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Effects of water inflow on the buffer – an experimental study

Andreas Åberg
Vattenfall Power Consultant AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

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Abstract

Water inflow and its effect on the buffer during installation until the backfill is completed is a major concern for the repository concept. In this study, a full-scale model with a reduced height of a deposition hole has been designed. The behaviour, after installation, of the buffer with bentonite rings and pellets at different water inflow rates has been studied. This report describes these tests and the results and conclusions that have emerged.

The result shows that piping occurs in all of the tests and that the bentonite pellets has no ability to seal the water pathways as long as there is a continuous inflow of water.

The wetting pattern seems predictable at the studied inflow rates. The water flows upwards at 0.01 l/min and downwards at 0.1 l/min.

Large heaving of the uppermost ring occurred compared to the lowermost due to the absence of overburden pressure.

Sammanfattning

Inläckage av vatten och dess påverkan under installation fram tills återfyllningen är på plats är en viktig frågeställning för bufferten och dess funktion. I den här studien har ett fullskaleförsök med reducerad höjd av ett deponeringshål utförts. Vattnets påverkan på bufferten, efter installation, bestående av bentonitringar och bentonitpellets för olika inflöden har studerats.

Resultaten visar att piping uppstår i alla försök och att bentonitpelletsen inte förmår täta ett läckage så länge ett inflöde pågår.

Vattnets spridningsmönster i pelletsen förefaller regelbundet för de studerade flödena. Vattnet klättrar uppåt i pelletsen vid 0,01 lit/min och rinner nedåt vid 0,1 lit/min.

Större hävning eller svällning av den övre ringen jämfört med den nedre har noterats vilket beror på avsaknaden av överlagringstryck.

Contents

1 Introduction

1.1 Background

Techniques for storage of nuclear waste material are currently evaluated at sites in Sweden and Finland. In Sweden, the Laxemar area in Oskarshamn and Forsmark area in Östhammar are concerned. In Finland, a storage will be built in Olkiluoto island in Eurajoki. The reference layout for the storage in Sweden and Finland is based on vertical deposition (KBS-3V). Horizontal deposition (KBS-3H) in drifts is however not abandoned as storage method but is developed further parallel to the vertical deposition method.

In the KBS-3V concept, the canisters are embedded in bentonite clay in the host rock in vertical deposition holes (Figure 1-1).

Water inflow and its effect on the bentonite buffer until the backfill is installed is a major concern for the repository concept. In order to achieve a low hydraulic conductivity, a bentonite buffer is installed around the canisters. The buffer consists of two bentonite parts; blocks and pellets. The blocks are installed under, around (as rings) and above the canister. Furthermore, there is a gap of an average of 50 millimetres between the blocks and the rock surface of the deposition hole. This gap is to be filled with pellets. The function of the pellets is to achieve the desirable average density of the system with blocks and pellets, thus reaching an adequately low hydraulic conductivity.

There are several potential issues with water inflow into a deposition hole. Piping and erosion may occur, which reduces the density of the buffer and might increase the hydraulic conductivity above the design value. Another issue is heaving of the blocks and rings, due to exposure to water. That may also decrease the final density of the buffer.

In order to determine the maximum inflow of water, that can be accepted into a deposition hole, a series of tests have been performed at the bentonite laboratory in the Äspö Hard Rock Laboratory outside Oskarshamn. Several studies in laboratory scale of piping and erosion of the buffer have previously been performed /Börgesson and Sandén 2006/.

1.2 Aims and scope

The aim of the study was to examine the behaviour of the bentonite buffer when it is exposed to water inflow and how the water distributes and affects the buffer. A description of the behaviour is presented and a discussion of what inflow that can be accepted into a deposition hole.

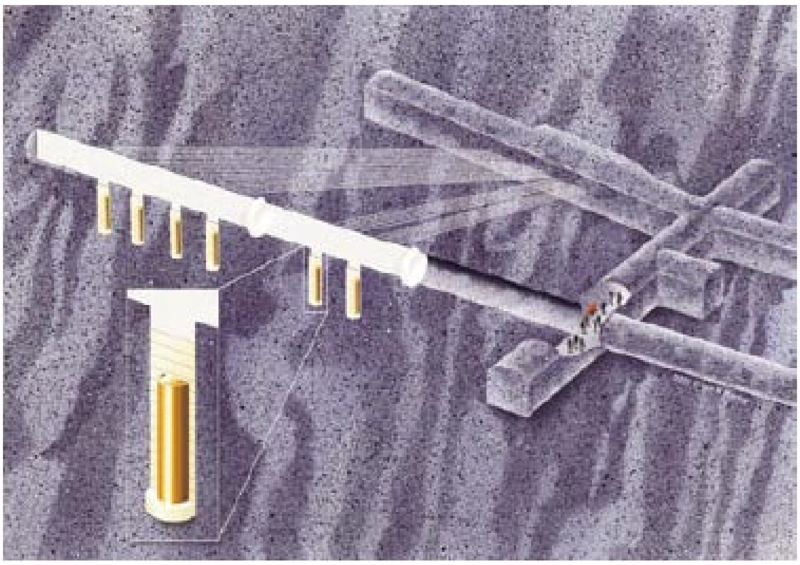

Figure 1-1. *Schematic view of storage of canisters in the KBS-3V concept /SKB 2008/.*

2 Method

The approach in this study was to experimentally represent an inflow to a deposition hole and to study how the water distributes and affects the buffer material, i.e. pellets and blocks or rings. The studied area has involved domain 2 and 3 in Figure 2-1. Domain 2 is blocks of bentonite and domain 3 a gap filled with bentonite pellets.

Inflow to a deposition hole can principally occur in several ways. A general target is that the inflow should be limited to 0.1 l/min, which also limits possible inflow scenarios. Due to the high water pressure at full repository depth, an inflow of 0.1 l/min likely occurs as singular point flows (Figure 2-2). One scenario would be that the maximum inflow, 0.1 l/min, occurs in one point. Another is that several inflow points with a total of 0.1 l/min occur. Based on this, two different water inflow rates from one point source were studied.

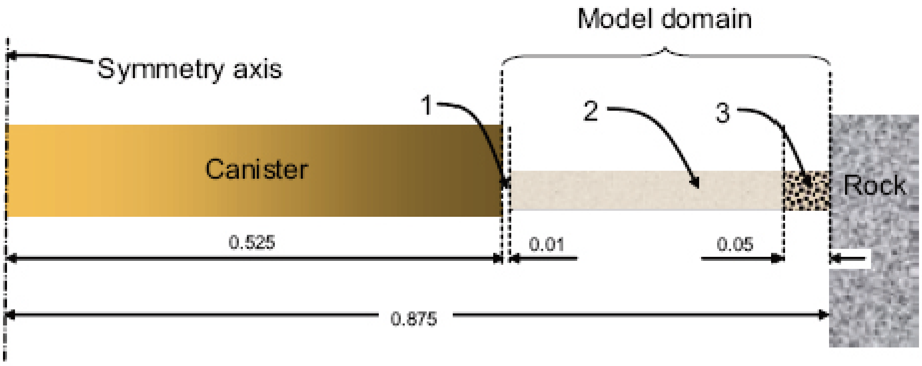

Figure 2-1. *A section of a deposition hole with canister, bentonite ring and pellets in the KBS3-V-concept /SKB 2008/.*

Figure 2-2. *Typical seepage pattern from a fracture zone /Bäckblom and Lindgren 2005/.*

2.1 Test setup, description and materials

The experiments were conducted in SKB:s bentonite laboratory in Äspö. The laboratory is located at ground level. An experimental setup was designed, consisting of a container simulating a deposition hole in full scale but with a reduced height. To simulate water inflow, an inlet was positioned on the container were water from a tank was injected by using a pump. A pressure and a flow meter for continuous logging were installed. Figure 2-3 displays a sketch of the test setup.

To simulate a water inflow from a discrete fracture in the rock, water was supplied in one point (Figure 2-4) at a fixed rate per minute by a pump. Regular tap water was used with an added salinity of 1% (50% NaCl and 50% CaCl), which is the most probable water type in a real installation. The same salinity has also been used in several tests at Claytech /Sandén and Börgesson 2008/.

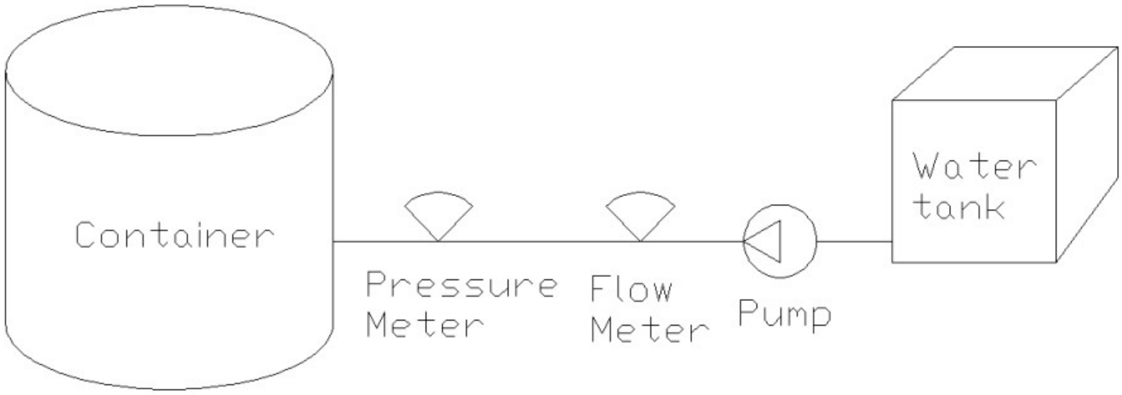

***Figure 2-3.** Sketch of the test setup.*

***Figure 2-4.** Water inlet and pressure meter at the container.*

2.1.1 The container

A container made of reinforced plastic (polycarbonate) was designed with a full-scale diameter at 1.75 m but with a reduced height of 1.1 m (Figure 2-5). The plastic is transparent which makes it possible to observe the water saturation and transport visually. Measurements of swelling can be performed from the surface of the container. Samples for water ratio measurements can be obtained from various depths and positions within the container using a standard 1,000 mm soil probe.

The container was designed to withstand a horizontal swelling pressure of at least 300 kPa. To prevent strain in the polycarbonate, and thereby an increasing diameter, the container was reinforced with eight rings of steel.

2.1.2 The equipment

The pump

The pump used in the tests was a Grundfos DME 8-10A with a maximum operating pressure of 10 bar and a maximal capacity of 7.5 l/h. It has a very large operating range for flow rate and pressure. The maximum pressure of 10 bar is not equal to field conditions but earlier tests have not reached water inflow resistance of that magnitude. As resistance to inflow increases, the operating pressure of the pump increases to the same extent in order to provide a constant flow of water. This is intended to simulate the field conditions, as an inflow from a fracture would create a hydraulic pressure at the interface between the rock and the pellets.

The flow meter

The flow meter used was a Alicat Scientific LC-series 100CCM.

The pressure meter

The pressure meter used was a GE Druck PT Pressure Transmitter.

The tecalan hose

The Tecalan hose used for the water inlet had a length of 3 m and a diameter of 10 mm before and 2.5 m and 6 mm after the flow meter. The flow in the system is laminar and the hose provides a small pressure drop. This, however, does not affect the pressure measurements for the higher inflow rate.

Figure 2-5. *The plastic container at delivery.*

2.1.3 Bentonite pellets

The pellets used in the study were Cebogel in Test 1 and 2 and MX-80 in Test 3 to 6. Cebogel was used in the first tests due to the fact that pellets of MX-80 were not available in larger quantities at that time. The two initial tests were therefore made to test the equipment with existing pellets that were in stock at Äspö.

Cebogel QSE pellets are manufactured by Cebo Holland BV as short cylindrical rods. The granules are made from activated sodium bentonite according to the manufacturer.

The MX-80-pellets are manufactured by American Colloid Co (Wyoming) from Volclay MX-80 granular sodium bentonite. The bentonite is compacted to briquettes of size 16.3×16.3×8.3 mm. The MX-80 bentonite has so far been used as SKB:s reference material /SKB 2008/.

2.1.4 Bentonite rings

The rings are manufactured from highly compacted MX-80 bentonite /SKB 2008/. They have an outer diameter of 1,650 mm, an inner diameter of 1,070 mm and a height of 500 mm. The properties of the rings have been measured in earlier tests and the bulk density is 2,100 kg/m^3 with a water ratio of 10% /Börgesson and Johanneson 2006/. Two rings were used in each test.

2.1.5 Test procedure

The pellets were installed manually in the gap and no compaction was made. Tests 1 to 4 were conducted with an inner cylinder instead of bentonite rings, thus studying only the water distribution in the pellets. The inner cylinder was also made of transparent plastic and attached to the bottom of the container (Figure 2-6 and 2-7). The inner cylinder made it possible to observe the water distribution also from the inside of the container.

Test 5 and 6 were made with two bentonite rings and pellets in the slot between the rings and the container, similar to field conditions. The setup made it possible to study the interaction between the pellets and the rings as well as the behaviour of the rings as they are exposed to water inflow and increased relative humidity (Figure 2-8).

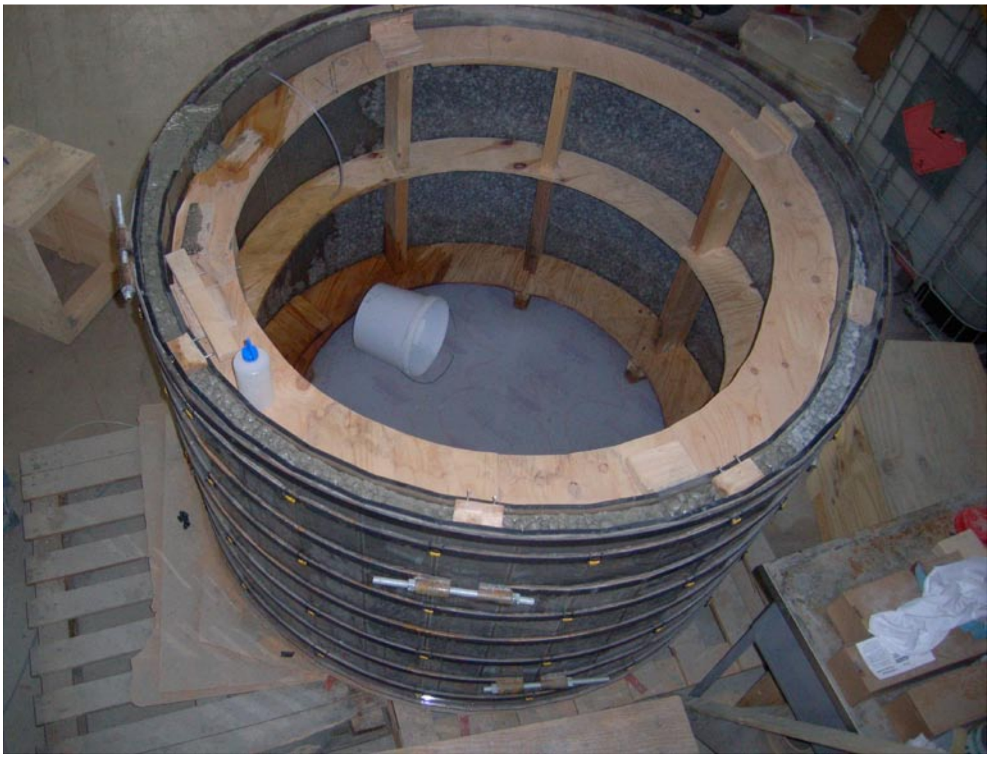

Figure 2-6. *The container with the inner cylinder used in Test 1 to 4.*

Figure 2-7. Pellets of type MX-80 after installation. The gap is 50 millimetres in average.

Figure 2-8. Test with bentonite rings and pellets.

A plexiglass lid was used in Test 5 and 6 to prevent any sudden changes in relative humidity.

The water inlet was installed in one single point halfway between the bottom and top of the container, i.e. 0.5 m from the bottom (Figure 2-9).

After the end of each test, the setup was dismantled and samples were taken for water ratio assessment. Photographic recording was made of the rings as they were dismantled and samples of the bentonite were taken for water ratio assessment.

Figure 2-9. Water inlet and pressure meter. The water pathway and the wetting of the pellets can be observed as darker areas through the container wall.

2.2 Documentation of the tests

The water inflow (kept constant) and water pressure were measured constantly during the tests. Detailed recording of the water distribution within the pellets was done by photographing regularly from the outside of the container. The heaving of the upper part of the blocks was measured periodically. The outer diameter of the container was measured before and after each test with pellets only and periodically during the tests with rings and pellets.

The following documentation were done for the tests:

- Measuring the outer diameter of the container
- Photographing the tests
- Photographing the wetting patterns
- Measuring the vertical displacement of the rings
- Assessments of water ratio
- Logging of water inflow (kept at constant rate)
- Logging of resistance to water inflow

Test 5 and 6 were disassembled by a demolition hammer and samples were taken for assessment of water ratio as well as numerous visual observations that were photographed.

3 Description of the tests

A total of six tests were performed (Table 3-1). Test 1 and 2 were made with Cebogel and Test 3 to 6 were made with MX-80-pellets.

Test 1 and 2 were done as a pre-test to verify the test setup with the inner cylinder and to calibrate the equipment. The pellets material used were Cebogel.

Test 3 and 4 were done with MX-80-pellets. The inner cylinder was used to study only the pellets and the water distribution within.

Test 5 and 6 were done with MX-80-pellets and bentonite rings inside the container similar to field conditions.

Table 3-1. Test matrix.

Test #	Inflow (l/min)	Time (days)	Description
1	0.1	1	Cebogel-bentonite and inner cylinder
2	0.01	9	Cebogel-bentonite and inner cylinder
3	0.1	7	MX-80-bentonite and inner cylinder
4	0.01	15	MX-80-bentonite and inner cylinder
5	0.1	6	MX-80-bentonite and rings
6	0.01	21	MX-80-bentonite and rings

4 Results

The data from each test is presented in Section 4.1 to 4.6.

4.1 Test 1 – Cebogel, 0.1 l/min

Test 1 was conducted to verify the function and to calibrate the equipment. The pellets used were Cebogel. The inflow in this test was the maximum rate: 0.1 l/min.

The measured flow and resistance to inflow (pressure) are presented in Figure 4-1. The result shows a nearby constant pressure build-up followed by a rapid pressure drop, probably caused by piping. The pressure is later increasing at a slow rate. The cause of the sudden drop in inflow after 20 hours is unknown.

Figure 4-2 shows the wetting pattern of the pellets over time.

Figure 4-3 shows the container 15 minutes after start were the water has started to spread via the bottom of the container.

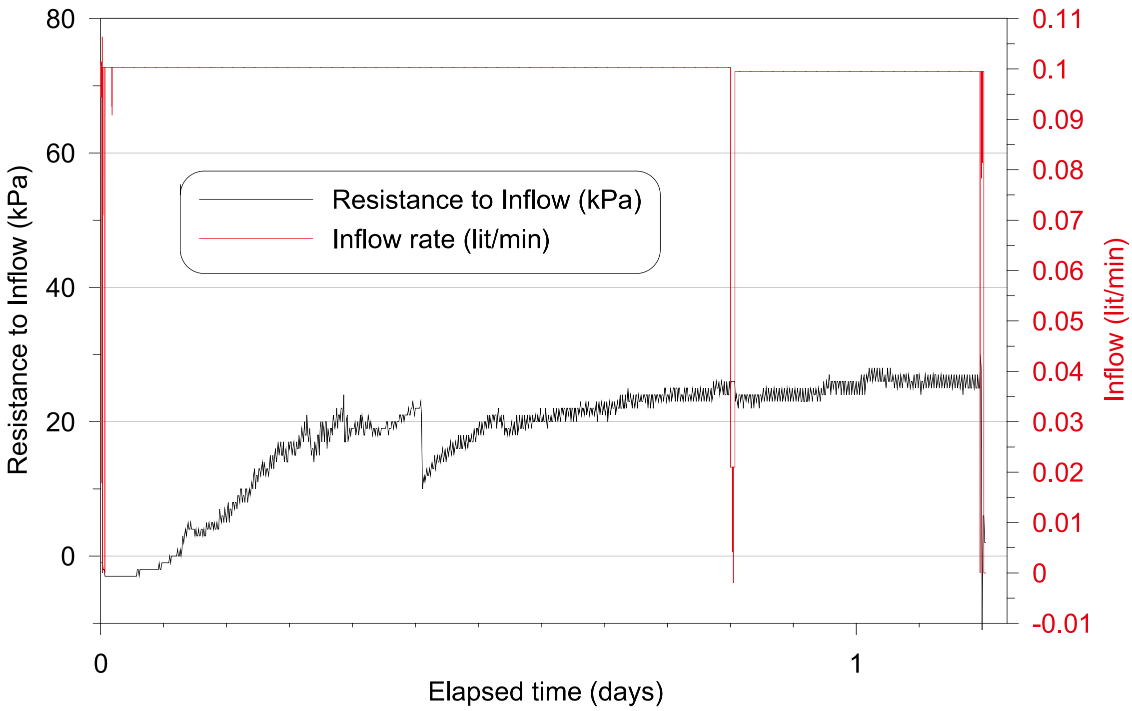

Figure 4-1. *Resistance to inflow and inflow rate Test 1.*

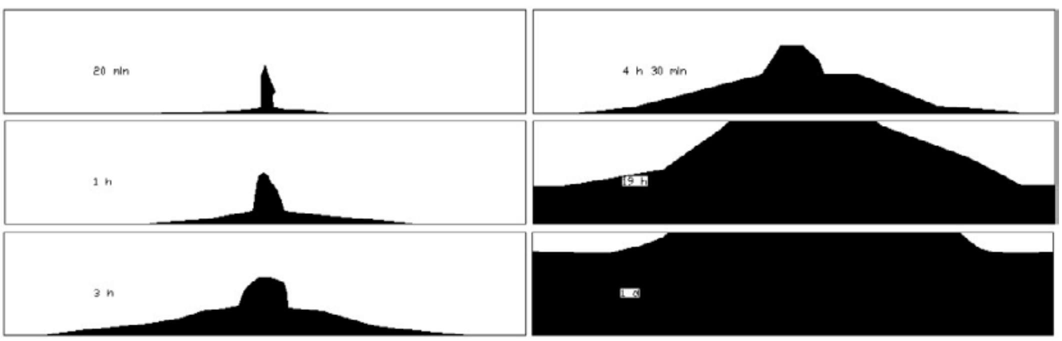

Figure 4-2. *Wetting pattern in Test 1. The black area is wet and the side of the container is projected as on a flat peace of paper with the position of the water inlet in the midpoint.*

Figure 4-3. *Test 1, 15 minutes after start.*

4.2 Test 2 – Cebogel, 0.01 l/min

Test 2 had the same purpose as Test 1 but was made using an inflow rate of 0.01 l/min instead.

The result shows a fairly even pressure build-up and some minor drops and peaks (Figure 4-4). A minor reduction of the pressure occurred at the later half of the test. At day eight, two peaks in the pressure of about 10 kPa occurred. The reason is uncertain but might indicate that the bentonite sealed the water pathway temporarily. The reason for the three drops in water inflow is unknown. The maximum pressure obtained in Test 2 is considerably higher than in Test 1. The maximum pressure was reached after about 25 h.

The wetting pattern is displayed in Figure 4-5.

Large swelling occurred above the inlet (Figure 4-6).

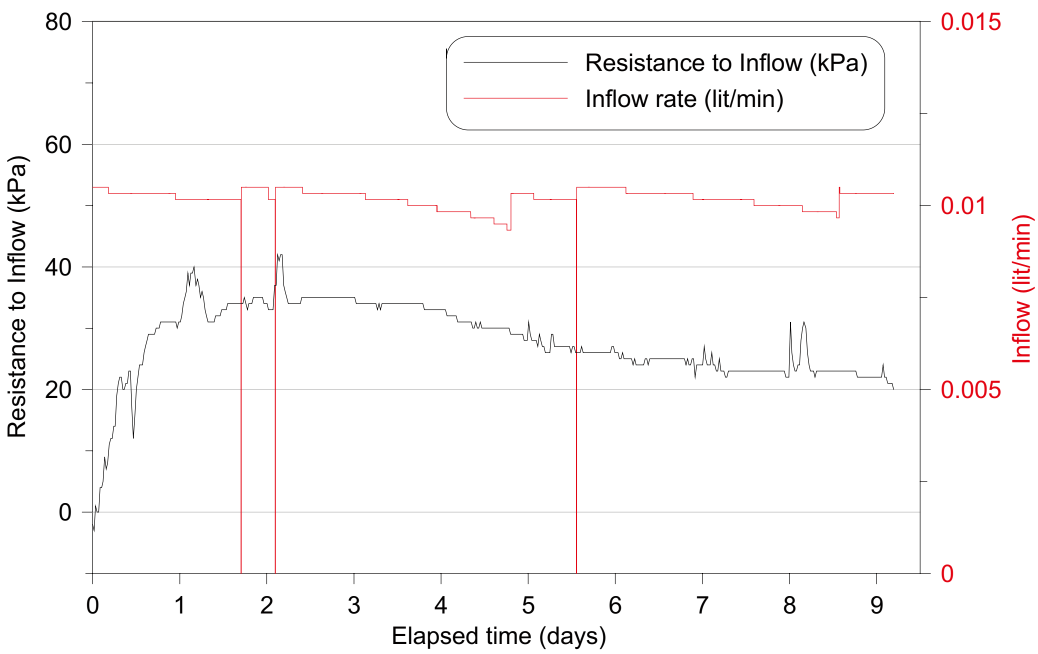

Figure 4-4. *Resistance to inflow and inflow rate Test 2.*

Figure 4-5. *Wetting pattern in Test 2.*

Figure 4-6. *Large swelling of the bentonite above the water inlet.*

4.3 Test 3 – MX-80, 0.1 l/min

The pressure increased rapidly. After three days, the inflow rate was decreased with the intention to give the system an ability to pressure build-up. At that high inflow rate, the inflow had reached a steady state condition and the water was flowing over to the inside of the container. The remaining part of the test showed fairly constant pressure in resistance to inflow. No pressure build-up was observed (Figure 4-7).

The wetting pattern is displayed in Figure 4-8.

The assessed water ratios of the pellets are displayed in Figure 4-9. Generally, higher water ratios have been observed at the upper part of the container and the highest above the water inlet.

After seven days, there were still dry spots within the wet pellets (Figure 4-10 and 4-11). Bentonite powder seems to have a better sealing ability than the pellets alone.

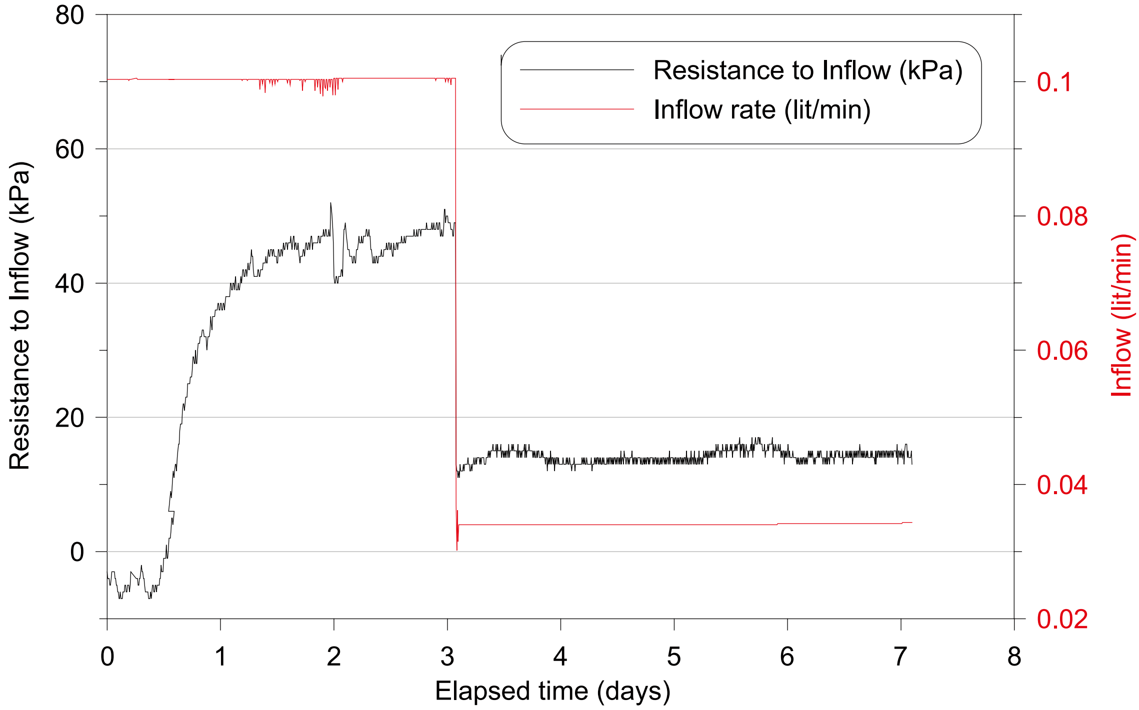

Figure 4-7. *Resistance to inflow and inflow rate Test 3.*

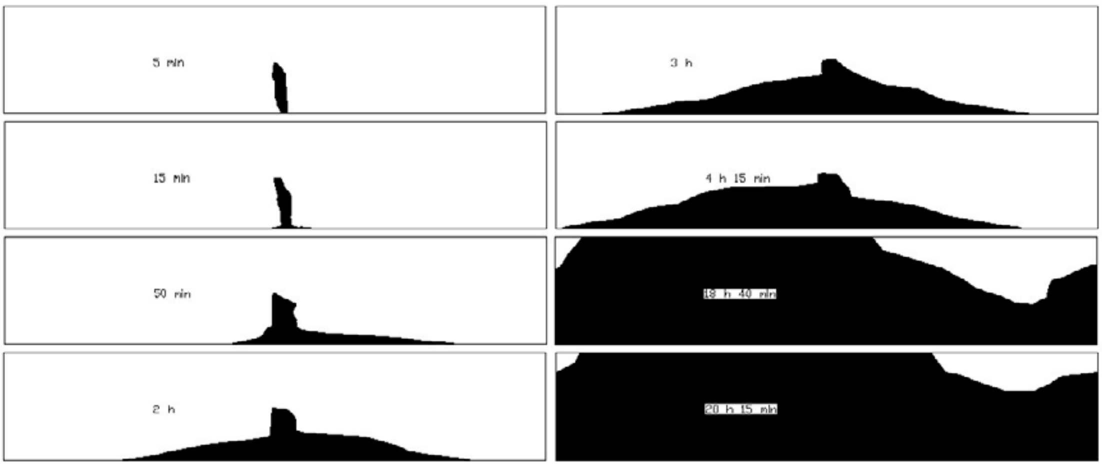

Figure 4-8. *Wetting pattern in Test 3.*

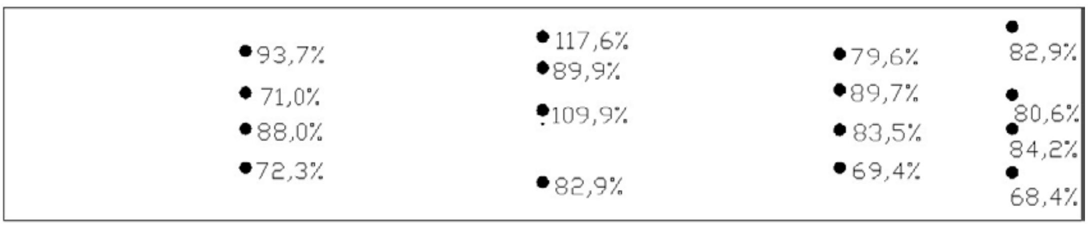

Figure 4-9. *Water Ratios assessed in Test 3. The water inlet is at the midpoint of the figure.*

Figure 4-10. *Almost intact pellets surrounded by finer material can be seen after seven days.*

Figure 4-11. *Finer grains that appears dry are distinguished by their lighten colour.*

4.4 Test 4 – MX-80, 0.01 l/min

The pressure increased with some minor drops to a maximum value after about seven days. The pressure was then fairly constant until the test was cancelled after another seven days (Figure 4-12).

The wetting pattern is displayed in Figure 4-13.

Fewer samples for water ratio assessment were taken compared to Test 3 because of the limited wet area. The results are displayed in Figure 4-14.

The pellets below the water inlet were still dry at the end of the test (Figure 4-15). More swelling of the bentonite occurred above the water inlet than the rest of the area (Figure 4-16) and water pathways after piping could clearly be seen (Figure 4-17 and 4-18).

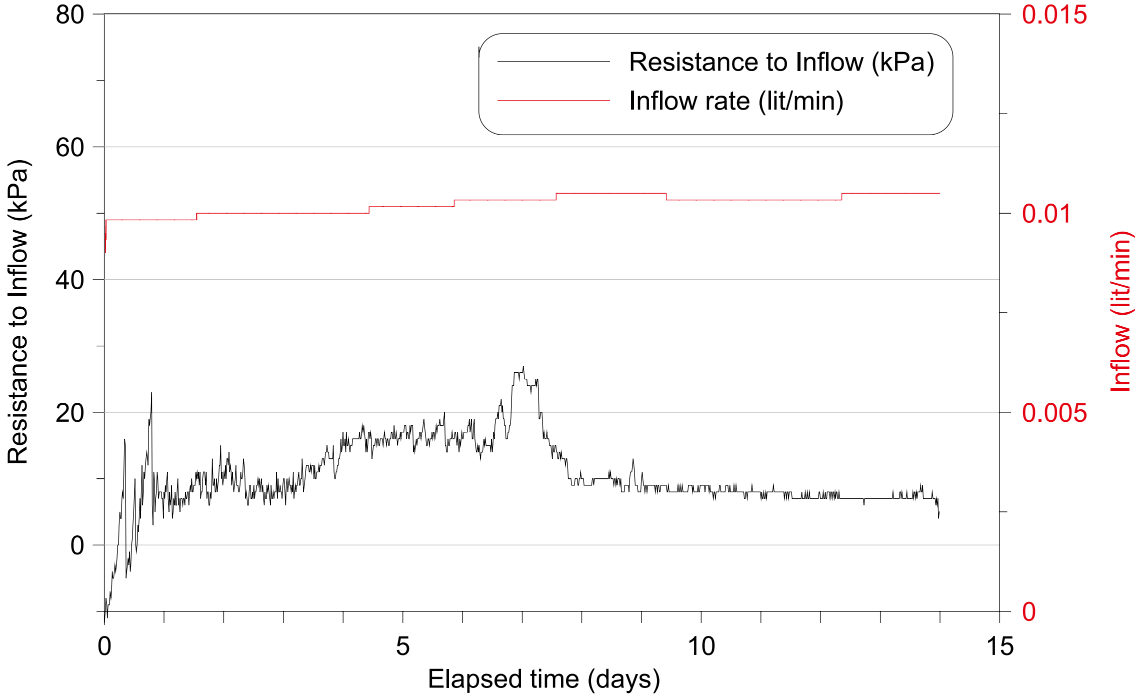

Figure 4-12. *Resistance to inflow and inflow rate Test 4.*

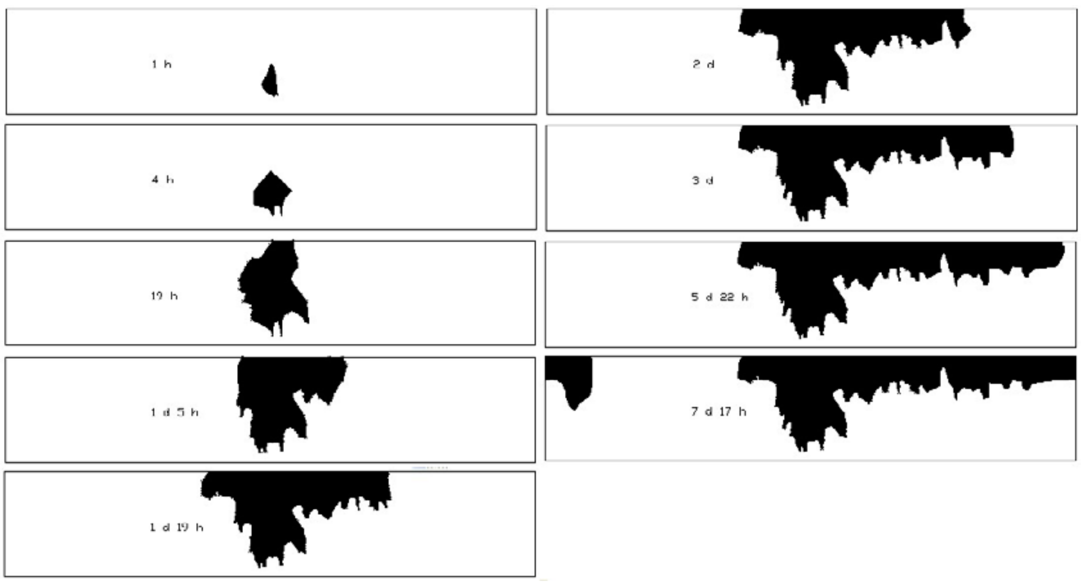

Figure 4-13. *Wetting pattern in Test 4.*

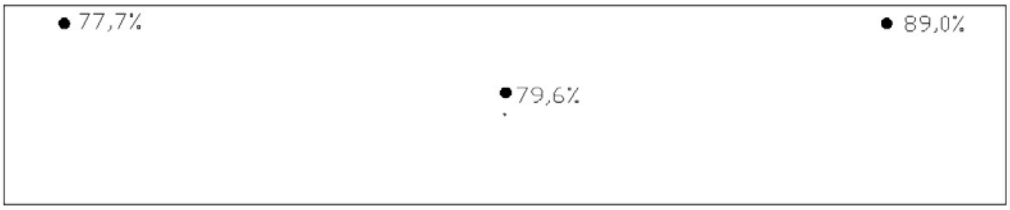

Figure 4-14. *Water ratios Test 4.*

Figure 4-15. *Dry pellets below the inlet at the end of the test.*

Figure 4-16. *Swelling of the bentonite above the inlet.*

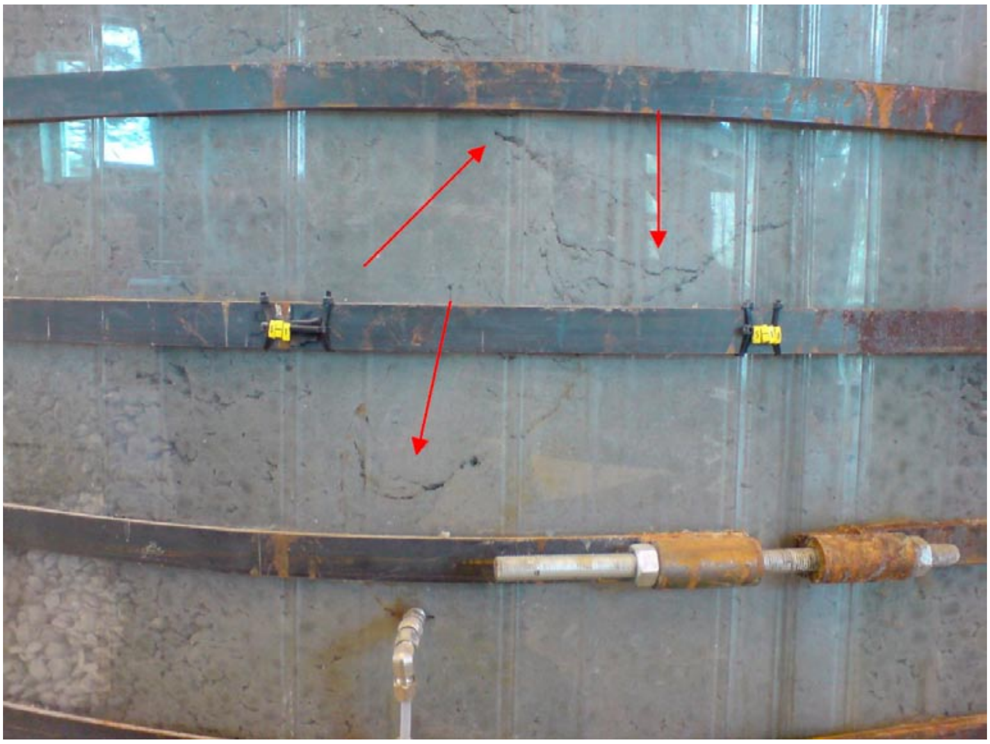

Figure 4-17. *Water pathways as a result of piping.*

Figure 4-18. *Water pathway as a result of piping.*

4.5 Test 5 – MX-80, rings, 0.1 l/min

The result shows a fairly even pressure build-up for 48 h. From that time, water started to flow over to the inside of the rings. The inflow was therefore reduced to a minimum, 7.5 ml/h (0.125×10^{-3} l/min). The pressure was restored rapidly within about 12 h and continued to increase (Figure 4-19). The resistance to inflow is significantly higher than the other tests. However, the very low inflow rate is probably giving the bentonite a better opportunity to seal and create a higher resistance.

The wetting pattern is displayed in Figure 4-20.

Locally, the rings had some cracks prior to test start, most certainly due to transportation and handling (Figure 4-21). After about 24 h, cracks occurred and pieces started to fall of the ring (Figure 4-22). More and larger cracks occurred after another 24 h (Figure 4-23). After 6 days, large cracks had emerged in the uppermost and smaller cracks in the lowermost ring (Figure 4-24). The test was then dismantled (Figure 4-25) and samples taken for water ratio assessment. The rings showed almost no effect of water. The moisture had only reached a few millimetres into the ring. Figure 4-26 shows the interface between the pellets and one of the bentonite rings.

The vertical displacement of the uppermost ring was measured periodically. The results are displayed in Figure 4-27.

The vertical displacement of the lowermost ring could not be measured until dismantling. The results are displayed in Table 4-1. The principle location of each position is displayed in Figure 4-28 where water inlet is at position 0 mm. The total circumference of the container is about 5,500 mm.

Samples were taken for water ratio assessment. The results are displayed in Table 4-2.

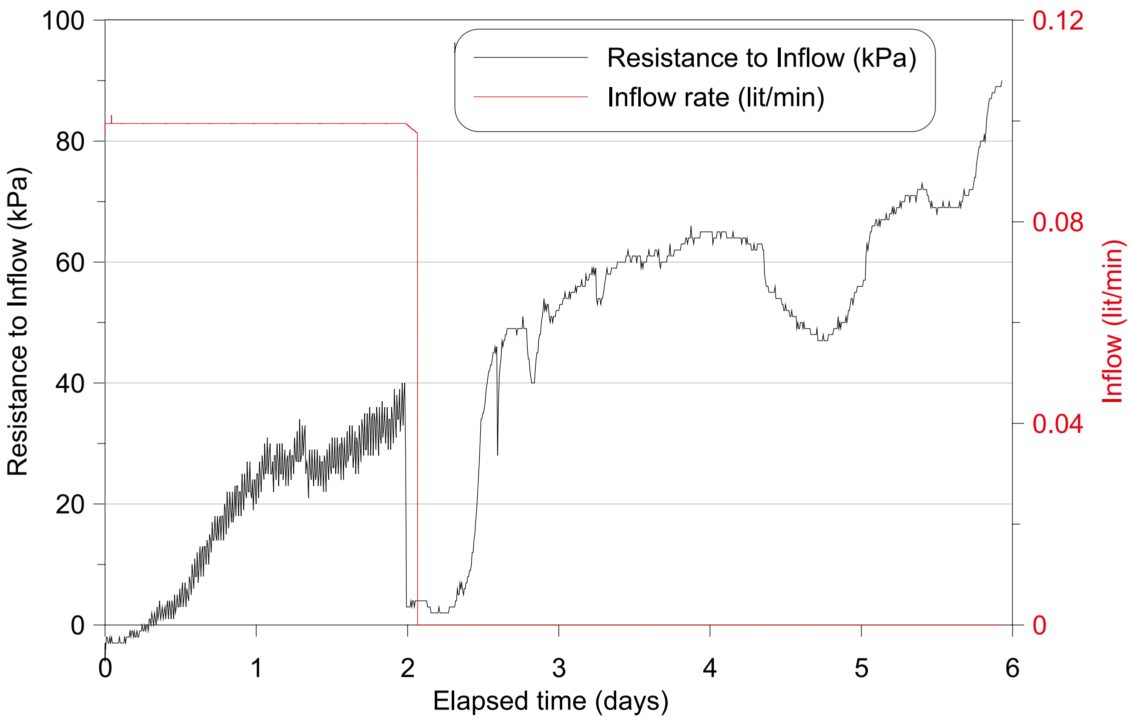

Figure 4-19. Resistance to inflow and inflow rate Test 5.

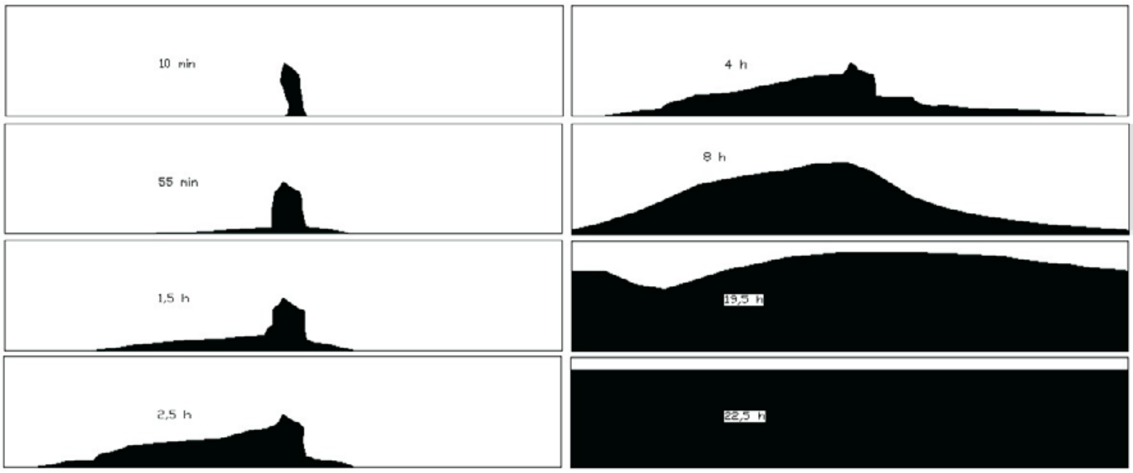

Figure 4-20. *Wetting pattern in Test 5.*

Figure 4-21. *Initial cracks in one of the bentonite rings.*

Figure 4-22. *Cracks on the outer side of the ring after about 24 h. Note that the plastic lid is visible above the text B1.*

Figure 4-23. *Large cracks in the ring after 48 h.*

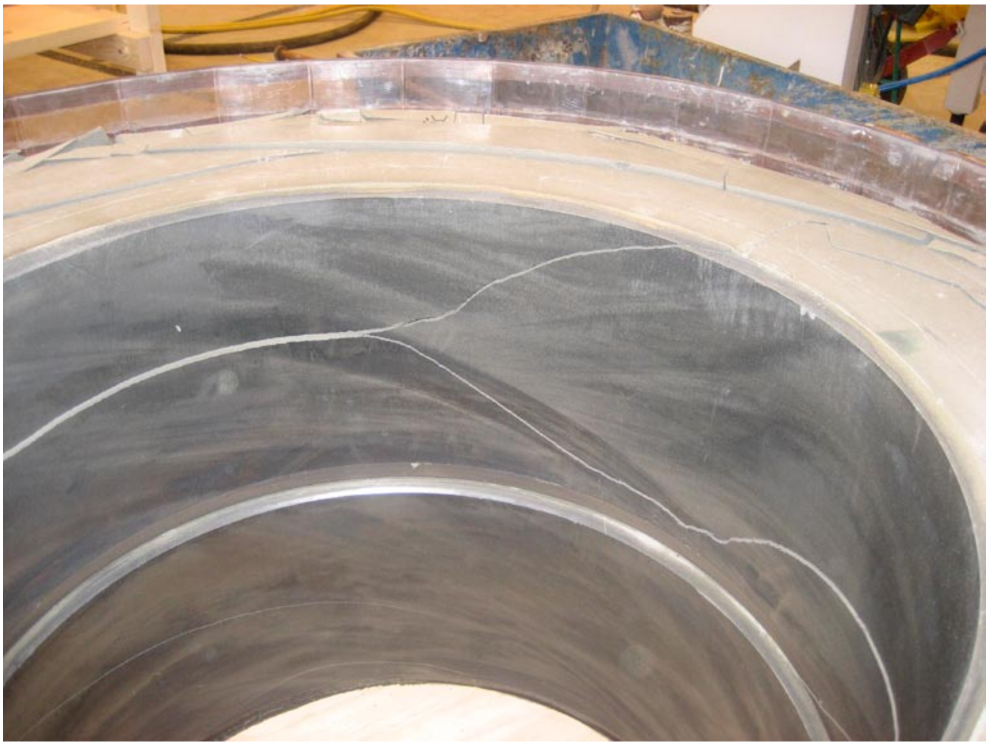

***Figure 4-24.** Large cracks on the inside of the uppermost ring after 6 days.*

***Figure 4-25.** Disassembling of the rings.*

Figure 4-26. *Bentonite ring, bentonite slurry and container wall during dismantling.*

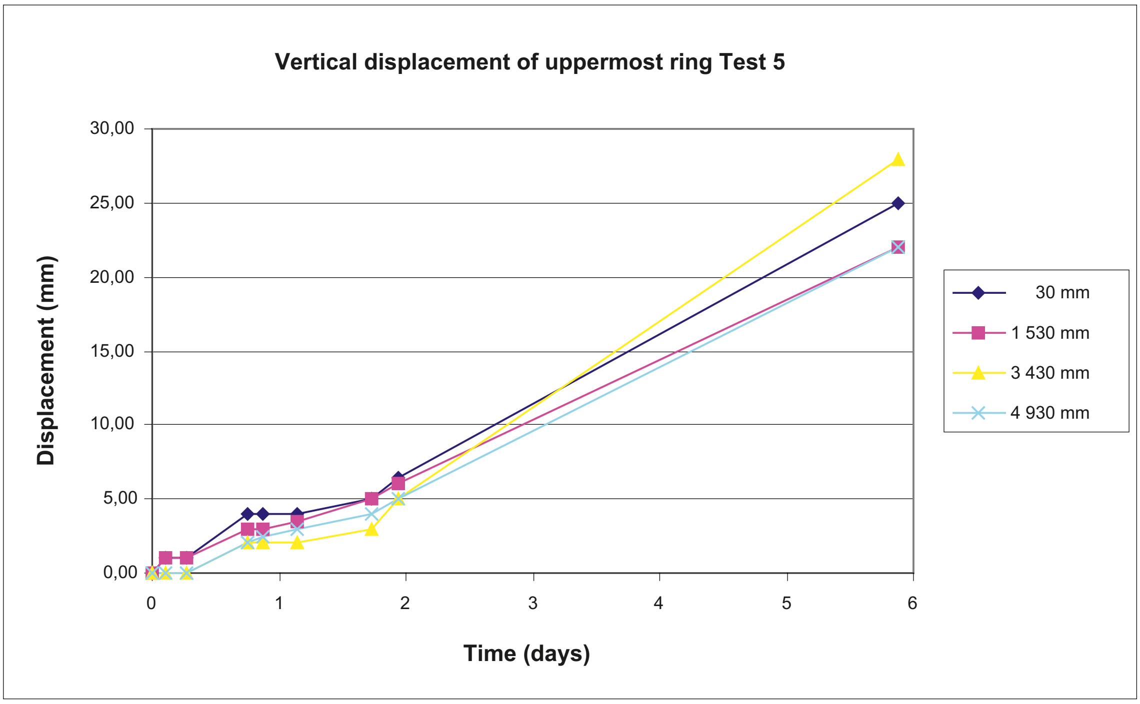

Figure 4-27. *Vertical displacement of the uppermost ring in Test 5. The positions are measured clockwise from the water inlet around the circumference of the container with the water inlet at 0 mm.*

Table 4-1. Vertical displacement of the lowermost ring.

Position (mm)	Vertical displacement (mm)
30	8
1,530	2
2,440	8
3,430	11
4,930	6

Table 4-2. Water ratios taken for assessment at dismantling.

Position	Water ratio (%)
Outer side of uppermost ring at top above water inlet	19.3
Ring 25 cm above water inlet, 12 cm from inside	20.0
Inner side of ring 25 cm above water inlet	16.8
Outer side of ring at top 60 cm right of water inlet	29.8
Pellets at water inlet close to the ring	47.9
Pellets at water inlet close to the outside of the container	69.5
Outer side of ring at water inlet	18.0
Inner side of ring at water inlet	16.3

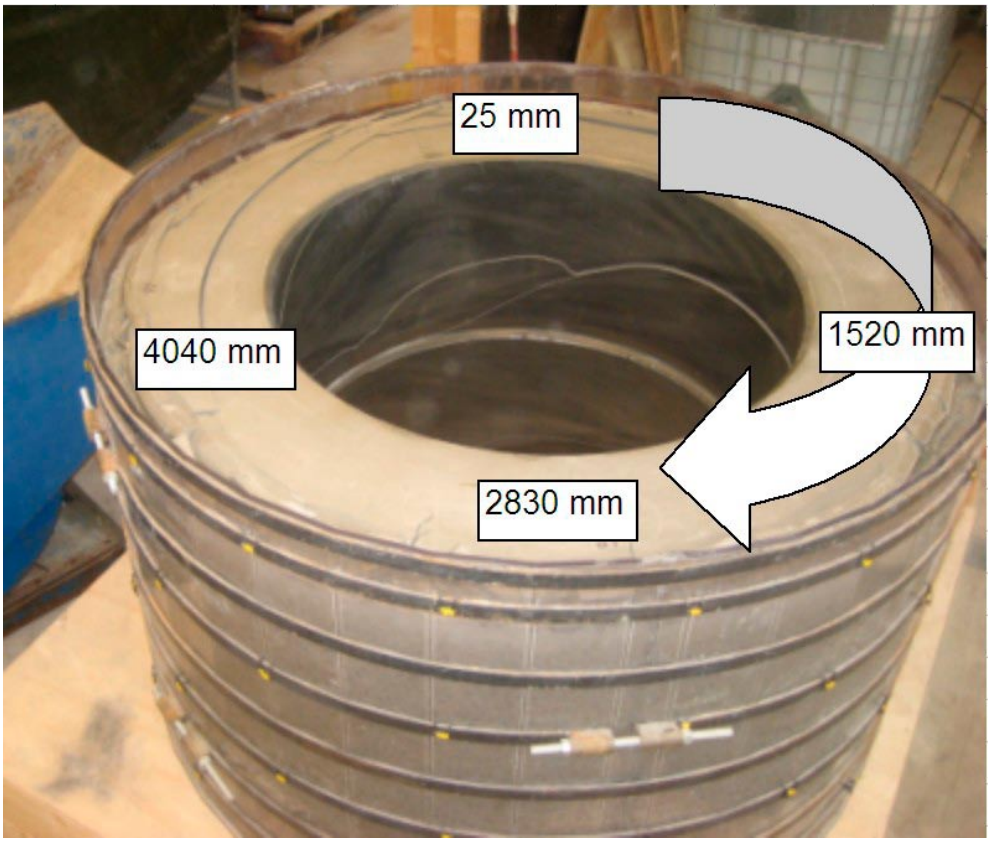

***Figure 4-28.** The positions of the samples are measured clockwise from the water inlet.*

4.6 Test 6 – MX-80, rings, 0.01 l/min

The test was run for 21 days. Figure 4-29 shows a slow increasing trend of the pressure with a few major pressure build-ups. Such peaks in pressure have not been observed in earlier tests. They might be due to interaction with the rings. The inflow rate displays an increasing trend and from day 6 with an increase of almost 50%. The pump is set to a constant rate and there is no obvious explanation to the increase, since the pump is very accurate.

The wetting pattern is displayed in Figure 4-30.

The vertical displacement of the uppermost ring was measured periodically and is displayed in Figure 4-31.

The vertical displacement of the lowermost ring could not be measured until dismantling. The results are displayed in Table 4-3. The location of each position follows the measurements in Test 5.

Table 4-4 displays water ratios assessed after dismantling. It seems that most of the water transport occurs near the outside of the container when the water ratios from the inner and outer side are compared.

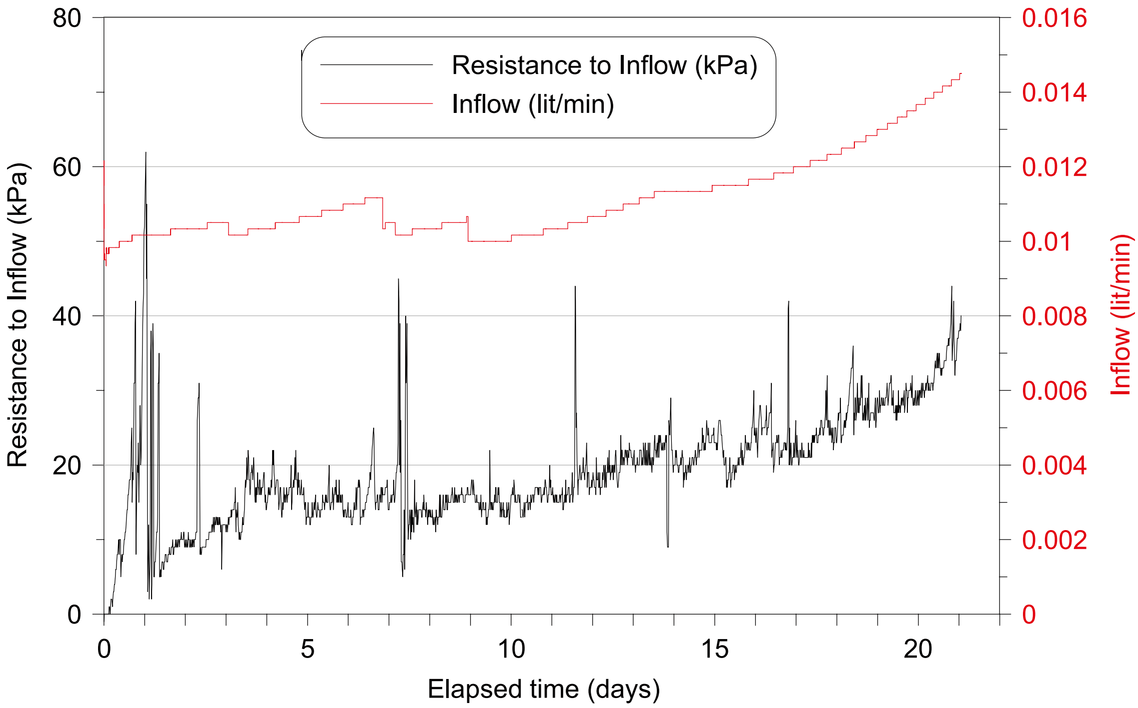

Figure 4-29. *Resistance to inflow and inflow rate Test 6.*

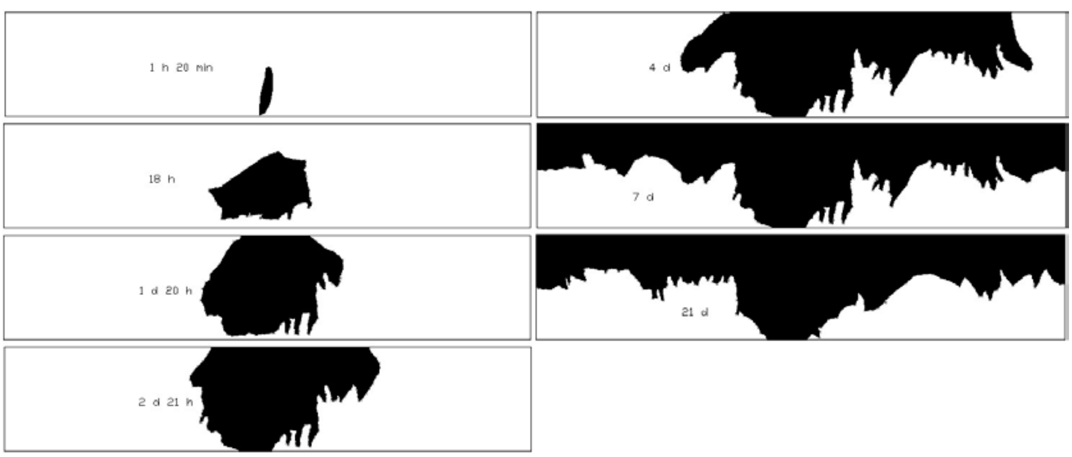

Figure 4-30. *The wetting pattern in Test 6.*

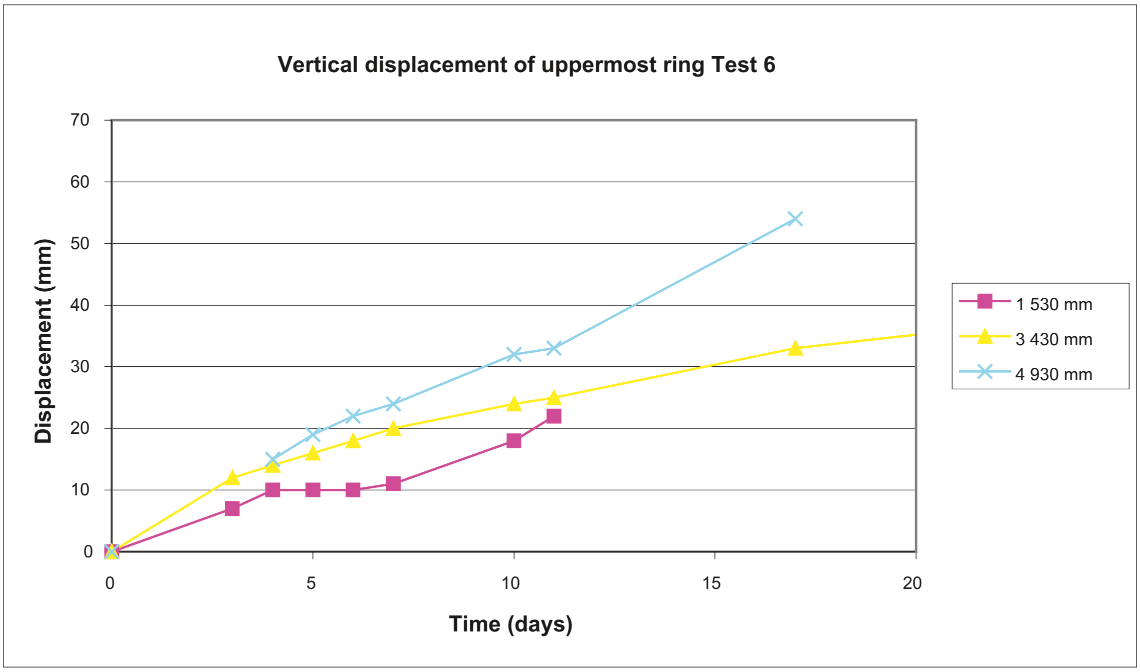

Figure 4-31. Vertical displacement of the uppermost ring in Test 6. The positions are measured clockwise from the water inlet around the circumference of the container with the water inlet at 0 mm.

Table 4-3. Vertical displacement of the lowermost ring.

Position (mm)	Vertical displacement (mm)
630 (7–3)	48
1,230 (7–5)	38
1,840 (7–7)	29
2,440 (7–9)	29
3,130 (7–11)	32
3,730 (7–13)	31
4,330 (7–15)	31
4,930 (7–17)	41

Table 4-4. Water ratios assessed in Test 6.

Position	Water ratio (%)
Outer side of uppermost ring, 25 cm from top	32.6
Outer side of uppermost ring at water inlet	22.7
Inner side of uppermost ring opposite side of water inlet	19.6
Outer side of uppermost ring opposite side of water inlet	26.3
“Dry” pellets opposite side of water inlet	17.9
Outer side of lowermost ring at water inlet	21.5
Outer side of lowermost ring opposite side of water inlet	19.7
Outer side of lowermost ring at pellets opposite side of water inlet	16.8
Inner side of lowermost ring opposite side of water inlet	19.8
Pellets at lowermost ring opposite side of water inlet	15.0
Initial value of pellets before test start	12.9

Because of the lid, the pellets gel flowed over the ring to the inside (Figure 4-32 and 4-33). Massive cracks occurred on the top of the uppermost ring (Figure 4-34). Major cracks occurred in the uppermost ring. The lowermost ring had only a few cracks (Figure 4-35). Transport of material occurred in the larger cracks in the uppermost ring Figure 4-36). The rings seemed nearly unaffected by the water (Figure 4-37). There was a distinct border between the dry and the wet pellets (Figure 4-38 and 4-39).

Figure 4-32. *Bentonite slurry on top of the ring.*

Figure 4-33. *Bentonite slurry on top of the ring.*

Figure 4-34. *Major cracks occurred in the uppermost ring.*

Figure 4-35. *Cracks on the inside of the uppermost ring.*

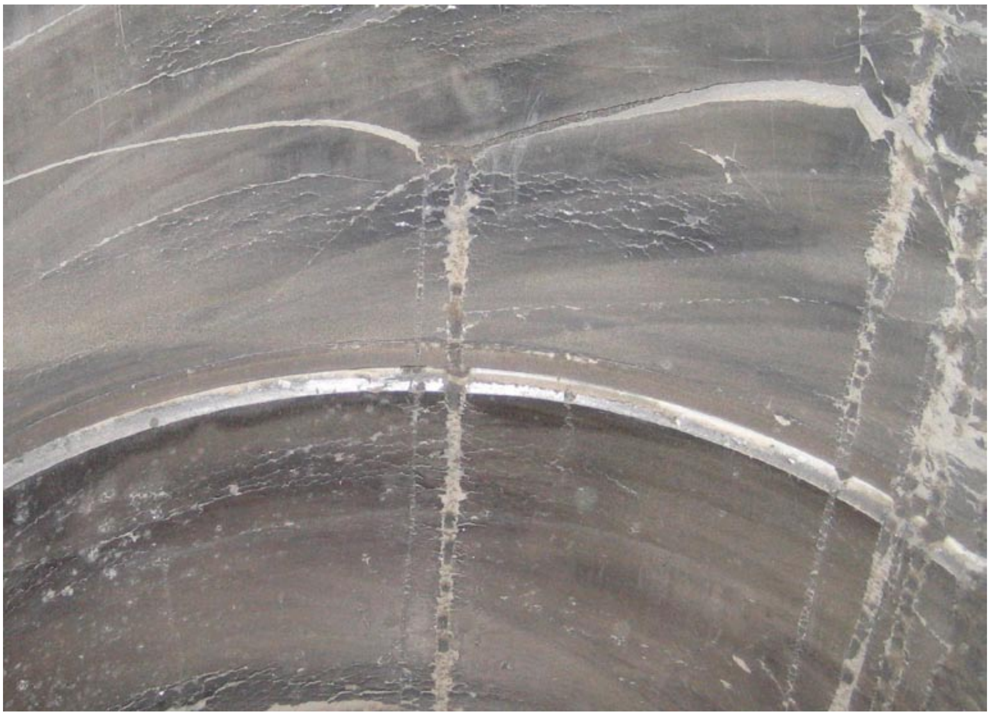

Figure 4-36. *Transport of material in a massive crack in the uppermost ring.*

Figure 4-37. *Outer side of the ring.*

Figure 4-38. *Intact dry pellets and pellets slurry above.*

Figure 4-39. *Distinct difference between dry and wet pellets.*

The water transport occurred in the pellets, few areas showed a homogenous gel and the pellets shape is still visible (Figure 4-40). It can clearly be seen that the outer side of the pellets is wet and the innerside is dry (Figure 4-41 and 4-42). The same area is marked with a red ring in both figures for comparison.

Figure 4-40. *Interface between pellets, ring and outer side of the container.*

Figure 4-41. Outside of the container with wet pellets.

Figure 4-42. *Insider of the container with most of the pellets dry.*

Attempts were made to measure the erosion. It turned out to be difficult to conduct the measurements in full scale. Water from different locations in the uppermost part of the container was collected in hoses and samples were taken for determination of the bentonite ratio. It was not possible to make any conclusion from the measurements.

The maximum change in diameter of the container was 7 mm in Test 6. The typical increase in diameter was 1–3 mm.

5 Discussion

The inflow rates and pressures are summarised in Figure 5-1. The highest pressures have been observed with MX-80-pellets, i.e. Tests 3 to 6. The behaviour of the pressure is completely different in Test 5 and 6 with bentonite rings. Higher peak values were registered and there are more pressure variations. It is likely that the roughness of the rings has an impact on the pressure build-up, as shear forces arises in the interface between the pellets and rings. The pressure in Test 4 is very moderate compared to Test 5 and 6 with rings.

The inflow was reduced in Test 3 and 5 in order to observe any pressure increase. The pressure dropped instantly in Test 3 and was then practically constant for the remaining part of the test. In Test 5 with rings, the pressure dropped and was restored within 12 hours and then continued to increase for the rest of the test with only some minor drops. The inflow was however considerably lower in the last part of Test 5, which might explain the high and increasing pressure.

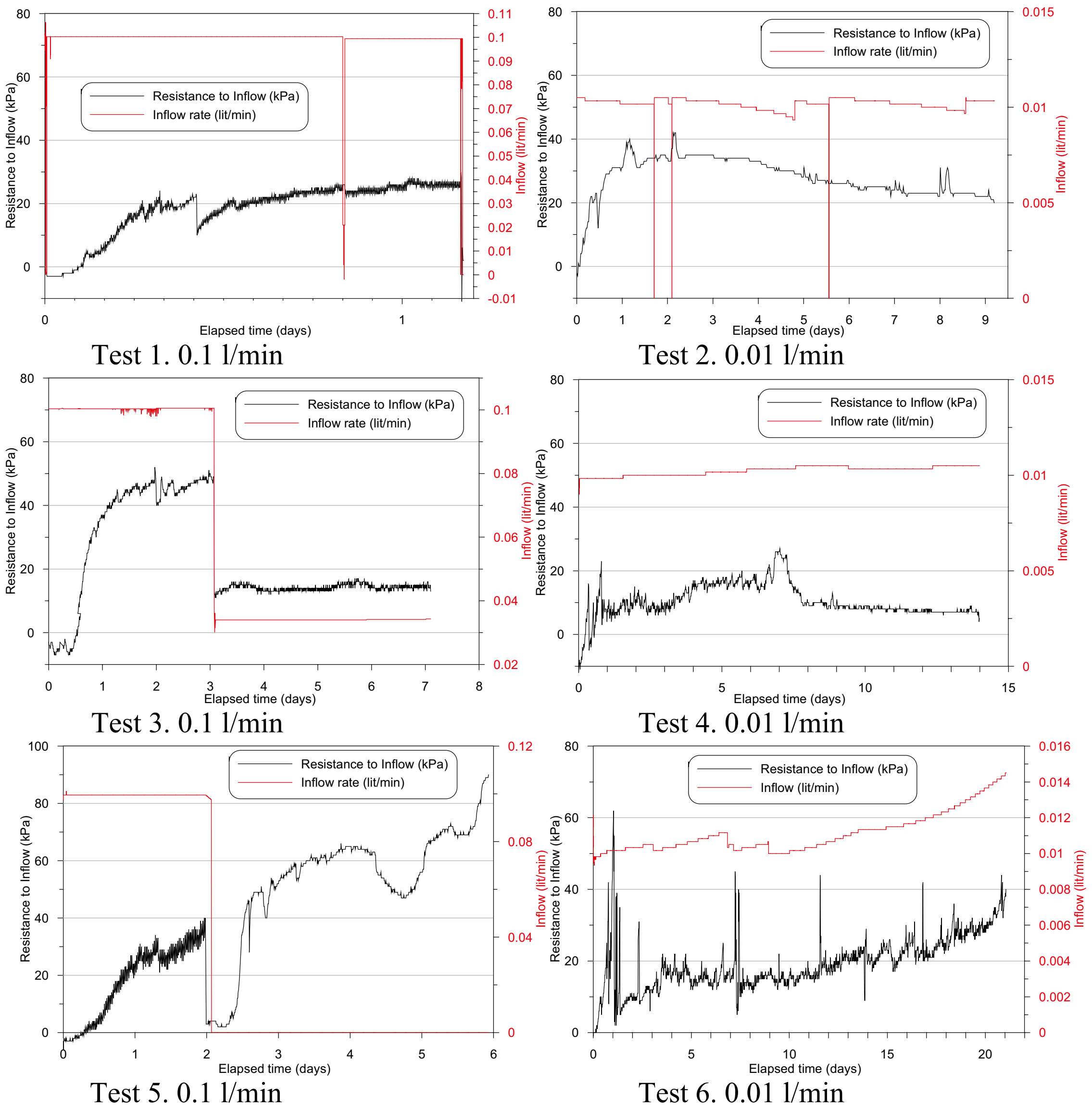

***Figure 5-1.** Inflow and pressure rates. Notice that the time scale differs.*

Comparing tests that only differ in inflow rate shows that pressures with the lower inflow rate are relatively high. This indicates a different behaviour in saturation and swelling for different inflow rates. At a lower inflow rate, the pellets has more time to absorb water, swell and seal. It is also observed that with the lower inflow; irregularities in the pressure can be seen which might indicate piping. It is noticeable that the tests with Cebogel (Test 1 and 2) show the opposite relation between pressure and inflow rate compared to the tests with MX-80 (Test 3 and 4). That indicates a different behaviour in swelling between MX-80 and Cebogel pellets.

The swelling behaviour differs in all the six tests. This can be seen by comparing the pressure build-up. However, any unambiguous conclusions are difficult to make. The swelling ability of the pellets is governed by the initial density. The swelling and water distribution can also, beside from the inflow rate, be influenced by the geometry of the pellets, the smooth surface of the container, by resisting forces in the pellets rings and so forth.

For a better view of the initial pressure build-up, the first 24 h has been plotted separately (Figure 5-2).

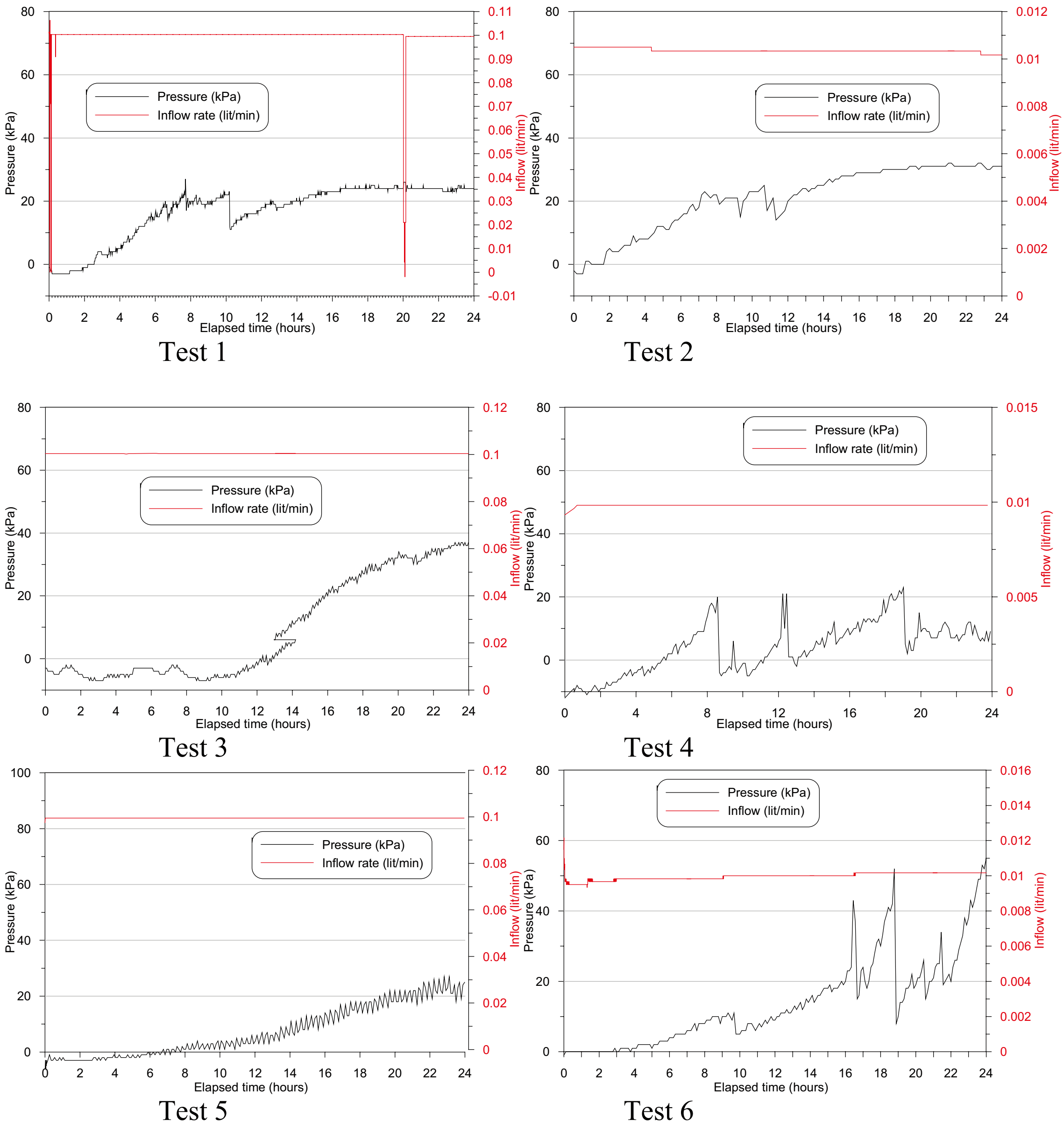

Figure 5-2. *The inflow rates and pressures the first 24 h.*

The first day, it can be seen that the pressure seem to develop slower with the rings in Test 5 and 6 compared to the earlier tests but the peak pressure is higher. Test 3 reaches almost twice the pressure after 24 hours compared to Test 5 with rings. The rings obviously affect the test outcome.

The pressure drop that follows piping is seen at 8–10 hours in Test 1, 2, 4 and 6.

5.1 Water distribution

The wetting pattern seems predictable at the studied inflow rates (Figure 5-3). The water distributes faster upwards than downwards at 0.01 l/min. This has also been observed in earlier laboratory tests /Börgesson and Sandén 2006/.

Gravity is the initial driving force as the water flows downwards. At 0.1 l/min, the pellets acts more like gravel and the water flows in the spaces between the pellets and fills the container from the bottom and up. At 0.01 l/min, the pellets start to swell and seal the pathway. The water is hereby forced to seek a new way; upwards and sideways. The reduced height of the container affects the water distribution as the water reaches the top. It is likely that a higher container would have given a different saturation pattern and that the water would have continued to flow upwards. The position and characteristics of the water inflow is probably crucial for the water distribution within the pellets.

Based on the regularity in the observations of the water distribution, it is possible to make an estimation of the rate that the water distributes upwards in the pellets. It is therefore also possible to estimate when water reaches the deposition tunnel from a certain position of a water inflow in the deposition hole. It is possible that another inflow rate will yield a higher rate of distribution upwards. More tests at different inflow rates are needed to verify this assumption.

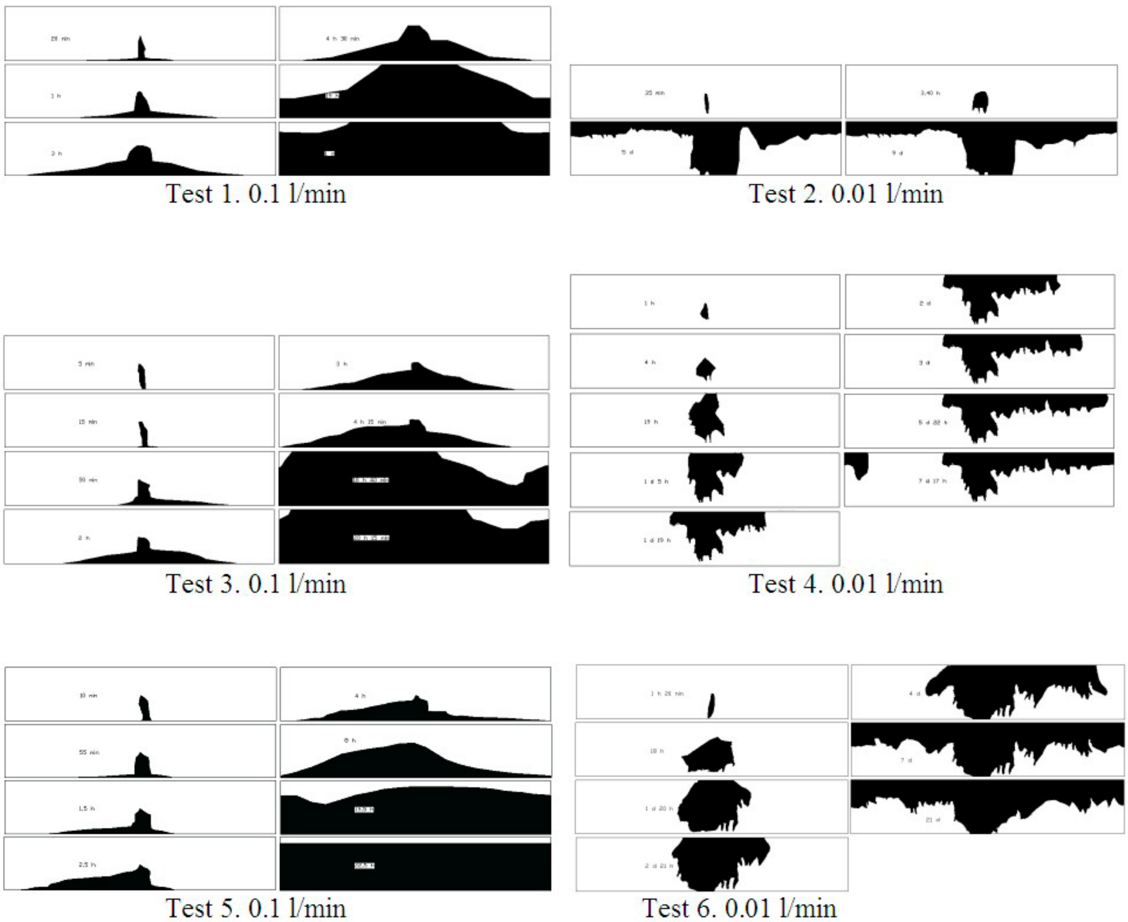

Figure 5-3. *Wetting patterns for Test 1-6.*

Since the water distributes relatively freely in the pellets at 0.1 l/min, the water would reach the deposition tunnel after about eight days based on the observations in this study.

The wet area is much larger for Test 6 than Test 4 at the same period of time (7 days) but the water reached the top of the container faster in Test 4. This might be a result of interaction with the rings in Test 6, but could also be by coincidence.

The water distributes mainly at the outer side of the container close to the container wall. This can be seen both from photos of the pellets and measurements of the water ratio at different positions. This is probably because of the container side that is smooth and provides a smaller resistance of water flow. A rough rock-surface will probably have a large impact on this behaviour.

There are relatively small variations in water ratio in the samples taken from the rings, except at the water inlet were a considerably higher water ratio was measured. The variation is larger in Test 6 considering the longer test period.

5.2 Heaving of the rings

Another issue for the repository is possible heaving of the bentonite rings and blocks. They are manufactured of bentonite granules that are compacted to blocks. Because of that, they have very low yield strength. When exposed to differences in relative humidity or localized water concentration, horizontal cracks occur.

The heaving rate is roughly the same at 0.1 and 0.01 l/min the first six days. Largest final heave was noted for Test 6 (i.e. at 0.01 l/min) but it is likely that a larger heaving would have occurred at 0.1 l/min if that test would have ran for a longer period of time.

Relatively large heaving of the uppermost ring occurred. Less heaving was observed of the lowermost ring. It is therefore inferred that the overburden pressure has a big impact. Further studies are needed for a better description of the heaving of the rings under field conditions. The heaving also needs to be studied during a longer period of time.

5.3 Swelling pressure

The increase in outer diameter of the container has been very moderate. Maximum change noticed was 7 mm in Test 6, which is about 0.1% of the total circumference. There is also an uncertainty in the method used to measure the diameter by a regular measuring tape. The conclusion, therefore, is that the horizontal swelling pressure is relatively small, on the other hand, no resistance to swelling upwards decreases the horizontal swelling pressure.

5.4 Erosion measurements

Attempts were made to measure the erosion. However, measurements in full-scale conditions turned out to be difficult. It is hard to get representative samples as the water emerges at different positions and differs over time.

6 Implications and proposals for future studies

The overall aim of this study was to provide an indication of what inflow that can be accepted into the deposition holes. The study has confirmed three concerns:

- The heaving of the blocks and rings can affect the final density of the buffer
- Piping occurs within the bentonite filling
- The water can reach the deposition tunnel and affect the backfill

The water climbs upwards at 0.01 l/min. It is likely that a water inflow with a low rate in the upper part of the deposition hole could reach the deposition tunnel within a few days at the worst circumstances. That would possibly result in heaving of the upper blocks as well as initiate erosion of the backfill.

The overburden pressure strongly influences the vertical displacement of the blocks. In this study, no overburden was applied. The roughness of the deposition hole is also expected to influence the results. In the tests, most of the water transport has occurred at the outer side of the container, following the smooth surface of the container wall. It is uncertain how actual conditions with a rough surface of rock and an overburden would affect the results.

It is observed that inflow rates at both 0.1 and 0.01 l/min results in piping and it seems that the water always finds a new path and that the bentonite has no ability to seal as long as there is a continuous flow of water. For the bentonite to be able to seal and establish a pressure build-up, the inflow has to be decreased to a very low rate.

In all it is found that more studies of the behaviour of the buffer and the water distribution within would be valuable. There is probably a large impact of random effects in the tests. The numbers of tests performed are too few to give any definite conclusions and the results hereby presented are therefore only indicative and provides information for further tests.

More tests for a longer period of time at conditions more similar to field conditions are needed to understand the heaving behaviour of the blocks and rings. Test with a full height container and a resisting overburden would give implications to if the height and time are important parameters.

Piping in the bentonite filling seems unavoidable considering the large water pressure at full repository depth. However, more studies are needed to conclude the behaviour and establish a design criterion.

7 References

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