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Vapor transport and sealing capacity of buffer slots ("sauna" effects)

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Abstract

A set of tests have been conducted which studied vapor transport in a slot between bentonite blocks and a heater (a copper tube). The purpose of these tests was to gain insight and understanding of how vapor interacts with compacted unsaturated bentonite blocks. Understanding this mechanism is central for assessing the so-called "sauna" effect, in which salt from inflowing groundwater is deposited in or near the bentonite buffer in a KBS-3 repository as the water is vaporized.

The heater in these tests has a diameter of 10 cm and the surrounding bentonite blocks have an outer diameter of ca 30 cm. The inner slot were approximately 5 mm wide and was fed with vapor by supplying water near the heater at the bottom of the set-up (the liquid water did not have direct contact with the bentonite). The different tests consisted mainly in differently configured bentonite blocks. In tests where the slot was directly opened to the environment it was demonstrated that substantial amount of vapor could be transported through the slot without being taken up by the (dry) bentonite. In tests where the slot was covered by a massive bentonite block, water condensation occurred, and only small amounts of water were lost to the environment. In general it was demonstrated that the main mechanism for taking up water in these systems is in form of local condensation of vapor – once a "nucleus" of condensed water has formed, the bentonite continues to take up water at this particular position. As a consequence of this type of "non-symmetric" water uptake, many bentonite blocks cracked due to uneven swelling.

Sammanfattning

En uppsättning tester har utförts där transport av vattenånga i en spalt mellan bentonitblock och en värmare (i from av ett kopparrör) har studerats. Syftet med dessa tester är att bättre förstå hur vattenånga interagerar med omättade kompakterade bentonitblock. En förståelse för sådana processer är central för att kunna utvärdera den s.k. ”bastu”-effekten, vilken innebär att salt i inflödande grundvatten deponeras i eller nära bentonitbufferten i ett KBS-3-förvar genom att vattnet förångas.

Värmaren i dessa tester har en diameter på 10 cm och de omgivande bentonitblocken en ytterdiameter på ca 30 cm. Den inre spalten är ca 5 mm bred och matades med vattenånga genom att tillföra flytande vatten i botten av systemet, nära värmaren (det flytande vattnet hade inte direktkontakt med bentoniten). De olika testerna bestod huvudsakligen i olika konfigurationer av bentonitblock. I tester där den inre spalten hade direkt kontakt med omgivningen demonstrerades att ansenliga mängder vattenånga kan transporteras genom spalten utan att tas upp av (den torra) bentoniten. I tester där spalten istället var täckt med ett massivt bentonitblock förekom endast små förluster till omgivningen. Testerna visade generellt att den dominerande mekanismen för bentoniten att ta upp vatten i dessa typer av system är genom kondensation av ånga – när väl en ”kärna” av kondenserat vatten har bildats, fortsätter bentoniten att ta upp vatten i denna position. En följd av denna typ av ”osymmetriskt” vattenupptag var att många bentonitblock sprack på grund av ojämn svällning.

Contents

1 Introduction

A potential problem within the KBS-3 concept for storage of nuclear waste (SKB 2011) is the so-called "sauna" effect. A "sauna" effect is conceivable in specific water inflow scenarios during the saturation phase of a KBS-3 repository, where a relatively large part of a tunnel section is supplied with water from a single fracture (or a few) entering the repository at a position in the lower part of a buffer hole (Figure 1). As a consequence of the relatively high temperature in such positions, water may vaporize and subsequently be transported in gas form to cooler locations higher up in the tunnel backfill. Such a mechanism, in turn, will increase the salt concentration in the remaining liquid phase. If the process continues long enough, salts may even start to precipitate. Once the system is water saturated (which it eventually will be although it may take a very long time in this scenario), the presence of larger amounts of salt in the vicinity of the canister may lead to increased corrosion rates, thus possibly compromising its integrity (Karnland et al. 2009).

The present work is a continuation of the study of "sauna" effects, earlier initiated by a consideration of vapor transport in pellets fillings (Birgersson and Goudarzi 2013). In that report, the study of "sauna" effects were divided into three broader categories

- Interaction between saline (ground)water and partly saturated bentonite, i.e. how salt is deposited in bentonite (process at the fracture/buffer interface).
- Transport of vapor through unsaturated zones of compacted bentonite blocks (process in the buffer). For the "sauna" effect to be active, this type of transport must be sufficiently effective; if the buffer bentonite instead takes up the water and seals off the pathways for vapor, the process of depositing salt ceases.
- Transport of vapor through unsaturated zones of bentonite pellets (process in buffer and buffer/tunnel backfill interface). Also in this region, the vapor transport must be sufficiently effective for the "sauna" effect to be active.

The present study fall in the second category and concerns vapor in the slot between the copper canister and the buffer bentonite.

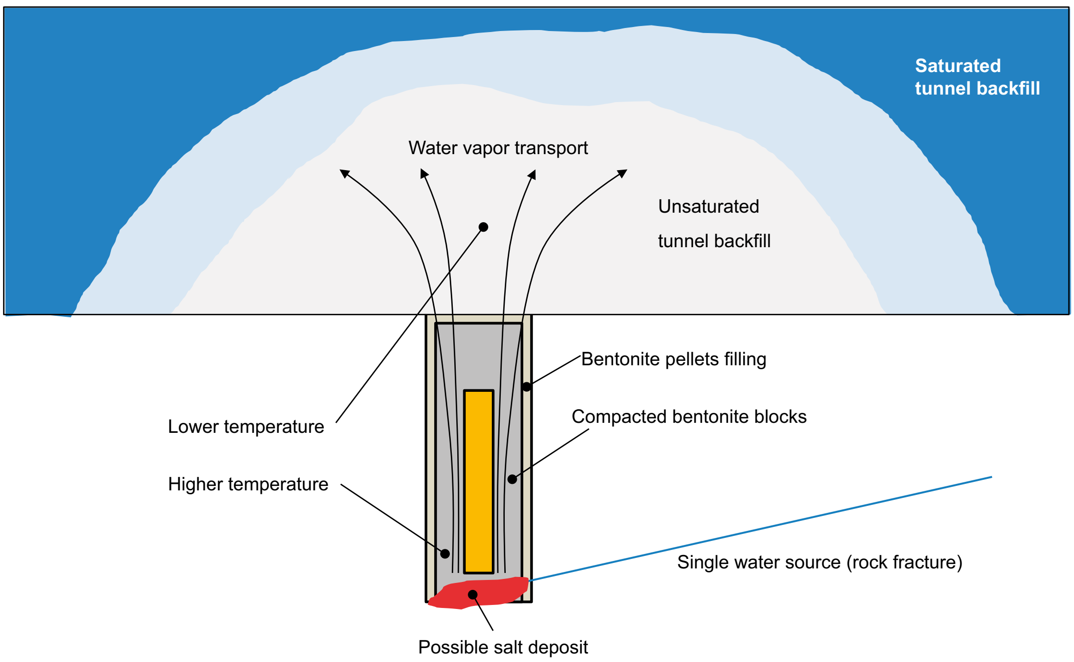

Figure 1-1. *Schematics of the "sauna" effect.*

2 Tests

2.1 Basic set-up

Figure 2-1 shows the principle of the test set-up, which to a certain extent is a model of a KBS-3 deposition hole. Mounted on a plastic plate is a copper tube which is heated by circulating water to approximately 80 °C. Closest to the copper tube, the plastic plate has a 40 mm deep and 5 mm wide groove into which water was fed from the outside, thus producing a vapor source. In tests with full access to water, the water level was adjusted to approximately mid-height of the groove, in order to ascertain no direct contact between bentonite and liquid water. One or several compacted unsaturated bentonite rings are stacked on the plate, concentric with the copper tube (Figure 2-1). In this way a slot between heater and bentonite rings can be achieved through which vapor may be transported. The outside of the set-up was covered by a plexiglass tube (see e.g. Figure 2-2). The blocks were made from MX-80 bentonite with an initial water-to-solid mass ratio of ca 16 %. The dry density of the rings were 1770 kg/m^3, and the dry density of the massive blocks (to be put on top) were 1680 kg/m^3.

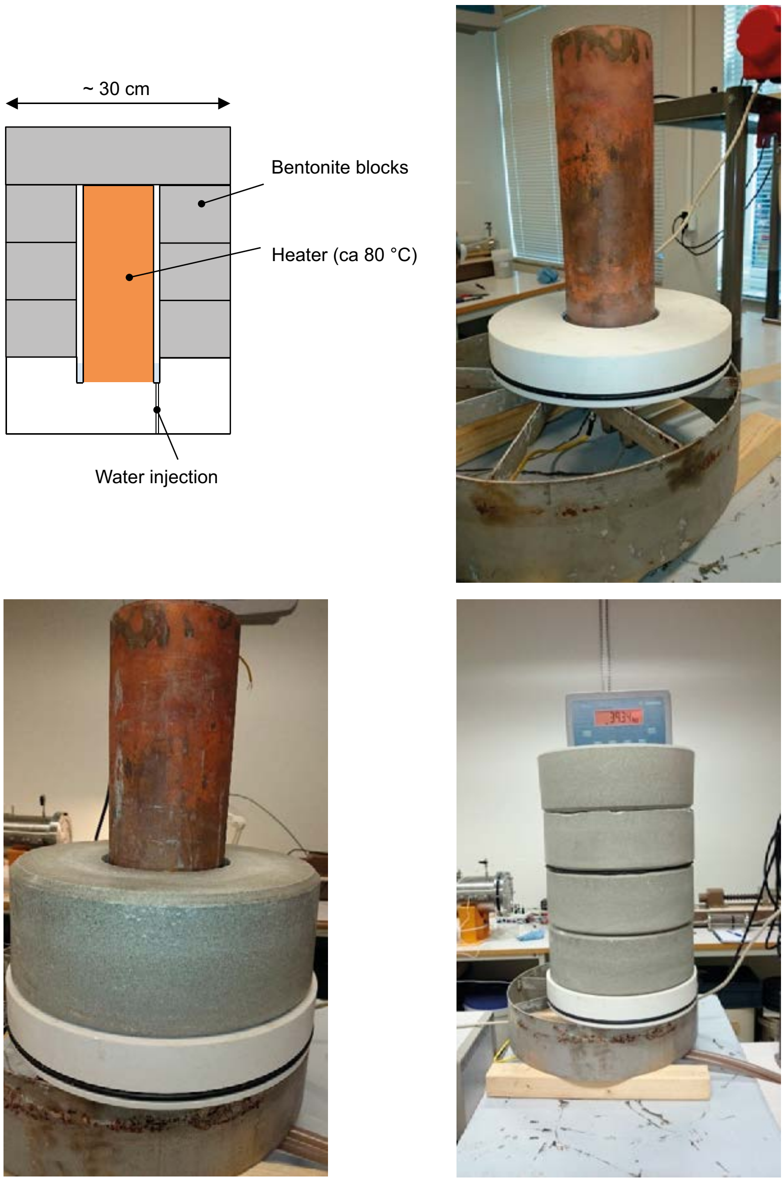

Figure 2-1. *Upper left: Schematic view of the test set-up. Upper right: The heater (copper tube) and bottom plate. Lower left: A single bentonite ring mounted. Lower right: Three bentonite rings and a massive top block mounted. The whole set-up is placed on a scale.*

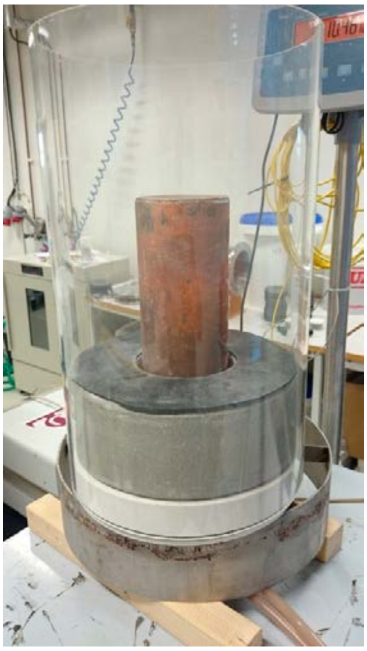

Figure 2-2. *Test 2 at the start of the test.*

The entire set-up was placed on a scale, giving a simple mean to measure water uptake/loss during the course of testing. The total amount of water consumed by the system was furthermore monitored by keeping track of the amount of water fed from the outside.

The study consisted of seven different tests. The conditions varied in these test were the amount and type of bentonite blocks, different ways of confining the blocks, and the way water was fed to the system. Table 2-1 summarizes the conditions under which each of the tests was performed. In addition to recording the water consumption during the course of the test, the system was dismantled at termination and visual inspection was made – with the particular purpose of identifying where water had accumulated. Furthermore, quantitative determination of water content was done in points of interest. Below follows a description of the results obtained in each test.

2.2 Test 1

This test was performed simply to test the equipment and is only listed here for completeness. It had a single bentonite ring of small inner radius, thus basically lacking a slot between bentonite and copper tube.

Table 2-1. Descriptions of performed tests.

Test	Bentonite blocks	Water supply	Block boundary
1	1 ring small inner radius	Full water supply	
2	1 ring large inner radius	Full water supply	Plastic mat
3	1 ring large inner radius	First no water supply, then full water supply	Plastic mat + cloth as convection inhibitor
4	2 rings, 1 large 1 small radius	Full water supply	Plastic mat + cloth as convection inhibitor
5	3 rings large radius, 1 massive block	Full water supply	Plastic mat + bentonite powder as convection inhibitor
6	3 rings large radius, 1 massive block	Limited water supply	Plastic mat + bentonite powder as convection inhibitor
7	3 rings large radius, 1 massive block, pellets on top	First no water supply, then full water supply, then full water supply 0.6 M $CaCl_2$	20 cm pellets filling on top, bentonite powder as convection inhibitor. Pre-cracked blocks.

2.3 Test 2

Test 2 was performed with a single bentonite ring covered on top by a plastic mat. The purpose of the plastic mat was to reduce the amount of water leaving the block during testing due to drying. Nevertheless, vapor was basically free to leave the system as the bentonite/tube slot was open to the environment. This test had full access to water as it was directly connected to a water reservoir on the outside. The set-up of test 2 is shown in Figure 2-2.

Figure 2-3 displays the water consumed during test 2. During ca 2.8 days, approximately 0.4 kg of water was fed to the system. Despite this consumption, the amount of water in the bentonite actually decreased during the test (with ca 0.1 kg), i.e. the bentonite dried. The total loss rate was thus approximately 0.19 kg/day. Although the bentonite lost water as a whole, it was also evident that water was taken up from the vapor flowing in the inner slot. This uptake manifested itself in swelling which caused the block to crack, as shown in Figure 2-4 (picture taken at termination).

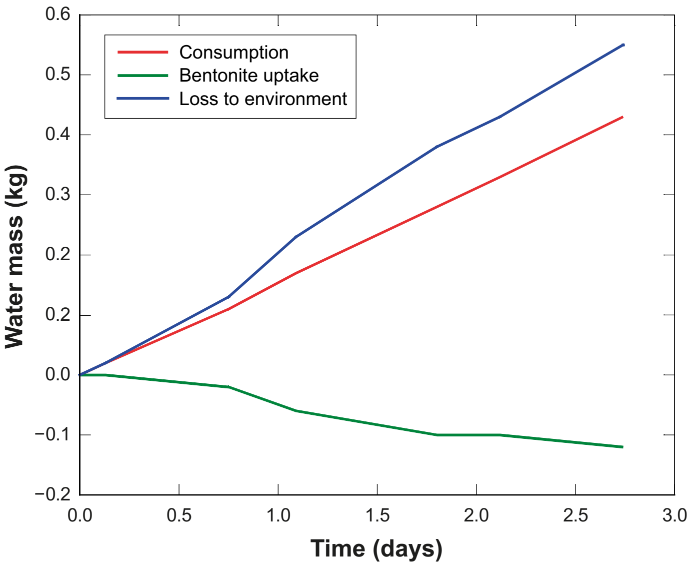

Figure 2-3. *Water consumption and uptake in test 2.*

Figure 2-4. *Test 2 at termination.*

Further inspection of the block (Figure 2-5) revealed that the water uptake had occurred locally in a condensation spot rather than uniformly (as suggested by the radial symmetry). This type of water uptake via a condensation "nucleus" was also observed in the previous study on vapor transport in pellets (Birgersson and Goudarzi 2013).

Note that although the water uptake from vapor appear to be rather extensive, the water content of the block as a whole decreased during the test. It can thus be concluded that significant water redistribution occurred in the block, which is supported by the observed cracking.

2.4 Test 3

In an attempt to reduce drying of the block, test 3 was performed with a convection inhibitor in form of a cloth sandwiched between the outer surface of the bentonite block and the confining plexiglass, as shown in Figure 2-6. Initially, this test was run for 4 days without water access. The conditions were otherwise the same as for test 2: a single bentonite ring was used covered with a plastic mat, and after the initial 4 days, the system was given full access to water. Figure 2-7 show the full water consumption and uptake history during the course of test 3. The bentonite is seen to lose approximately 0.15 kg water during the phase without water access. This loss is comparable to that measured in test 2, and consequently indicates that the convection inhibitor did not have a significant influence on drying of the block. Moreover, after connecting the external water reservoir (day 4), the water consumption is seen to be similar to that in test 2 (ca 0.15 kg/day).

Figure 2-5. Bottom side of the bentonite ring in test 2 after termination. Vapor has been taken up unevenly, by local condensing.

Figure 2-6. Test 3 at the start of the test.

During the stage with water access, the bentonite mass stayed more or less constant. This behavior could indicate that the available water vapor simply were transported through the inner slot without interacting with the bentonite. As in the case of test 2, however, such an interpretation is not correct, as illustrated by the massive local swelling occurring at this stage; the bentonite ring quickly cracked when water was applied, and the inspection of the block after test termination clearly showed local water condensation (Figure 2-8).

It must thus be concluded that water was simultaneously taken up locally in a “condensation nucleus”, while the block simultaneously lost water by drying, at basically the same rate.

2.5 Test 4

Test 4 was performed with two bentonite rings, the top one having a radius small enough as to basically seal off the inner slot (see Figure 2-9). The test had full access to water during the whole test period, and a convection inhibitor in the form of a cloth was used, as well as a plastic mat on top of the top block.

Water consumption and uptake is shown in Figure 2-10. In contrast to test 2 and 3, this test actually shows water uptake during the first 2 days of the test. The loss rate at this stage was furthermore ca 0.05 kg/day, which is significantly lower than measured in the earlier tests. After the first 2 days, however, the uptake basically ceased, leaving the system in a “steady-state” where the same amount of water as consumed was lost to the environment. The loss rate also increased to ca 0.1 kg/day.

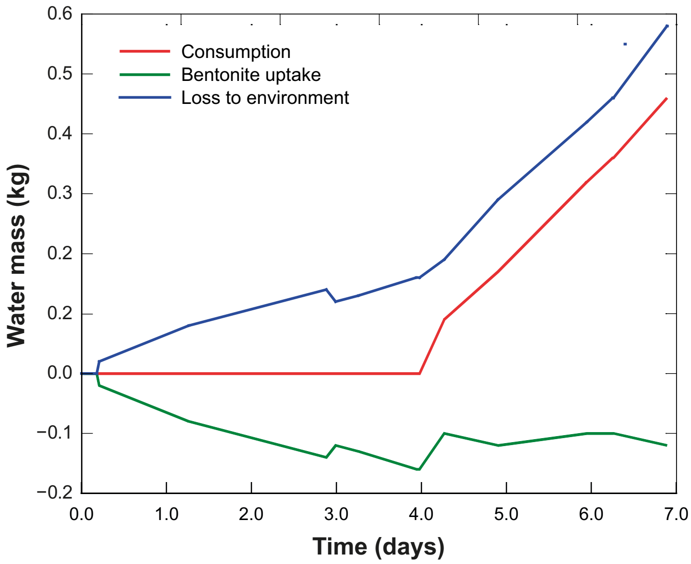

Figure 2-7. *Water consumption and uptake in Test 3.*

Figure 2-8. *Left: Test 3 at termination. Right: Bottom side of the bentonite ring showing a condensation “nucleus”.*

Figure 2-9. *Test 4 at the start of the test. The top ring had an inner radius small enough as to basically seal off the inner slot (bottom right).*

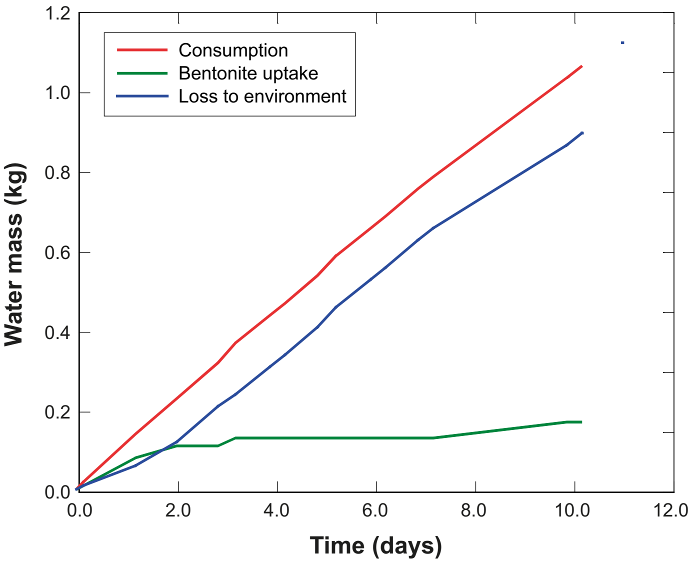

Figure 2-10. *Water consumption and uptake in test 4.*

As shown in Figure 2-11, inspection of the bentonite at test termination showed localized water uptake – of the same type as also documented in tests 2 and 3. This inspection also showed massive cracking of the lower block while the top block had a single crack (Figure 2-11). Combining these observations with the observed water uptake, it seems reasonable to conclude that the bottom bentonite ring took up water during the first two days of the test, since the top ring basically functioned as a seal in this set-up. As a consequence of the water uptake, the bottom ring swelled and developed massive cracks, through which vapor escaped during the final part of the test (days 2–10).

The water content was measured in samples taken at different positions, as showed in Figure 2-12. Not surprisingly, the amount of water locally had increased significantly in the bottom block as compared to the initial water content. Note, however, that the variation of the water content varies significantly in some cases at the same height, demonstrating the non-symmetric water uptake (compare e.g. sample #1 and #7).

Figure 2-11. *Test 4 at termination. Left: the top side of the top ring. Middle: Top side of bottom ring. Right: Bottom side of bottom ring.*

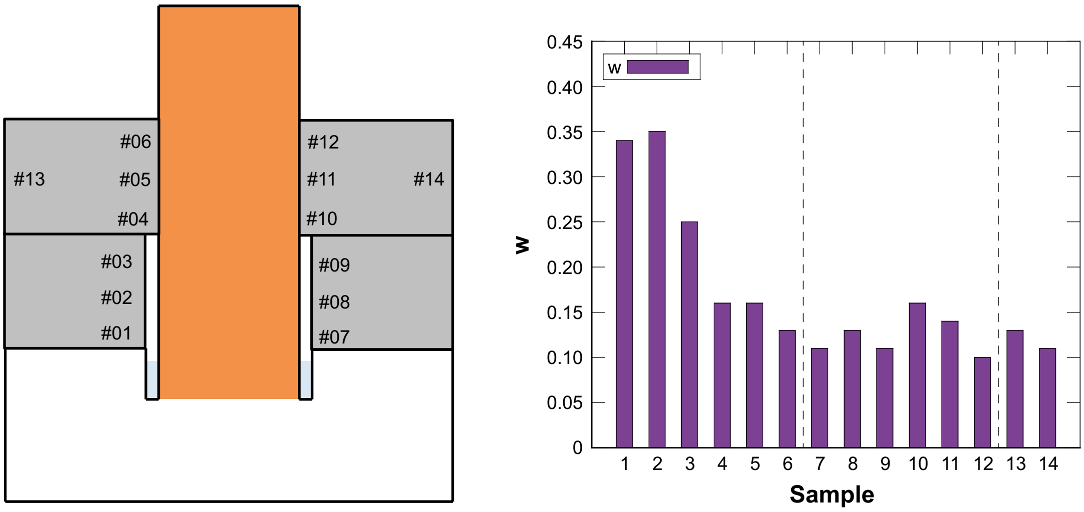

Figure 2-12. *Water-to-solid ratio (w) in samples taken during the excavation of test 4. The left figure shows the approximate positions of the samples.*

It should also be recognized that the values of water-to-solid ratios presented in Figure 2-12 (and generally in this report) represent the average values in the samples taken. Consequently, these values alone cannot be e.g. integrated to a total amount of water in the system. The total mass of each sample is listed in the appendix.

2.6 Test 5

Test 5 consisted of three bentonite rings stacked on top of each other (all having a radius giving a copper tube/bentonite slot of approximately 5–10 mm) as well as a massive block on top. The set-up was thus identical with that shown schematically in Figure 2-1. The spacing between the outer side of the blocks and the plexiglass tube was in this test filled with bentonite powder (MX-80, water-to-solid mass ratio 16 %), as shown in Figure 2-13. On top of the top block was placed a plastic mat. In order to adjust the height of the stacked rings, a piece of plastic mat was also placed in between the mid ring and the top ring. The system had full water access during the whole course of the test. The water consumption and uptake is plotted in Figure 2-14.

In contrast to the water consumption in the earlier tests, test 5 is shown to have very little loss to the environment (Figure 2-14), less than 0.01 kg/day. It is thus evident that the layout of this test – with a massive block functioning as a lid over the copper tube/bentonite slot, and with bentonite powder functioning as a seal on the outside – basically made it isolated from the environment.

Figure 2-15, Figure 2-16, and Figure 2-17 show the state of the bentonite blocks at the time of termination. A clear condensation point was shown in the massive top block (Figure 2-15, left part). Apparently, water vapor transported through the inner slot condensed in this point. Note that the condensation is localized, which seems to be always the case (compare with earlier tests in pellets).

***Figure 2-13.** Test 5 at the start of the test.*

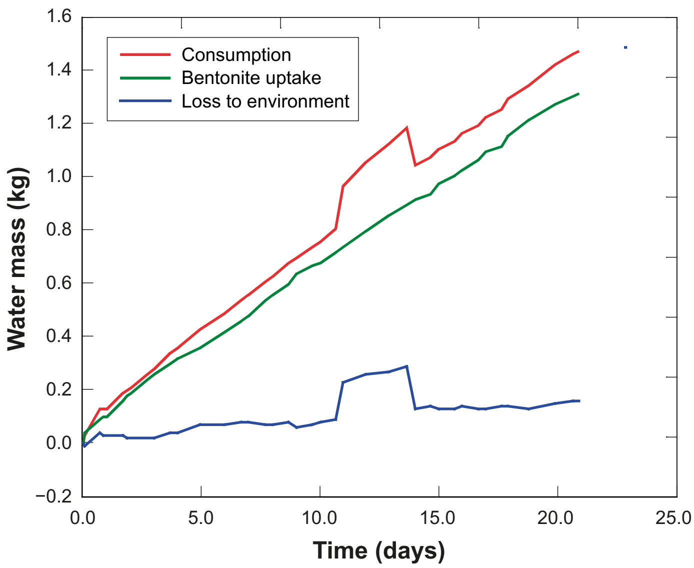

***Figure 2-14.** Water consumption and uptake in test 5. The "hunch" in the consumption curve is an artefact due to incorrect measuring during this time interval.*

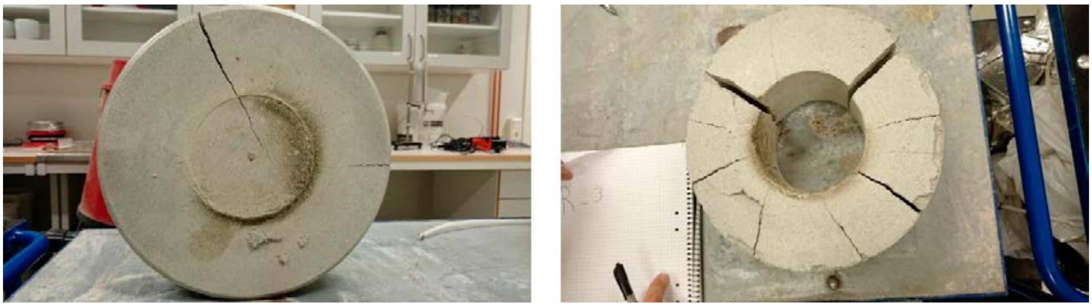

***Figure 2-15.** Bottom side of the massive top block (left). The top ring seen from the top side (right).*

Figure 2-16. *The mid ring seen from the top side. The blue coloring is due to a plastic mat which was placed in between this and the top ring in order for the blocks to line up with the copper tube.*

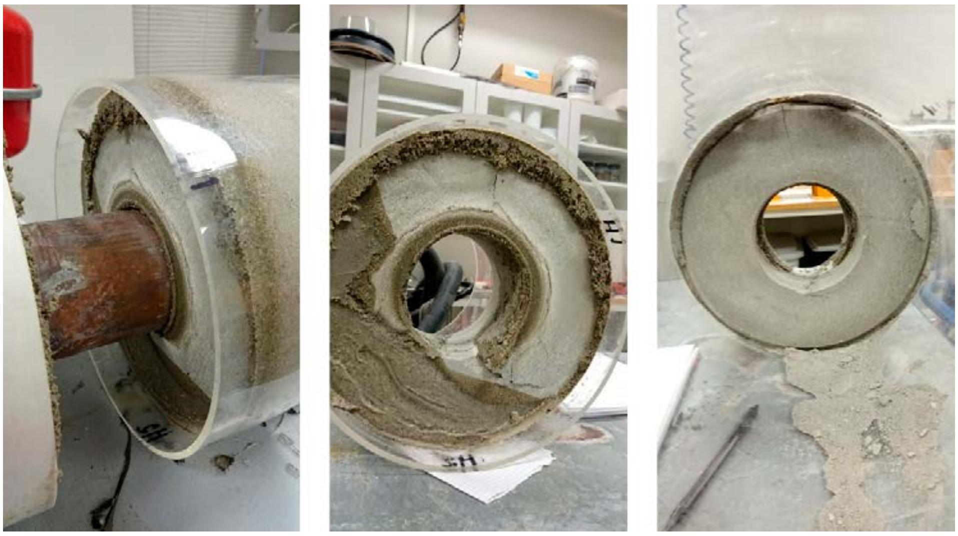

Figure 2-17. *Swelling occurred to such an extent in the bottom ring of test 5 that it could not be easily removed from the outer plexiglass (left). Middle picture: bottom side. Right picture: top side (right).*

Condensation is also clearly visible in the top ring (belonging to the same "nucleus" as the condensation in the massive top block, see right part of Figure 2-15). As a consequence of water uptake in this ring, it was severely cracked. In contrast to the behavior in test 4 – where the cracks functioned as escape paths for vapor – this cracking did not cause changed behavior in water uptake of the bentonite. This behavior indicates that the outer bentonite powder efficiently stopped further vapor transport.

The mid ring was much less affected by water uptake, although still showing a few cracks (Figure 2-16). No water condensation was observed in this block.

In the bottom, localized water uptake had occurred, as shown in Figure 2-17. A mistake was unfortunately made during the termination/excavation process, as the water present in the bottom slot (Figure 2-1) was not emptied before the set-up was tilted. This water consequently flowed out between the bottom ring and the bottom plate as is seen in Figure 2-17. Despite this misfortune, several relevant observations could be made in the bottom ring.

In the inner slot substantial water uptake was evident on the bottom side of the ring (as seen in Figure 2-17), and significant amount of water – with associated swelling – had also accumulated in the outer powder filled slot. Actually, the swelling in the powder in the outer part was so extensive that it was not possible to detach the bottom ring from the plexiglass. Instead the plexiglass and the ring was dismantled in one piece (Figure 2-17, left). The inner part of the bottom surface area of this ring was, on the contrary, relatively dry (disregarding the water stemming from tilting the set-up). At the same time, the ring was basically free of cracks. An interpretation of the combination of these finding is that a main path for vapor was through the interface between the bottom ring and the bottom plate, without significant water uptake in the middle of the block, before condensing in the outer, cooler parts.

Figure 2-18 shows the water-to-solid mass ratios measured in the system at termination. The data reflect the accumulation of water in the bottom of the system, but also the condensation occurring in the massive top block.

The water content data collected in bentonite associated with the inner slot is plotted as a function of height in Figure 2-19. This test clearly shows that significant amounts of vapor can be transported in the slot and condensed far from the original water source. In particular, water uptake in these types of systems do not occur in a symmetric fashion.

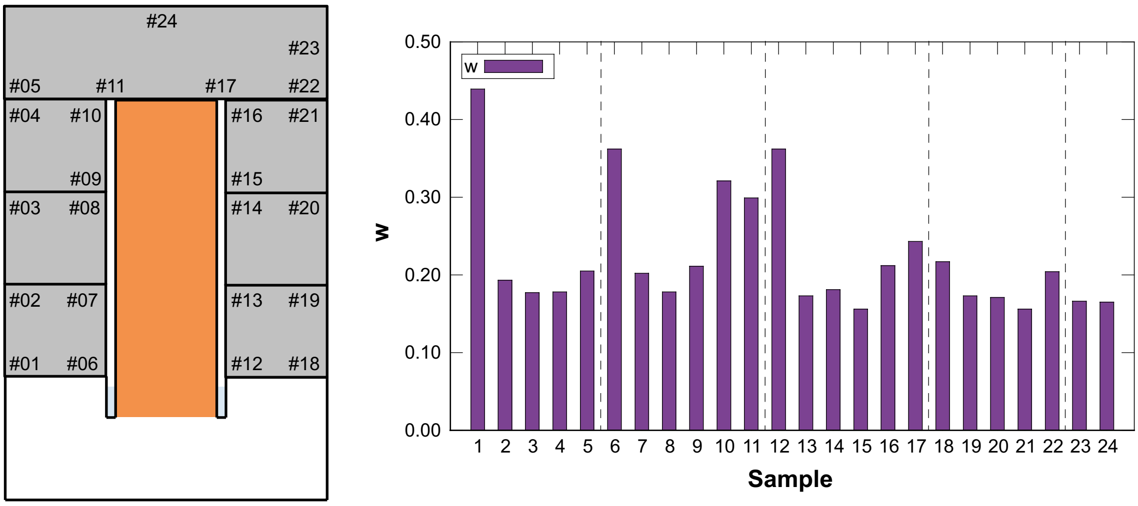

Figure 2-18. Water-to-solid ratio (w) in samples taken during the excavation of test 5. The left figure shows the approximate positons of the samples.

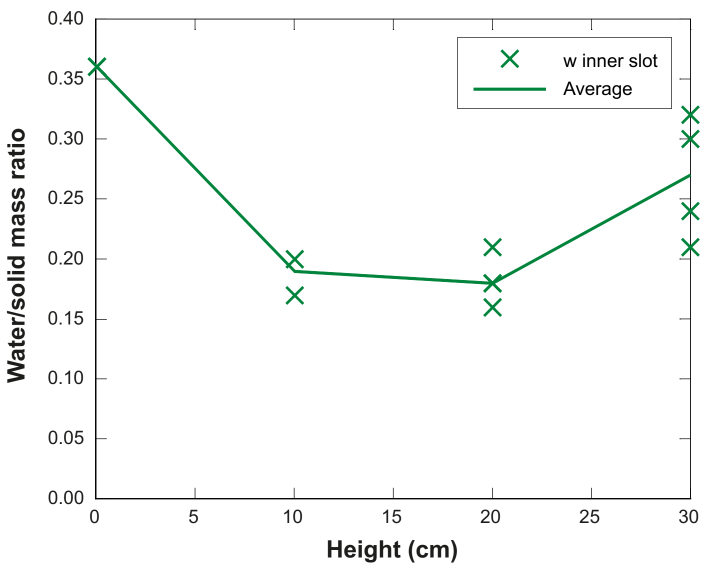

Figure 2-19. Water distribution in the bentonite nearest to the inner slot in test 5.

2.7 Test 6

Test 6 had an identical configuration as test 5: three rings and a massive bentonite top block. In contrast to Test 5, however, in this test was the water access restricted to ca 8 ml/day – giving a reduction of water consumption of approximately an order of magnitude as compared to test 5. The reduction of water inflow was achieved by feeding the system with water from a flow controlling unit (GDS instruments).

Figure 2-20 shows water consumption and uptake during the whole course of test 6; as the consumption (now controlled) was much lower than in previous tests, the testing time was considerably longer – almost 90 days – in order to consume a comparable amount of water.

Figure 2-20 reveals that the bentonite took up water also with restricted water access in this type of slot geometry. The constant rate of the water uptake indicates that the capacity of transporting water away from possible condensation points in this system (to the environment) is considerably slower than the rate at which water was fed, i.e. much lower than 8 ml/day. The observed loss to the environment should consequently be attributed to drying of outer parts of the bentonite, independent of whether the system had access to water or not.

In this case, however, the water uptake is similar in size to the amount of water lost to the environment. Thus, the relative loss of water is considerably higher in this test as compared to test 5. The absolute loss rate, however, is similar in these two tests, in the range 0.004–0.009 g/day. This similarity also indicates that water lost to the environment comes from the outer parts of the system, relatively independent of the moisture distribution in the slot.

The blocks showed significantly less damage at excavation as compare to test 5 (Figure 2-21). Although they showed some cracks, all blocks still held together. Note that a comparable total amount of water was added to this system as compared to previous tests. Thus, the rate at which water is being fed to the system strongly influence the damage that is done to the blocks.

No visible sign of water condensation was found on the top block or the top ring. However, the bottom ring showed the flaky pattern, significative for water condensation (right picture in Figure 2-21). Thus, condensation of vapor did occur also with restricted water supply.

The measured water-to-solid ratios, however, show no indication of water accumulation in the lower ring (Figure 2-22). The water was much more evenly and symmetrically distributed in this test as compared to test 5, but with a clear trend of increasing water-to-solid ratio with height (Figure 2-23). Also, in the lower parts, at trend of increasing water content with radius is distinguishable.

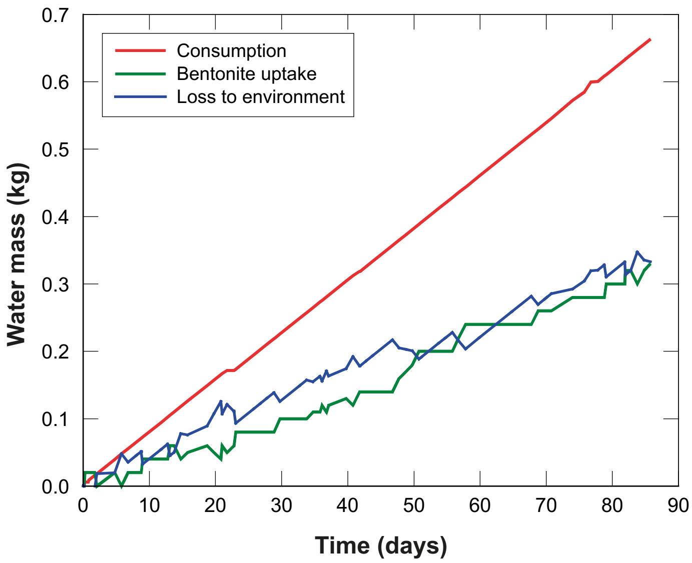

Figure 2-20. *Water consumption and uptake in test 6.*

Figure 2-21. *Excavation of test 6. Left: The top of the massive top block. Second to left: bottom side of the top block. Second to right: bottom side of the top ring. Right: top side of the bottom ring.*

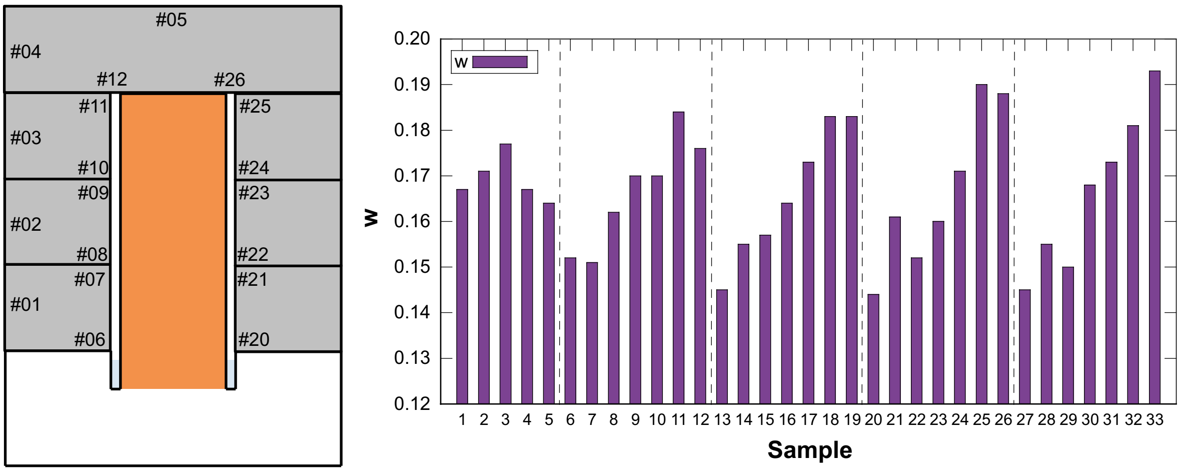

Figure 2-22. *Water-to-solid ratio (w) in samples taken during the excavation of test 6. The left figure shows the approximate positons of the samples. The samples not indicated in the left figure (Sample 13–19 and 27–33) represent the same type of vertical series as samples 06–12 and samples 20–26, but oriented perpendicular to the plane of the picture.*

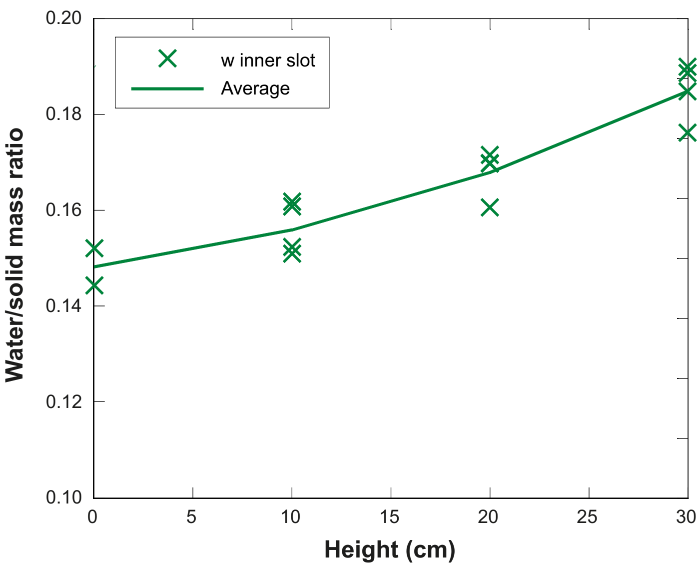

Figure 2-23. *Water distribution in the bentonite nearest to the inner slot in test 6.*

Combining the observations made at excavation, it must be concluded that (some) water have condensed in the lower ring, but either is this amount below detection level, or has the water been further transported (upwards) through the bentonite. Since inspection gave no visible evidence of condensation in the top part of the slot, the mechanism for the water accumulated in the top (e.g. vapor transport/condensation or transport in the bentonite) cannot be identified.

2.8 Test 7

The set-up of test 7 was similar to that of test 5 and test 6: Three bentonite rings stacked on top of each other, and a massive top block functioning as a lid over the inner slot (Figure 2-1). In this case the bottom ring and the top ring were "pre-cracked" by cutting them in half. The "cracks" at these two levels were oriented perpendicular to each other.

In test 7 a sequence of phases were conducted:

- A "dry" sequence – i.e. no water supply – with plastic mat on top of the set-up (identical with test 5 and test 6).
- A "dry" sequence with 20 cm pellets on top of the set-up (plastic mat removed).
- A "wet" sequence – i.e. free access to water – with pellets on top.
- A "wet" sequence with saline water (and pellets on top).

The water loss during the first sequence is plotted in Figure 2-24. During 16 days the system lost approximately 60 g of water to the environment. The loss rate is thus approximately 0.004 kg/day, similar to what was measured in tests 5 and 6. This observation confirms the conclusion that the loss of water is due to drying of the outer parts of the bentonite in this set-up, independent of the moisture distribution in the inner slot.

In the second phase of test 7 the plastic mat on the top of the set-up was removed and replaced by a 20 cm thick layer of bentonite pellets (MX-80), as pictured in Figure 2-25. The set-up was then continued to be run without water supply for 14 days. The loss of water during this period corresponded roughly to 0.01 kg/day (Figure 2-26). Hence, replacing the plastic mat with pellets gave an increase of the drying rate of a factor of ca 2.5.

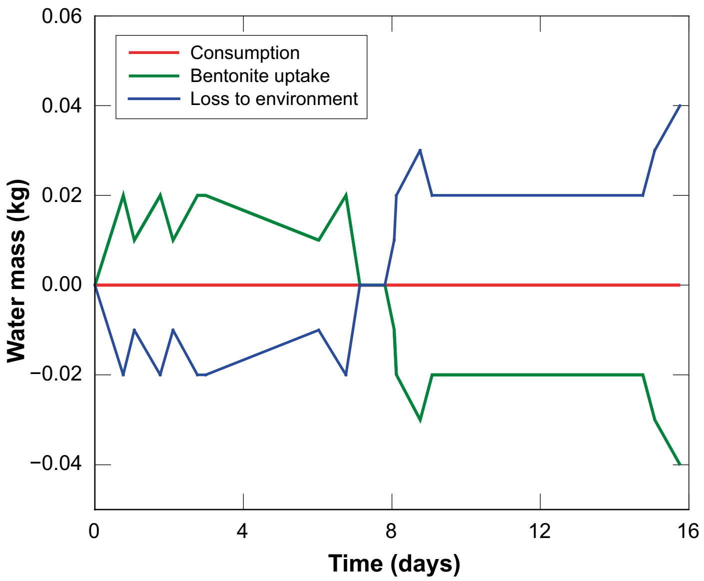

Figure 2-24. *Water consumption and uptake during the first phase of test 7. In this phase, no water was supplied to the system. The top was covered with a rubber mat at this stage.*

***Figure 2-25.** Test 7 with a 20 cm thick pellets filling replacing the rubber mat as top seal.*

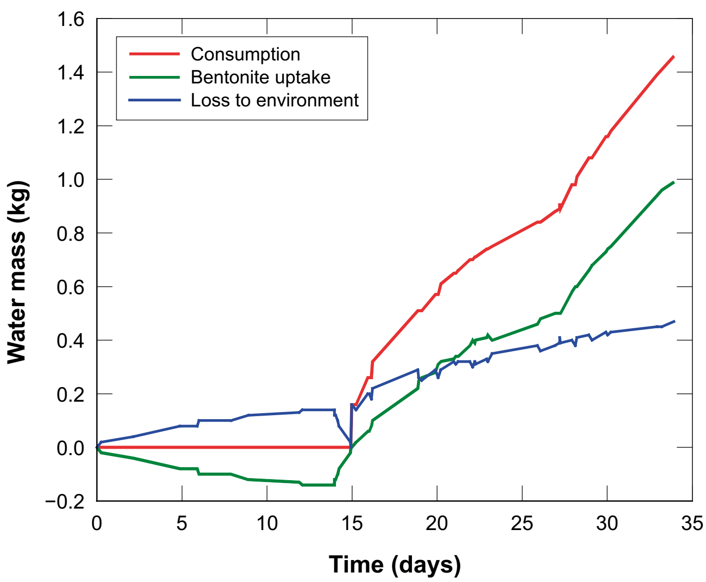

***Figure 2-26.** Water consumption and uptake during the second, third and fourth phase of test 7.*

During the third phase the system had free access to water, similar to test 5. Consequently, the bentonite started to increase its water content (Figure 2-26). The loss rate to the environment continued at basically the same rate as during the second phase. Again, this observation confirm the relative independence of water uptake and water loss using this set-up (which, in turn, indicates that the inner slot can be considered a closed system).

In the final stage of test 7, the tap-water used in all previous tests was replaced by a 0.6 M $CaCl_2$ solution. The presence of salt lowers water vapor pressure (at constant temperature). It could thus be expected that the water uptake rate should slow down as the system was given access to the $CaCl_2$ solution. On the contrary, however, the water up-take increased after changing waters (day 27). The increase is too large to be explained by the increased density of the salt solution.

A possible explanation for this behavior is that the salt solution actually got direct contact with the bentonite, i.e. that water was taken up in liquid form by the bentonite. An indication that this was the case is that the bottom ring had swelled inwards toward the copper tube to such an extent that it partly cracked when removed during excavation (Figure 2-27, bottom right).

The water distribution measured at termination is shown in Figure 2-28. In the pellets filling in the top was observed pellets of distinctly different color (Figure 2-27). These were seemingly distributed randomly throughout the filling. The average water content of two samples was 0.127 for the darker pellets and 0.106 for the lighter ones.

The massive top block showed cracks and a distinct condensation "nucleus", in very much the same way as the same type of block in test 5 (Figure 2-15). A comparison of the top rings in the two tests, on the other hand, showed less cracking damage in the present test (Figure 2-15 and Figure 2-27). The probable explanation is that less strain as a result of water uptake was induced in the ring of test 7 due to the pre-cracking.

The bottom ring had swelled massively. Similar to test 5, water was accumulated in the inner slot and in the outer part, with a dryer part in between. It may be speculated that the presence of a (pre-) crack enhanced the vapor transport from the inner to the outer part in this test.

The presence of saline water caused corrosion of the copper tube, as shown in Figure 2-27.

Figure 2-29 shows the water content measured in the inner slot as a function of height. Water was accumulated in the top and bottom.

This test thus mainly confirms the picture from test 5, that vapor can be transported significant distances before condensing.

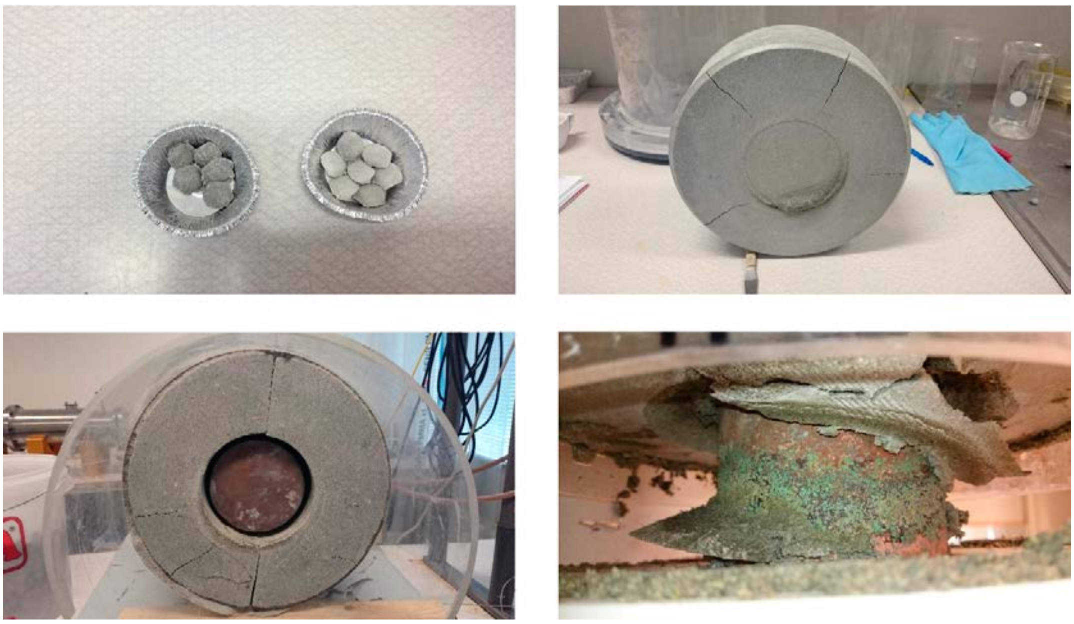

Figure 2-27. *Termination of test 7. Top left: Darker and lighter pellets found in the top. Top right: bottom side of the massive top block. A condensation "nucleus" is clearly seen, very similar to the observation in test 5. Bottom left: top side of the top ring. The pre-crack is located vertically in the picture. Bottom right: bottom side of the bottom ring separated from the bottom plate.*

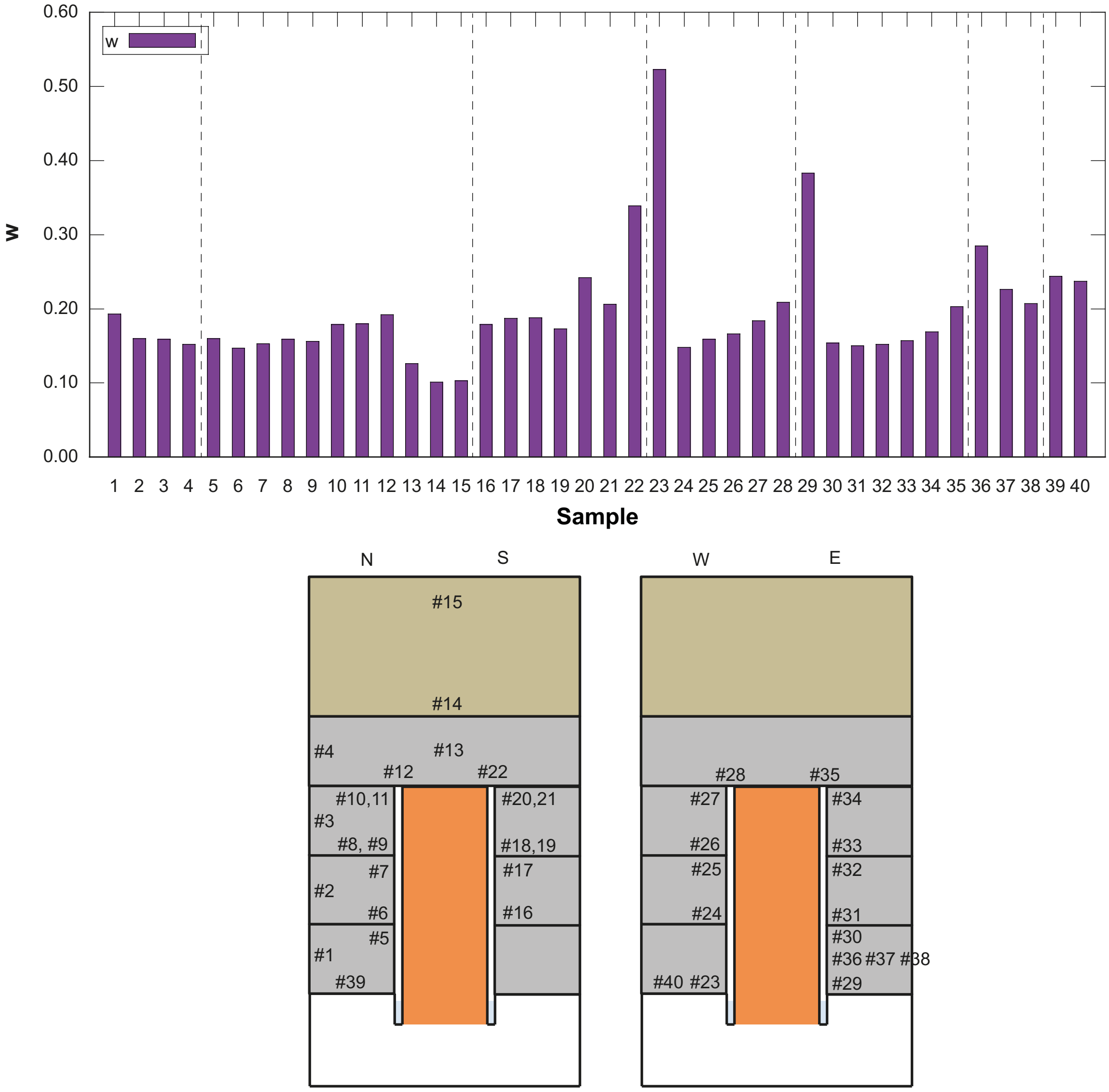

Figure 2-28. Water-to-solid ratio (w) in samples taken during the excavation of test 7. The lower figure shows the approximate positons of the samples.

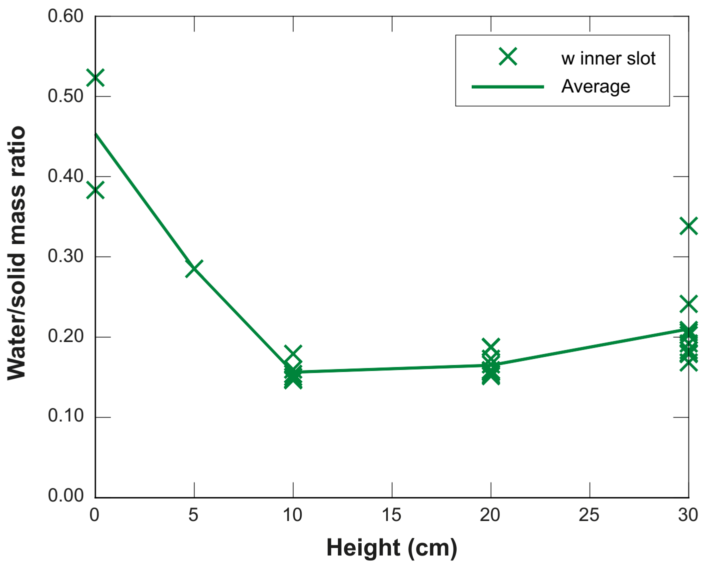

Figure 2-29. Water distribution in the bentonite nearest to the inner slot in test 7.

3 Conclusions

Transport and uptake of vapor in a slot between a heater and bentonite blocks have been studied in a set of tests. Vapor was shown to be able to be transported rather far in this type of slots without substantially being absorbed by the bentonite; a substantial amount of water was lost to the environment in tests where the slot was directly opened to the environment (tests 2 and 3). This behavior agrees with the observation of vapor transported in pellets fillings, where also major loss to the environment was observed under certain conditions (Birgersson and Goudarzi 2013). Notice that the (intial) water content in the bentonite in these tests are low (about 17 %) and the material thus have a huge affinity for taking up water – the water chemical potential in the dry bentonite corresponds to a "suction" on the order of 50 MPa. The present observations thus strengthen the conclusion that there appears to be a kinetic barrier for dry bentonite to efficiently take up water directly in vapor form (note, however, that bentonite do take up water in vapor form, as evident when e.g. recording retention curves (Dueck 2004)).

Rather than uniform water uptake directly from the vapor phase, the dominating mechanism of water uptake observed in this study is that of localized water condensation: as the present test set-up (as well as a KBS-3 repository) inevitably has variations of temperature and relative humidity, condensation of water vapor occurs locally and, to a certain degree, randomly in many of the tests. Once water have condensed somewhere in the system, more water uptake is promoted at the same position. This type of localized uptake was observed in the lower bentonite ring in several of the tests, as well as in the massive top block, in tests where such a block was present. The observation of water condensation in the massive top block is an additional proof that vapor may be transported relatively far before being taken up by the bentonite – in this case ca 30 cm. On the other hand, the observation also show that the presence of such top blocks – which is the case in the KBS-3 concept – effectively inhibits further vapor transport. Water condensation was also the observed dominating water uptake mechanism in the earlier studies made on pellets slots. It must thus be concluded that condensation phenomena are crucial to account for when vapor transport under these types of conditions are considered. Note that the tests performed did not demonstrate the actual sealing of an inner slot – to do that they must be conducted for much longer time periods.

As a consequence of localized water condensation, many bentonite rings did crack due to uneven swelling. In certain cases the cracking was severe. This type of cracking could potentially be expected in the early stages of the evolution of a KBS-3 repository, since localized water condensation seems to be a typical water uptake mechanism. The development of cracked blocks affected the present tests inasmuch as additional pathways for vapor were opened. In tests where the outer parts of the set-up was sealed with bentonite powder, it was however demonstrated that potential vapor lost from these pathways were negligible. Note, however, that this observation does not imply that an outer pellets slot in a KBS-3 repository necessarily will function in the same way.

One test was performed in which the water consumption was restricted by approximately one order of magnitude as compared to having full water access. Also under such a condition did water condensate locally, as revealed by visual inspection (in the bottom bentonite ring). In this case, however, no increased water content was measured at the condensation point. It is unclear whether this is because the amount of water taken up in this way was small, or whether the condensed water had continued to be transported through the bentonite. The general trend observed in this particular test was an increased water content at higher positions of the set-up. The less "violent" water consumption in this test also caused much less block damage.

Less block damage was also observed in a performed with pre-cracked blocks (but with full water access). Pre-cracked blocks may thus be worth considering if uncontrolled block cracking is wished to be avoided.

References

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Dueck A, 2004. Hydro-mechanical properties of water unsaturated sodium bentonite: laboratory study and theoretical interpretations. PhD thesis. Lund University.

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Appendix A

Sample masses

Table A-1. Total mass (solid+water) of samples taken in test 4–7. Unit is gram.

Sample no.	Test 4	Test 5	Test 6	Test 7
1	21.90	76.51	49.29	60.86
2	31.92	85.89	48.08	61.72
3	17.24	81.94	59.57	15.28
4	21.80	86.18	53.29	19.67
5	27.20	51.00	34.69	33.72
6	36.44	51.16	36.56	37.23
7	32.54	56.53	28.75	22.47
8	29.76	60.21	27.74	34.23
9	51.29	54.38	37.99	35.25
10	32.80	54.52	28.07	31.34
11	58.92	46.83	29.07	42.45
12	34.89	49.91	28.51	39.90
13	43.34	61.04	41.16	45.91
14	45.42	58.15	30.43	40.95
15		48.80	35.46	42.37
16		55.02	17.90	38.71
17		37.22	25.89	42.68
18		63.05	50.85	43.20
19		33.73	22.49	41.85
20		36.99	27.63	28.47
21		37.94	49.14	45.16
22		39.78	36.42	35.80
23		39.29	35.06	25.19
24		36.88	35.34	34.16
25			47.46	33.96
26			36.37	33.68
27			60.16	39.01
28			38.55	42.08
29			41.43	46.27
30			31.53	43.49
31			42.34	49.02
32			33.38	57.02
33			44.83	61.51
34				52.61
35				41.18
36				37.73
37				59.16
38				82.37
39				41.17
40				28.43
41				32.34
42				33.68
43				39.74

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