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Piping and erosion in buffer and backfill materials

Current knowledge

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Abstract

The water inflow into the deposition holes and tunnels in a repository will mainly take place through fractures in the rock and will lead to that the buffer and backfill will be wetted and homogenised. But in general the buffer and backfill cannot absorb all water that runs through a fracture, which leads to that a water pressure will be generated in the fracture when the inflow is hindered. If the counter pressure and strength of the buffer or backfill is insufficiently high, piping and subsequent erosion may take place.

The processes and consequences of piping and erosion have been studied in some projects and several laboratory test series in different scales have been carried through. This brief report describes these tests and the results and conclusions that have emerged. The knowledge of piping and erosion is insufficient today and additional studies are needed and running.

Sammanfattning

Vatteninflödet i deponeringshålen och tunnlarna i ett slutförvar sker i huvudsak genom sprickor i berget och medför att buffert och återfyllning beväts och homogeniseras. Men i allmänhet kan inte bufferten eller återfyllningen absorbera allt vatten som koncentrerat rinner genom en spricka varför ett vattenövertryck bildas när innflödet hindras. Om inte mottrycket och hållfastheten i buffert eller återfyllnad är tillräckligt stora kan pining med åtföljande erosion uppstå.

Processerna och konsekvenserna i samband med piping och erosion har studerats i några projekt, varvid ett flertal laboratorieserier i olika skala har genomförts. I denna korta rapport beskrivs sammanfattande de försök som har utförts och de resultat och slutsatser som framkommit. Kunskapen är idag otillräcklig och fler studier behöver utföras och pågår.

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1 Introduction

Water inflow into the deposition hole and the deposition tunnel will take place mainly through fractures and will contribute to the wetting of the buffer and backfill. However, if the inflow is localized to fractures that carry more water than the swelling buffer or backfill can adsorb, there will be a water pressure in the fracture acting on the filling material. For the buffer and some of the backfill concepts there is a slot between the rock and the buffer/backfill that is either empty or filled with pellets. This means that the swelling bentonite is a gel in the beginning of the wetting, which increases its density with time as the water goes deeper into the bentonite. This gel is usually too soft to stop the water inflow. The results may be piping in the bentonite, formation of a channel and a continuing water flow and erosion of bentonite slurry. For the in situ compacted backfill the total pressure on the rock wall may be too small to withstand the increasing water pressure and the result will be similar.

Piping and erosion are studied in conjunction with studies for the KBS-3H concept and in the Baclo project.

Piping and the ability of the bentonite to seal have mainly been studied in the KBS-3H project. One report with tests done up to 2004 has been published /Börgesson et al. 2005/. The work after 2004 has not yet been published but is referred to as /Sandén and Börgesson 2006b/.

Erosion and related processes have mainly been studied in the Baclo project. One report has been written and is going to be published /Sandén and Börgesson 2006a/.

The processes of piping and erosion are important for the understanding and assessment of the initial period of the repository before full water saturation and pore water pressure equilibrium has been reached. This brief report will summarize the present knowledge of the processes and the tests done so far.

2 Processes

The piping and the erosion are different processes but are closely linked.

Piping may take place and the pipes remain open if the following conditions are fulfilled:

1. the water pressure pwf in the fracture is higher than the sum of the counteracting total pressure from the clay and the shear resistance of the clay, when the water flow is prevented by either the swelling bentonite or the compacted backfill,
2. the hydraulic conductivity of the clay is so low that water flow into the clay is sufficiently stopped to keep the water pressure at pwf and keep a high hydraulic gradient in the clay,
3. there is a downstream location available for the removal of eroded materials in order for the pipe to stay open.

Erosion will take place if the drag force on the clay particle from the water movement is higher than the sum of the friction and attraction forces between the particle and the clay structure.

The consequence of the piping will be a channel leading the flowing water out to dry or unfilled parts of the repository. Since the clay swells the channel will reduce in size with time but on the other hand the erosion will counteract and tear off bentonite particles and thus increase the size of the channel. There is thus a competition between swelling clay and eroding clay. If the inflow is low and the increase in water pressure slow the pipe may seal before water pressure equilibrium has been reached.

After completed water saturation and homogenisation of the buffer and backfill and re-establishment of the hydrostatic water pressure the water pressure will be separated from the swelling pressure according to the effective stress theory. The pipes or openings caused by the erosion will thus be healed and a swelling pressure established if the density and resulting swelling pressure are high enough to overcome the internal friction. Later on there is very little risk of piping since piping requires a strong and fast increase in water pressure gradient locally in the rock at the contact with the buffer or backfill.

A process that may prevent the piping and water flow from spreading is a combined compression and valve formation of the clay. When the unsaturated clay is compressed by the water pressure the density increases and the total stress in the compressed clay increases. This in turns increases the frictional forces and if the resistance can be as high as the water pressure there will be no break through of water. This process either requires a very thin slot where valve formation can take place or a material that may be compressed in combination with a favourable geometry. The compression of clay will thus also create an opening before the water inflow is stopped. There is thus another process involved, which could be named "hydraulic compaction". It will only take place in unsaturated materials.

The processes involved in the piping and the erosion are complicated and not very well known. Today they cannot be modelled in a relevant way.

The ability of the bentonite to stop water inflow from a fracture and thus prevent piping and erosion depends on a number of factors and variables, the following being the most important:

Bentonite properties:

- Actual swelling pressure from the bentonite.
- Swelling properties.
- Water content.
- Shear strength and friction of the bentonite.
- Hydraulic conductivity.
- Compressibility.
- Degree of saturation.

Geometry:

- Width of slot with low bentonite density.
- Availability of free space for water collection.

Rock hydrology:

- Water inflow rate.
- Connectivity with other fractures.
- Water pressure increase rate when water flow is stopped.
- Maximum water pressure.
- Water chemistry (salt content).

The vulnerability of buffer and backfill materials to piping and erosion has been investigated in the laboratory regarding the influence of several of those factors.

3 Scenarios

Depending on the material, the geometry and the rock hydrology the scenario of events at the contact between a fracture and the buffer or backfill may be different.

Pellets filling in the slot between the bentonite blocks and the rock surface

In the main KBS-3V concept the slots between the rock and the bentonite blocks in the deposition holes and between the rock and the blocks in the deposition tunnel will be filled with bentonite pellets. Since the slots filled with pellets are rather large (about 5 cm in the buffer and about 0.5 m in the backfill) the time for the swelling blocks to fill the slot with a bentonite with high enough density in order to stop the water inflow will be very long (several months to several years). In addition, the density of the pellets alone is too low, so the water inflow may not be stopped. This means that the inflow of water into the slot with pellets may continue and the wetting of the pellets will create a gel, spreading to a large part of the slot. An increasing part of the pellets filled slot may be filled with water until the flow path leaves the slot and either enters the backfill or spreads to the neighbouring section of the deposition tunnel.

Laboratory tests on pellets fillings have shown that the water tends to move downwards when the water inflow rate is high ($q \geq 0.1$ l/min), while it tends to move upwards when the water inflow rate is low or ($q \leq 0.01$ l/min) /Sandén and Börgesson 2006a/. It is thus likely that the pellets filled slot in a deposition hole will be filled with water at high water inflow rate but not at low. At low water inflow rate the upwards water movement may instead cause the water flow to leave the deposition hole.

The water flow may not stop but continue during a long period until a tight plug has been built at the end of the deposition tunnel and the slots at the rock surface have been filled with water. The flow will in large parts take place in channels that may transport bentonite through erosion (treated later).

Sealing arrangement on top of the deposition holes

In order to prevent that water flows out of the deposition hole an arrangement that resembles the arrangement proposed for the distance blocks in KBS-3H may be applied at the top of the deposition hole. Such an arrangement could be to use a very good fit of the upper bentonite block (a slot of only a few mm) and a supporting ring that covers the peripheral part of the deposition hole and is fixed to the rock floor. With such an arrangement the slot that needs to be closed by the swelling bentonite is small enough to be self sealed according to tests done for KBS-3H. Such type of arrangement could thus prevent piping and erosion from the deposition hole into the tunnel.

Slot without pellets filling between the bentonite blocks and the rock

An alternative design that has been proposed and may be used in some deposition holes is to have a smaller slot (~3 cm) between the blocks and the rock surface and no pellets in the slot. Such an arrangement could also be used in the deposition tunnel but with a much larger slot.

The consequences of water inflow at such an arrangement will be very similar to when pellets is applied in the slot. If the water inflow is rather high the slot may be too wide to be able to seal and the slot will be filled with water before the water pipes out into the tunnel.

A similar arrangement with a sealing ring on top of the deposition hole can also be used and will improve the situation.

In situ compacted backfill

If in situ compaction is used for the backfilling the situation will be different but the swelling pressure of neither 30/70 bentonite/sand mixtures nor in situ compacted Friedland clay is high enough to prevent piping. Most likely there will be channels between the backfill and the rock that will spread along the rock surface from the inflow points if the inflow rate is high enough. The limit were the backfill can absorb the inflowing water without channelling is not known but probably rather low. This process will accelerate the wetting process rather much and piping may also go into the inner parts of the backfill. The piping is expected to continue until almost full saturation is reached and further water flow out from the backfill is stopped by a tight plug.

4 Experimental studies of piping phenomena

The piping tests have been done in three different scales. The results show that the bentonite is very sensitive to piping and erosion and that it may take a considerable time until it heals if the inflow in one spot from a fracture is strong and the build-up of water pressure in the fracture is fast.

Basic laboratory tests in small scale

A large number of tests were performed with samples with 5 cm diameter and 10 cm length /Börgesson et al. 2005/. The work was mainly focused on understanding the process in which the swelling in the bentonite is competing with the eroding water. The main purpose of the tests was to find the levels of water pressure and water flow at which the bentonite is sealed and the water flow is stopped.

The tests were divided into two main types, *flow-controlled* and *pressure-controlled*. In the flow-controlled tests, the water flow was held at a constant level by use of a GDS in such a way that the water pressure is increased to 1 MPa in 10 minutes if the flow is stopped by the sealing ability of the bentonite. In the pressure-controlled tests, the water pressure was held at a constant level by use of gravity.

Figure 4-1 shows the design of the test equipment. Water was forced to flow in a pre-bored hole with the diameter 2–4 mm. In an alternative design there was a slot between the sample and the steel ring instead of a pre-bored hole. Figure 1 also shows the consequences of piping. A pipe has been formed along the sample in a test with the alternative design.

The following parameters were varied: channel diameter (2 and 4 mm), salt content of water (0 and 1%), sample length, water flow rate and water pressure. The density and water ratio of all samples were ~2,000 kg/m^3 and ~17%. The results are summarised in Figure 4-2, which shows the water pressure as a function of the flow rate and the combinations that yielded sealing. For the flow controlled tests no sealing was reached at flow rates >0.001 l/min and for the pressure controlled tests no sealing was reached at a water pressure >4 kPa.

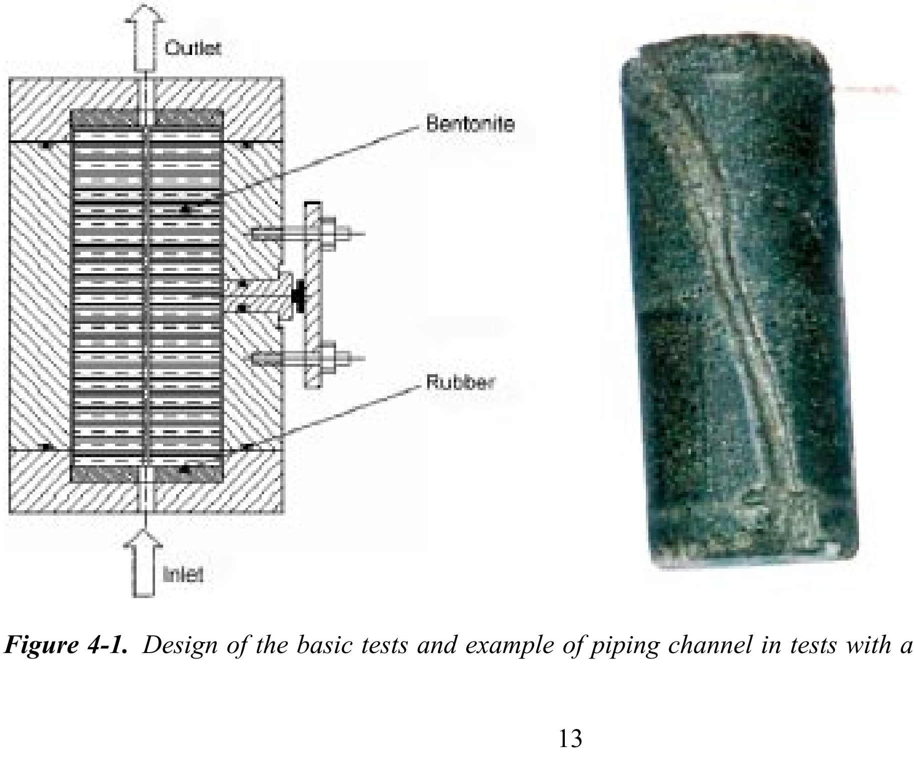


Figure 4-1. *Design of the basic tests and example of piping channel in tests with an outer slot.*

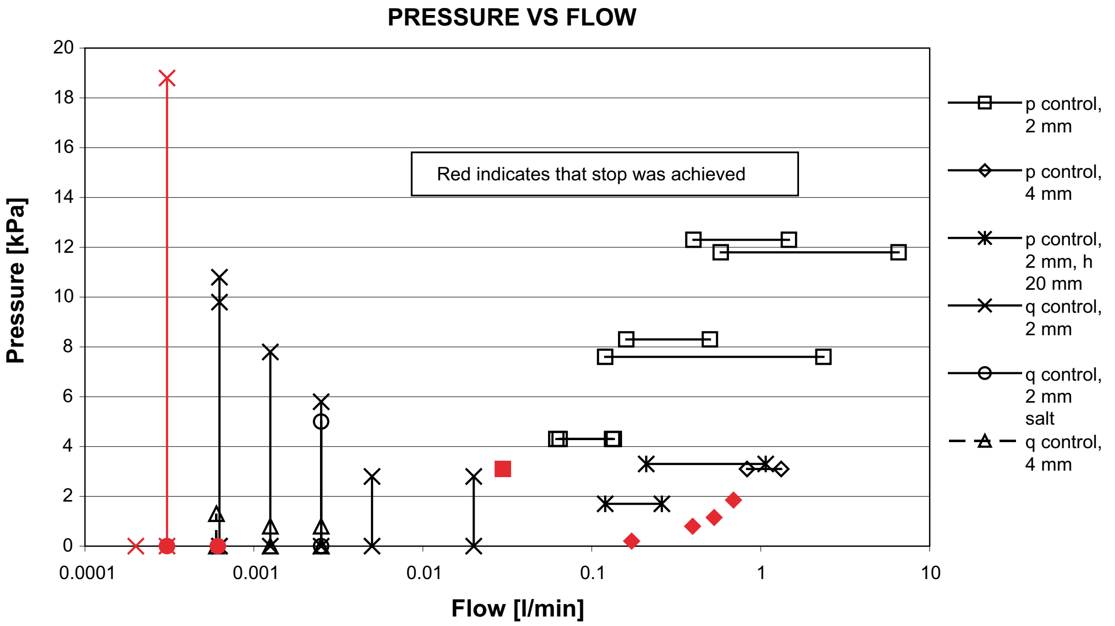


Figure 4-2. *Results from the small scale tests. All results with a flow rate >0.4 l/min are pressure controlled (constant water pressure and measured flow rate) while all results with flow rate <0.4 l/min are flow controlled (constant flow rate and measured water pressure).*

Sealing tests in scale 1:10

The sealing of the distance blocks in KBS-3H has been investigated in several tests with the diameter scaled 1:10. The reason for increasing the test scale from the basic tests was that the processes are complicated and require actual geometries and scenarios.

Three test series have been run. In these tests series the geometry of a distance block section with surrounding rock was modelled and inflow of water to the super container section was scaled. An inflow of between 0.01 l/min and 1.0 l/min was simulated by using the same time for filling up the free space of the super container section with water as the corresponding water inflow would yield in real scale. Figure 4-3 shows the test set-up exemplified by the set-up for test series 3. The tests were done in the following steps:

1. Filling of the super-container section with water (1–10 days depending on the simulated water inflow rate).
2. Start increasing the water pressure at a preset pressure increase rate (0.1–1.0 MPa/h in most tests) until the water pressure 2–5 MPa was reached.
3. Measurement of water inflow and water pressure in the super container section and measurement of total pressure on the periphery of the distance blocks and measurement of forces on the outer surface of the distance block.
4. Careful examination of the bentonite after completed test.

Figure 4-4 shows an example of measured results from a test. The super container section was filled in 1 day. Then the water pressure was increased. The figure shows that the distance block sealed the water pressure 5 MPa but the figure also shows that the swelling pressure (measured total pressure) in the slot was very low when the water pressure was applied. Then the measured total pressure increased concurrently with the increase in water pressure and decreased in a similar way after the water pumping was stopped. This shows that it is not the swelling pressure that seals but a pressure related to the water pressure.

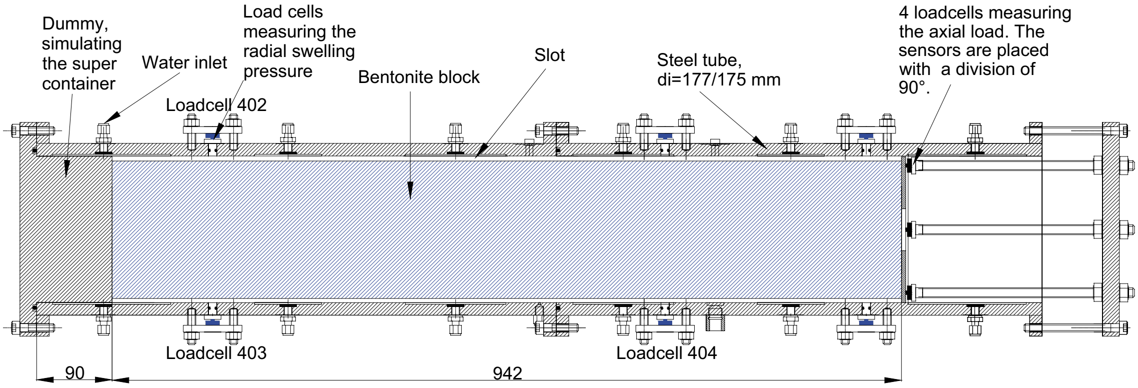
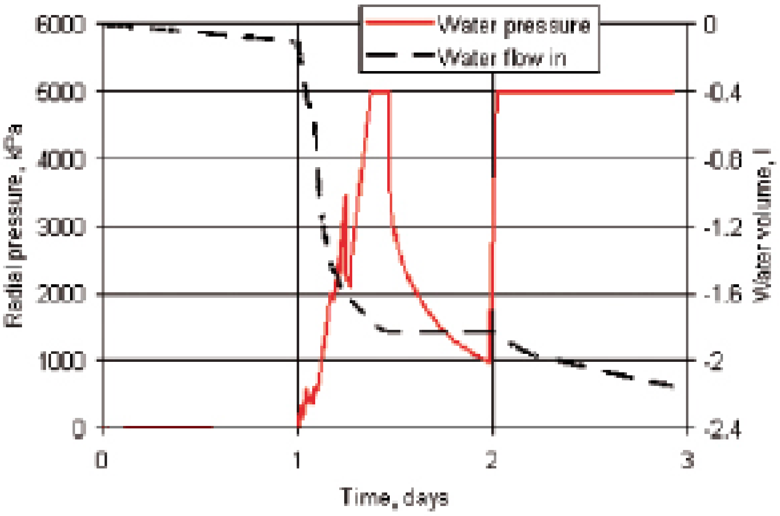


***Figure 4-3.** Equipment used for the sealing tests in scale 1:10 for KBS-3H (test series 3).*



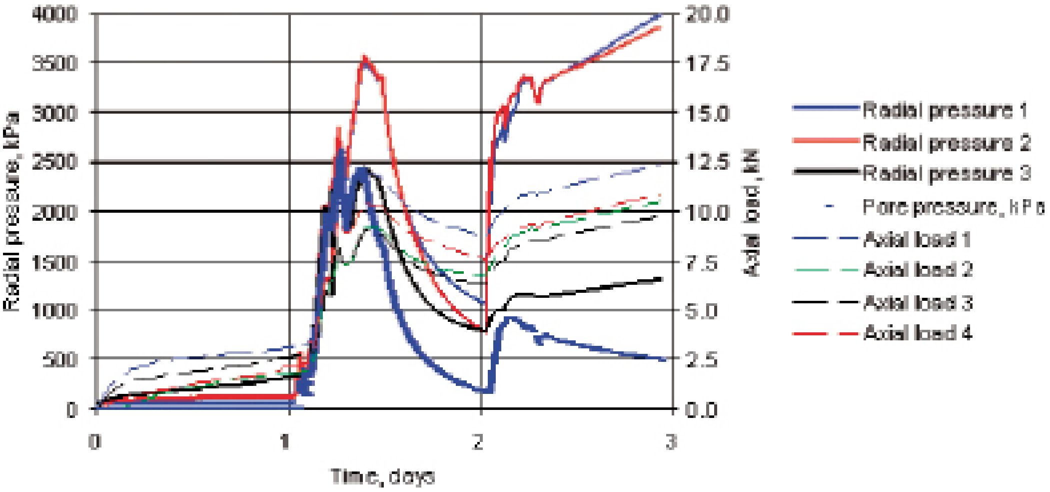


***Figure 4-4.** Results from a sealing test in the scale 1:10 with 5 mm slot all around the distance block. The upper diagram shows the measured inflow and the applied water pressure in the super-container section. After 1 day a pressure ramp of 1 MPa/h was applied. The distance blocks could resist 5 MPa water pressure. The pressure equipment run out of water but was refilled the following morning. The lower diagram shows the measured swelling pressure and the measured axial loads.*

Sealing tests in large scale

One laboratory test series in large scale has also been run. Bentonite blocks with the diameter ~0.8 m and thickness 0.35 m have been enclosed in a test equipment similar to the 1:10 scale test equipment and similar tests have been performed. Six tests have been reported by /Börgesson et al. 2005/. They confirm the results from the 1:10 scale tests.

Field observations

The piping phenomena have been observed in two field tests in Äspö HRL (LOT and the full scale test LASGIT). In LASGIT the flow rate was about 0.1 l/min, which yielded an erosion rate of about 1 g/l that remained for almost 2 months before the leakage was stopped in an artificial way.

Conclusions and observations

The piping and sealing tests have yielded interesting knowledge of the sealing and piping problems but have also shown the complexity of the processes. The following conclusions have been made so far:

- Except for the swelling properties of the bentonite the following factors seem to be the most important ones for the sealing ability:
  - Geometry.
  - Water inflow rate.
  - Water pressure increase rate at stopped water flow.
- Pellets filling or bentonite gel does not have high enough resistance to piping unless the water pressure is very low or the geometry is favourable.
- It takes long time until a swelling pressure high enough to withstand the expected high water pressure in fractures is generated, which means that for the installation phase that process will probably not be able to stop piping and erosion.
- It seems that there is another process that stops piping, namely a clogging and compression of particle or pellet assemblies in narrow geometries, which in combination with the valve effects and friction between walls hinder water from penetrating.
- Once an open pipe that leads water has been formed it is very difficult for the bentonite to stop the water flow. It requires either that the flow temporarily is stopped so that the bentonite have time to swell and seal or that both the flow rate and the water pressure increase rate are slow enough.

5 Experimental studies of erosion phenomena

The following erosion test types have been performed so far or are on-going:

- Measurement of erosion in the basic laboratory tests in small scale.
- Water flow along bentonite blocks.
- Water flow in tubes filled with bentonite pellets (see Figures 5-1 and 5-2).
- Water flow in a slot filled with pellets.

In these tests the amount of eroded water has been measured at different times. The flow rate (0.001–1 l/min), the salt content of the eroding water (0–3.5%) and the length of the bentonite filling (0.1–3 m) have been varied. The results have yielded the following conclusions and observations:

- The erosion expressed as weight of eroded clay divided to the volume of eroding water is a useful definition.
- The erosion decreases with time. The accumulated eroded mass plotted as a function of the accumulated water flow is close to a straight line in a double logarithmic diagram and has an inclination less than 1.0 as shown in the example in Figure 5-1.
- The erosion can be rather high in the beginning of a test but always ends lower than 10 g/l if sufficient time is allocated. 1 g/l was observed in the leaking water in LASGIT.
- The erosion seems to be higher for saline water than for non-saline water.
- The erosion seems to increase with erosion length although this trend is not very unambiguous.
- No clear influence of water flow rate on the erosion expressed as weight of eroding material divided to the volume of the eroding water has been observed.

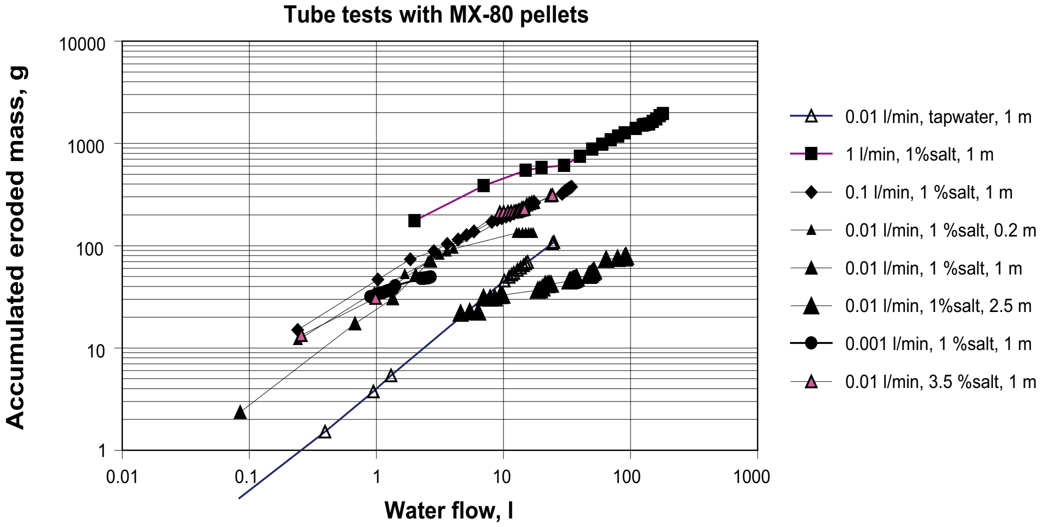


Figure 5-1. Measured accumulated eroded mass plotted as a function of the accumulated water flow for the tests on pellets in a Plexiglas tube.

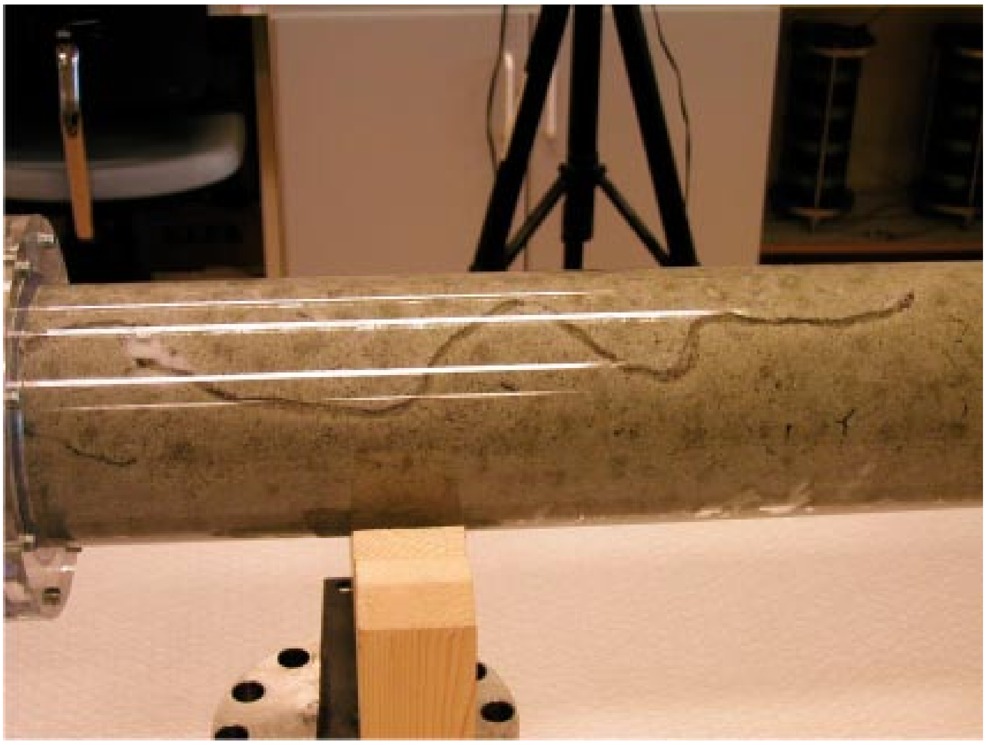


Figure 5-2. *Photo of one of the erosion test on pellets in a Plexiglas tube. Salt content: 1%. Flow rate: 0.1 l/min.*

6 Final remarks

Piping, erosion and subsequent sealing is a complicated process with many components, which are much depending on the hydraulic behaviour of the rock. The uncertainties are considerable regarding both the influence of the rock hydrology and the ability of the buffer to resist these processes. For the KBS-3H concept, a preliminary demand is that one canister position must be able to handle the inflow 0.1 l/min and a pressure increase of the water pressure in a fracture intersecting the tunnel of 100 kPa increase per hour. This could thus be transferred to demands on the deposition hole, but it is not obvious that the demands should be equal. Furthermore, the time required for the buffer to seal such an inflow from a fracture is not known.

The knowledge of when piping and erosion occur and the consequences are not enough known today. Further tests are ongoing and planned.

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