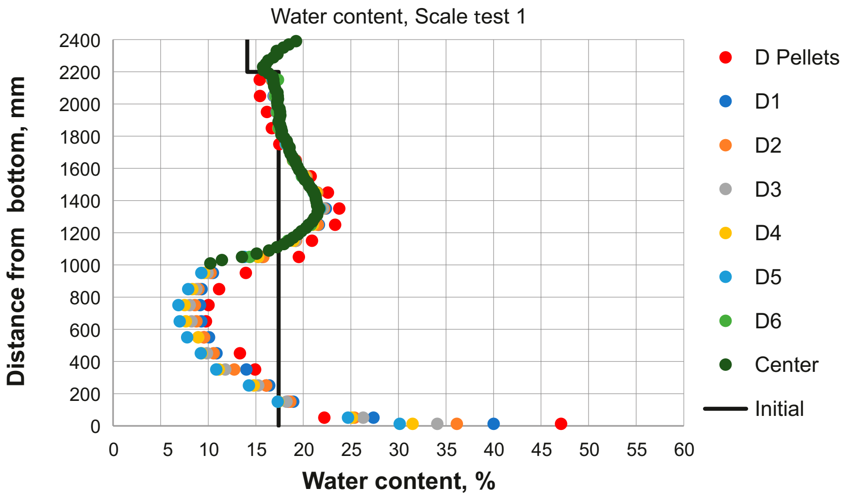
Results from Scale test 1, direction C

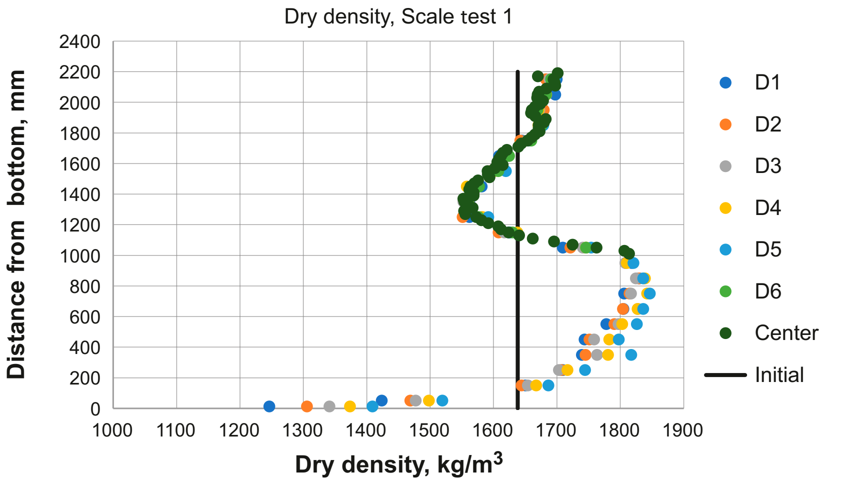


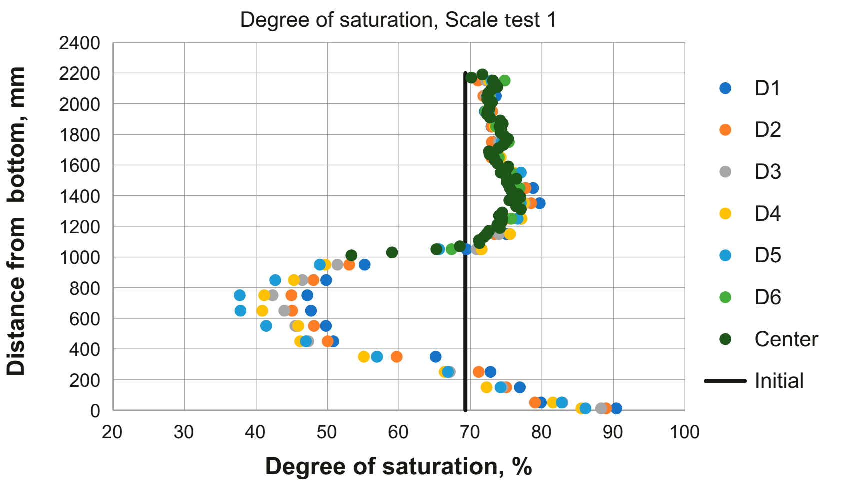




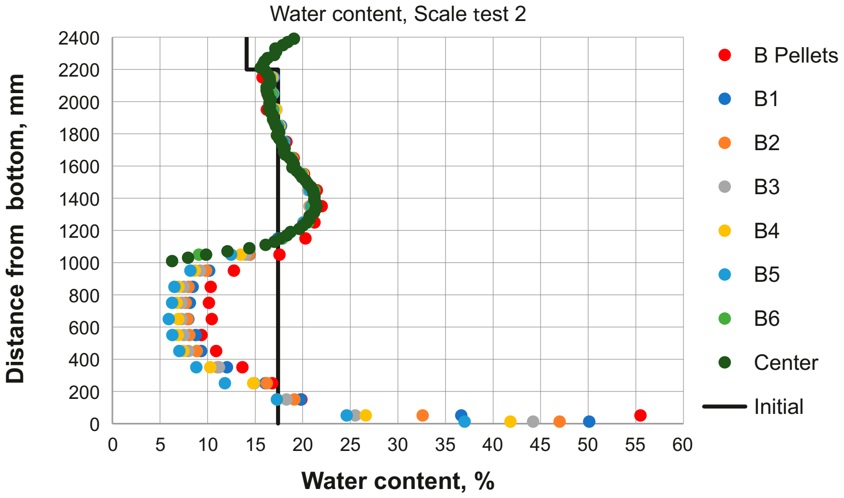
Results from Scale test 1, direction D

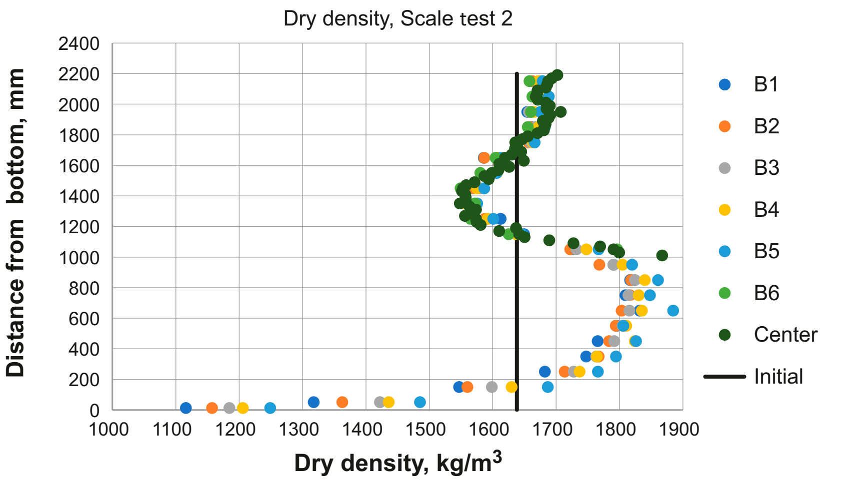


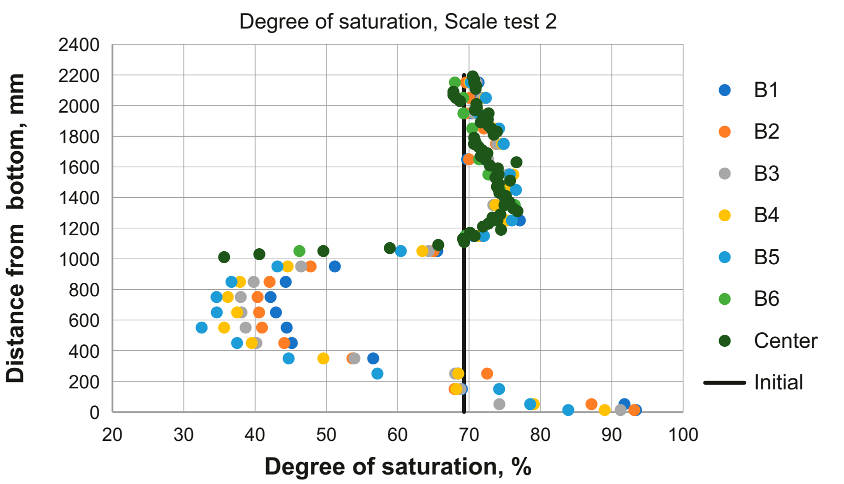




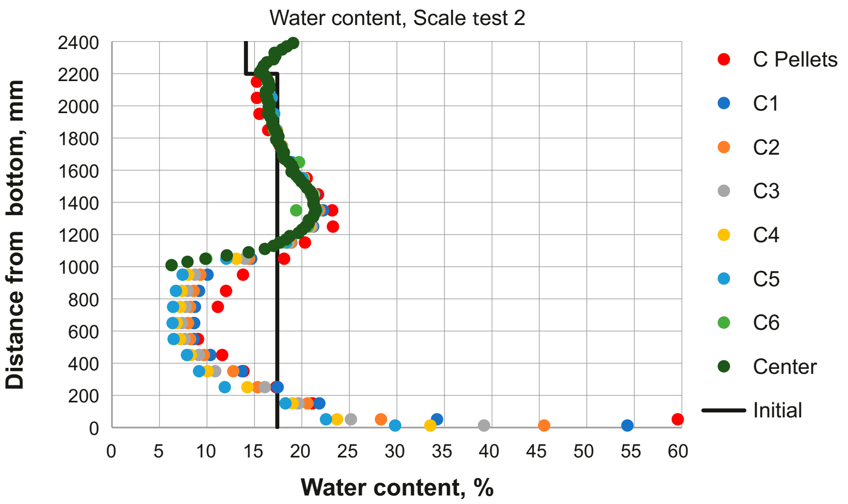
Results from Scale test 2, direction B

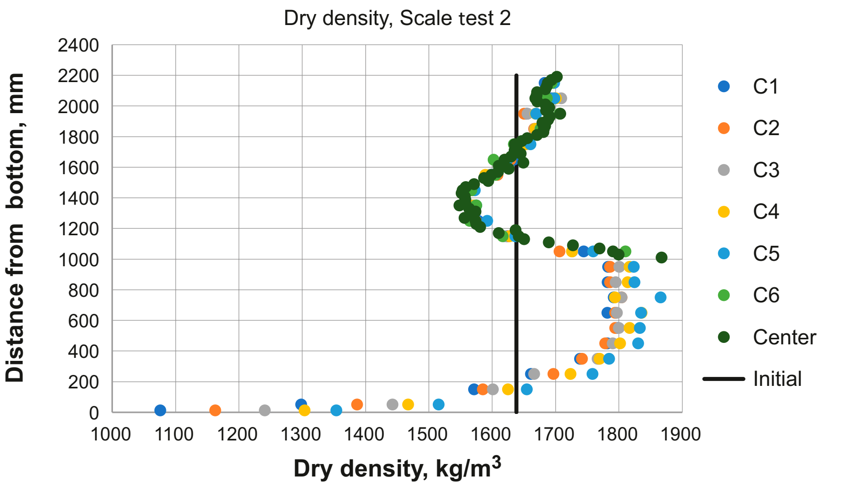


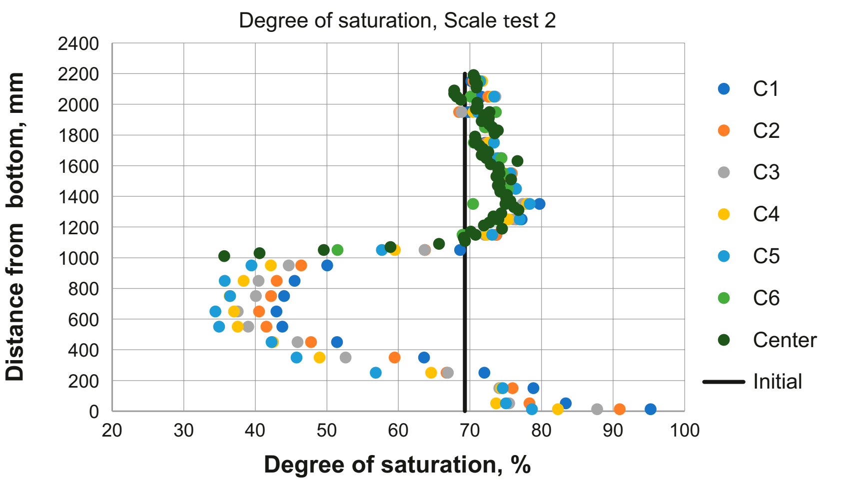




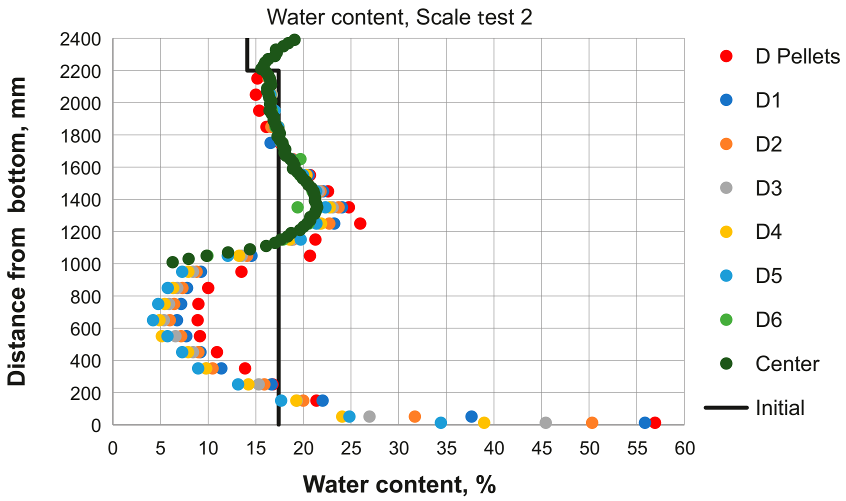
Results from Scale test 2, direction C

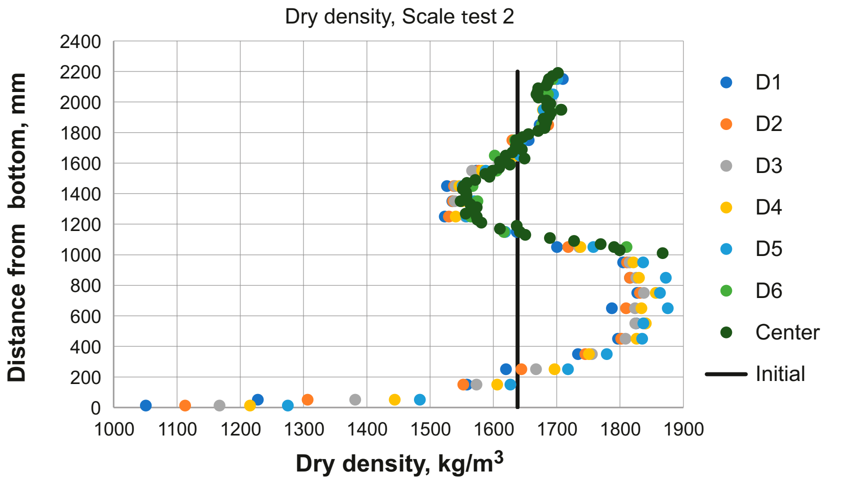


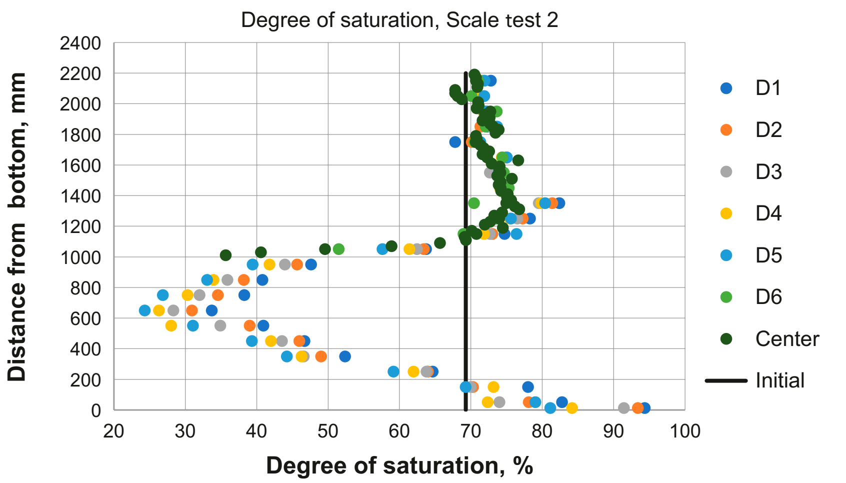




Results from Scale test 2, direction D







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