R-08-135

Deep repository-Engineered barrier system

Erosion and sealing processes in tunnel backfill materials investigated in laboratory

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Keywords: Buffer, backfill, piping, erosion, relative humidity.

Abstract

SKB in Sweden and Posiva in Finland are developing and plan to implement similar disposal concepts for the final disposal of spent nuclear fuel. Co-operation and joint development work between Posiva and SKB with the overall objective to develop backfill concepts and techniques for sealing and closure of the repository have been going on for several years.

The investigation described in this report is intended to acquire more knowledge regarding the behavior of some of the candidate backfilling materials. Blocks made of three different materials (Friedland clay, Asha 230 or a bentonite/ballast 30/70 mixture) as well as different bentonite pellets have been examined. The backfill materials will be exposed to an environment simulating that in a tunnel, with high relative humidity and water inflow from the rock. The processes and properties investigated are:

1. Erosion properties of blocks and pellets (Friedland blocks, MX-80 pellets, Cebogel QSE pellets, Minelco and Friedland granules).
2. Displacements of blocks after emplacement in a deposition drift (Blocks of Friedland, Asha 230 and Mixture 30/70).
3. The ability of these materials to seal a leaking in–situ cast plug cement/rock but also other fractures in the rock (MX-80 pellets).
4. The self healing ability after a piping scenario (Blocks of Friedland, Asha 230 Mixture 30/70 and also MX-80 pellets).
5. Swelling and cracking of the compacted backfill blocks caused by relative humidity.

The erosion properties of Friedland blocks were also investigated in Phase 2 of the joint SKB-Posiva project "Backfilling and Closure of the Deep Repository, BACLO, which included laboratory scale experiments. In this phase of the project (3) some completing tests were performed with new blocks produced for different field tests. These blocks had a lower density than intended and this has an influence on the erosion properties measured. The erosion properties of MX-80 pellets were also investigated earlier in the project but an additional test series have been performed. These additional tests examined the influence of fine clay material mixed with the pellets, a topic not previously examined. These tests showed that the powder had strong influence on the erosion rate during the first 24 hours of water flow but after that time period the erosion rate was unaffected by the presence of fines.

The investigation of how backfill blocks move when water enter slots between them produced predictable results. Two types of tests were performed; in one the displacement was measured and in the other the development of swelling pressure as physically constrained blocks attempted to separate was monitored.

In the course of these tests the influence of the initial slot width is determined to be very strong. The majority of the tests were done using Friedland clay blocks. In these tests water influx to a small initial slot resulted in rather large movements, with deformation starting immediately. A large initial slot resulted in smaller overall movement with deformation not starting until about 1.5–2 days after test start. Tests done using Asha 230 behaved in a manner similar to the Friedland blocks, but those made of the 30/70 mixture showed no movement.

The self-sealing ability of MX-80 pellets was tested and showed that a water flow of 0.01 l/min and 0.1 l/min through a volume filled with MX-80 pellets will result in transport of fine material within the water and these fines subsequently swell and seal slots with an aperture up to 150 μm.

The sealing ability of a saturated backfill after a simulated piping scenario was also tested. After three weeks of healing of an intentionally installed piping feature that had been given access to water, the hydraulic conductivity was measured again. The specimens made of Friedland and Asha 230 showed a very strong ability to seal the hole while the 30/70 mixture couldn't seal the drilled hole at all. MX-80 pellets installed at a dry bulk density approximating that achievable in a backfilled tunnel were also tested. At this density the specimens had not healed adequately in three weeks and were unable to withstand renewed water percolation along the defect.

Experiments where compacted backfill blocks (in small scale) were exposed to a high relative humidity for three months were also performed. During the tests the water uptake from the air humidity was measured and stability of the blocks was monitored. Compacted blocks were found to be very sensitive to the air humidity and prone to cracking if relative humidity is not in balance with the suction within the blocks.

Sammanfattning

SKB i Sverige och Posiva i Finland, utvecklar och planerar för liknande förvars koncept för slutförvaret av utbränt kärnbränsle. Ett samarbete och gemensamt utvecklingsarbete mellan Posiva och SKB med målet att utveckla backfill koncept och teknik för att täta och försluta ett förvar pågår sedan flera år.

Undersökningen som beskrivs i denna rapport syftar till att ge mer kunskap när det gäller hur några av de aktuella backfillmaterialen reagerar när de utsätts för de förhållande som råder i en deponeringstunnel med hög relativ fuktighet och vatten inflöde. Följande problemområden har undersökts:

1. Erosionsegenskaper för block och pellets (Friedland block, MX-80 pellets, Cebogel QSE pellets, Minelco och Friedland granuler).
2. Rörelser hos block efter inplacering i en deponeringstunnel (Block av Friedland, Asha 230 och Mixture 30/70).
3. Materialens kapacitet att täta en läckande plugg cement/berg eller andra sprickor i berget (MX-80 pellets).
4. Materialens självläkningförmåga efter ett pipingscenario (Block av Friedland, Asha 230, Mixture 30/70 och MX-80 pellets).
5. Svällning och sprickbildning hos backfillblock genom upptag av fukt från omgivande luft.

Erosionsegenskaperna hos block av Friedlandlera undersöktes också i fas 2 av Bacloprojektet men några kompletterande undersökningar har gjorts på block från den storskaliga produktionen på Bjuv. Dessa block hade en lägre densitet än den avsedda vilket visade sig påverka erosions-egenskaperna. Erosionsegenskaperna hos MX-80 pellets har också undersökts tidigare i fas 2 av projektet men ytterligare tester har gjorts för att närmare studera hur mängden fint material blandat med pelletsen påverkar resultaten. Försöken visade att det lösa materialet hade en stark inverkan på erosionshastigheten under de första 24 timmarna men sedan var erosionshastigheten ungefär densamma som för proven utan löst material.

Undersökningen av hur block rör sig efter inplaceringen när vatten tränger in mellan spalterna gav mycket logiska resultat. Två typer av försök gjordes; antingen mättes deformationen eller så mättes den uppbyggda kraften. Huvuddelen av dessa försök gjordes med block av Friedlandlera. En liten initial spalt (0–0.5 mm) resulterade i stora rörelser, över 7 mm, som startade omedel-bart, medan en större initial spalt (5mm) medförde relativt små rörelser, ungefär 2mm, som inte började förrän efter ca 1.5–2 dygn. Block tillverkade av Asha materialet uppförde sig ungefär på ett liknande sätt medan blocken gjorda av 30/70 blandningen inte rörde sig alls.

Förmågan att täta sprickor testades i en speciell utrustning med en artificiell spalt som kunde ställas till olika sprickvidder. Försöken visade att vatten som strömmar genom en volym fylld med MX-80 pellets transporterar med sig fint material som sväller och tätar sprickor med en vidd upp till 150 µm. Försöken gjordes med vattenflöden på 0.01 l/min och 0.1 l/min.

Läkningsförmågan hos det vattenmättade backfill-materialet efter ett tänkt piping-scenario testades också. Efter att den hydrauliska konduktiviteten hos de mättade proven hade bestämts avmonterades de och ett hål borrade rakt igenom provet. Efter montering fick proven återigen tillgång till vatten under en treveckors läkningsperiod varefter den hydrauliska konduktiviteten bestämdes igen. Proven av Friedland och Asha 230 visade en stark förmåga att självläka medan 30/70 blandningen överhuvudtaget inte läkte. Prov av MX-80 pellets testades också. Dessa var satta till en densitet motsvarande den torra bulkdensiteten hos en fyllning, ungefär 980 kg/m^3. Denna densitet är låg och proven lyckades inte att läka helt under en 3 veckors period.

Experiment har också gjorts med kompakterade backfill block som har utsatts för hög relativ fuktighet under lång tid, ungefär tre månader. Under försökstiden vägdes proven med bestämda intervall för att kunna bestämma vattenupptaget och dessutom studerades eventuell sprickbildning. Försöken visade att blocken är känsliga för den omgivande luftfuktigheten. Ett sätt att lösa problemet kan vara att öka den initiala vattenkvoten hos blocken, vilket gör dem mer okänsliga för en hög relativ fuktighet.

Contents

1 Introduction

The investigations performed in this subproject belong to the third Phase of the joint SKB-Posiva project "*Backfilling and Closure of the Deep Repository, BACLO*". The overall objective of the BACLO project is to develop backfilling concepts for the deep repository that can be configured to meet SKB's and Posiva's requirements in the chosen repository sites. The project was divided into four Phases, of which two have already been performed:

- Phase 1: Desk studies to identify and select preferred concepts for further studies. This Phase has been completed.
- Phase 2: Laboratory scale experiments and more profound analyses to study the preferred concepts and for selection of very few main alternatives.
- **Phase 3: Pilot tests with temporary equipment to verify engineering feasibility of the main alternatives and for qualifying methods for showing compliance.**
- Phase 4: Large scale field-tests – overall verification and dress rehearsal of non-nuclear operation.

The third Phase of the BACLO project started in the beginning of 2006. The project is divided into several subprojects comprising of following type of activities:

- Laboratory investigations.
- Technical development, design and investigations.
- Large-scale tests on feasibility.
- Analysis and reporting of the performed work.

A number of uncertainties concerning the block backfill concept were identified in the second phase of the Baclo programme. The work described in this report was planned to study processes taking place during the installation and early saturation phase of the tunnel backfill. The objectives of the work are to study:

- Erosion properties of blocks and pellets.
- Displacement of blocks after emplacement.
- Self healing ability of piping channels.
- Sealing ability of gaps and fractures.
- Effect of relative humidity on swelling and cracking of compacted blocks.

This report deals with parts of the subproject "Laboratory investigations".

2 Performed tests

2.1 General

Backfilling of deposition tunnels is planned to be done by emplacement of pre-compacted blocks of bentonite, see Figure 2-1. The blocks will be piled, filling up about 75–80% of the tunnel volume. The remaining space between blocks and rock is to be filled with bentonite pellets. During and after emplacement of blocks and pellets a number of scenarios can develop due to water inflow from the rock. These scenarios will affect the materials and perhaps also the functioning of the backfill material. A number of critical issues have been identified and investigated.

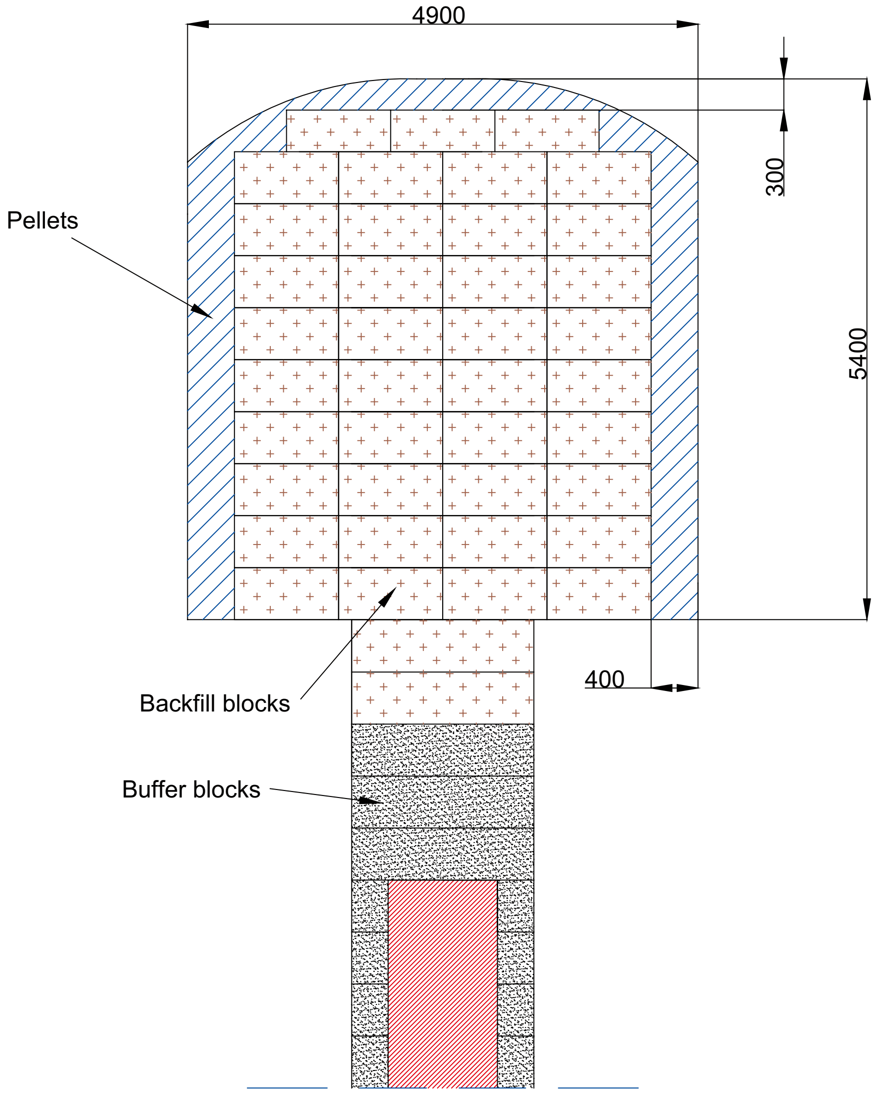


Figure 2-1. Schematic drawing showing an example of the geometry of a deposition tunnel backfilled with blocks and pellets.

2.2 Test types

The investigations performed in this subproject belong to Phase 3 of the BACLO project. In Phase 2 a number of different test types were used in order to study the behavior of the backfill materials during emplacement and during the early saturation /Sandén et al. 2008/. In Phase 3 it was decided to perform some complementary tests regarding the erosion and piping investigations in order to gain a better understanding of the processes and also to do a number of other complementing laboratory investigations. The following test types have been undertaken to accomplish the goals set out for this work:

1. **Erosion of pre compacted blocks**. A number of erosion tests were performed in Phase 2 of the project. These tests were however made on blocks from a test-compaction and the density of these blocks was considerably higher than the blocks that were produced later. Completing tests have been done for Phase 3 on blocks taken from the production that had a lower density than intended. The long-term behavior of the erosion has also been investigated.

2. **Erosion of bentonite pellets.** This subject was also investigated in Phase 2 of the Baclo project. The pellet material investigated was MX-80. The results were however not entirely consistent. One conclusion from the tests was that the variation of results probably depended on the influence from bentonite powder mixed with pellets. In this new test series a number of tests have been performed were the amount of powder has been controlled. In addition a number of other candidate materials have been investigated.

3. **Large slot tests.** This test type was also performed in Phase 2 of the project. The material tested was MX-80 pellets. A new test series have been performed using Cebogel QSE pellets (see description in Chapter 2.3).

4. **Displacement of backfill blocks during the installation Phase.** After emplacement of backfill blocks in a deposition drift, they will be exposed to inflowing water from the surrounding rock. The effect of water, penetrating into the slots between the blocks and subsequent swelling has been investigated.

5. **Required plug tightness in order to stop erosion of backfill materials**. After plugging of a deposition drift there will be leakage between the plug and the rock and in fractures in the rock. The bentonites ability to seal these leaks has been investigated by using specially designed equipment.

6. **Self-healing ability of some backfill materials**. The backfill materials ability to seal a channel after development of a piping feature has been investigated. Holes have been drilled in saturated specimens and the materials ability to seal this hole after a period of healing has been investigated.

7. **Relative Humidity induced swelling of backfill blocks**. The backfill blocks will absorb water from the air humidity after emplacement. This may cause swelling and cracking of the blocks. The phenomena have been investigated in special designed equipment, where compacted specimens were exposed to a high relative humidity. The specimens were weighed and inspected at pre-selected intervals.

2.3 Materials and water used in the tests

Different materials have been used in the various test undertaken, see Table 2-1. All materials are under consideration as future candidates for use as backfill:

- **Mixture bentonite/ballast 30/70**. The ballast consists of crushed rock from Olkiluoto (0–5 mm) /Keto et al. 2005/. The bentonite is a high grade Ca-bentonite from Milos, Greece (IBECO Deponit CA-N) with a smectite content of 80–85% /Karnland et al. 2006/.

- **Friedland clay**. Mixed layer clay from Germany with a smectite content of about 25–35% /Karnland et al. 2006/. Both powder (blocks) and granules (erosion tests) are tested. The granules consist of broken fragments. The pieces are even-grained with a size of about 8 x 8 x 4 mm.

- **Asha 230 B**. A low grade Na-bentonite from India with an assumed smectite content of about 60% (no data sheet or reference available).

- **MX-80 pellets**. Specially made pellets consisting of MX-80 Wyoming bentonite with a smectite content of about 80% /Karnland et al. 2006/. The pellets are "pillow" shaped with the dimensions 18 x 18 x 8 mm.

- **Cebogel QSE pellets**. A commercial bentonite pellets with a montmorillonite content of about 80% (according to data sheet from the deliverer). Extruded cylindrical rods with a diameter of 6.5 mm and a length of 5–20 mm. The origin of the material is Milos, Greece. The pellets are delivered by Cebo Holland BV.

- **Minelco**: The material is very inhomogeneous in granule size (55% is > than 4 mm and 3% is < 1 mm). Dry density of filling about 975 kg/m^3. The material origins from Milos and was delivered as a raw material that could be used for backfilling. No data regarding smectite content is available.

The following water solutions have been used in the tests:

- **Water1**, tap water.
- **Water2**, water with salinity of 1% (50/50 $NaCl/CaCl_2$).
- **Water3**, water with salinity of 3.5% (50/50 $NaCl/CaCl_2$).

The most probable water type during the installation Phase is type 2, but due to possible deep saline groundwater "upconing effect" in Olkiluoto, /Pastina et al. 2006/, a number of tests were done with a higher salinity of the water (3.5%). Completing tests were done with tap water.

Table 2-1. Table showing a compilation of the materials and in what experiments they have been used for Phase 3 of the Baclo project.

Material	Erosion, pellets	Erosion, block	Block disp.	Sealing ability of fractures	Healing ability after a piping scenario	RH induced swelling	Large slot test
MX-80 pellets	■			■	■		■
Cebogel QSE	■						■
Friedland	■	■	■		■	■	
Minelco	■						
Asha 230 B			■		■	■	
30/70 Mixture			■		■	■	

2.4 Laboratory determinations

In the tests performed the following definitions were used:

Water content

The bulk mass (m_b) of the sample was determined by use of a laboratory balance. The sample was dried in an oven for 24 hours at a temperature of 105°C. The dry solid mass (m_s) of the sample was then determined immediately after take out. From these measurements the water mass was calculated:

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

and the water content of the sample determined:

$$w = \frac{mw}{ms} \qquad \text{3-2}$$

Density

In some of the investigations the bulk density was determined after test termination. The sample was weighed, first in air (m_b) and then submerged into paraffin oil (m_{bp}). The volume of the specimen was then calculated:

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

where ρ_p is the paraffin oil density. The bulk density of the specimen was then calculated according to:

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

Dry density and degree of saturation

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

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

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

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

In the calculations different ρ_s have been used for the different materials /Karnland et al. 2006/:

MX-80	2,780 kg/m^3
Friedland	2,780 kg/m^3
Minelco	2,780 kg/m^3
Asha 230 B	2,900 kg/m^3

3 Erosion of precompacted blocks

3.1 General

During installation of backfill blocks in a deposition tunnel they may be exposed to water inflow from the surrounding rock. The water will come in contact with the block surface and depending on the inflow rate; gaps between the blocks and other environmental factors, a number of scenarios can be envisioned. The most obvious scenario is that material will erode from block surfaces.

Tests to study the erosion properties of blocks were done in Phase 2 of the Baclo project /Sandén et al. 2008/. Those tests simulated the installation phase in a tunnel where filling with blocks was occurring. They were performed using large blocks of Friedland clay that were cut to suitable sizes by use of a band saw. The water inflow rate and the salt content in the water were varied in these tests. The results from the tests were as initially anticipated, showing a large influence of the water flow rate and of the water salinity, while the test length seemed to have a small impact on the erosion rate. The number of test performed was limited.

New backfill blocks, made of the same material, have been produced at Höganäs Bjuf AB for use in the field tests at Äspö HRL. These blocks have a considerably lower density than the blocks used in the Phase 2 tests. In order to check the erosion properties of these new blocks some completing erosion tests have been done. An additional aim was to study the long-term behavior of blocks exposed to water flow along their surface.

3.2 Test description

The new tests described in this report were performed in the same way as the old test series, using the same test equipment. The blocks were placed in a groove made of a steel profile, Figure 3-1. The length of the groove was 1 meter. A preselected water inflow was applied in one end and was allowed to travel along the block surface. The steel profile had an inclination of about 1%, close to that envisaged for an emplacement tunnel in a KBS-3V repository.

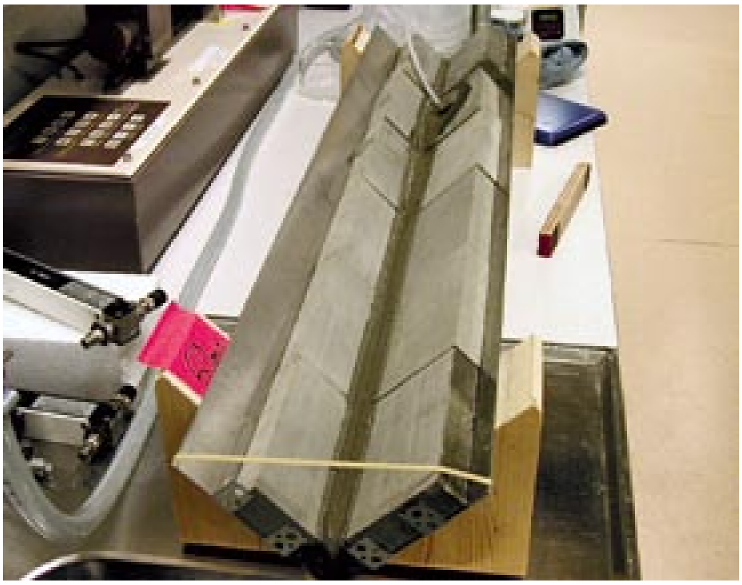


Figure 3-1. *Picture from one of the earlier performed tests. The picture shows a 1m long steel profile filled with blocks of compacted bentonite. A constant water flow was applied in one end and the amount of eroded material in the other end was measured.*

The following was controlled/measured during the tests:

Water flow

- **Water flow into the system.** This was set to a selected value on the microprocessor controlled pump used to supply water to the test.

- **Water outflow from the system.** Samples of exiting water were taken, weighed and then placed in an oven at 105° where the water was evaporated. After drying the container was weighed again. With this procedure the amount of water flowing out per unit time could be calculated. When the flow rate was 0.1 l/min or higher, water samples were taken from the downstream exit at regular intervals. = For flow rates of 0.01 l/min or lower all the water during a certain time period was collected as a single sample.

Erosion measurements

- **The amount of eroded material in the water**. The water samples taken from the exiting water, see description above, were also used to determine the amount of clay contained in the water by evaporating the water in an oven at 105°C and determining the residue. The mass remaining was corrected for salt originally in the water. For water flow rates of 0.1 l/min and higher, water samples were taken from the downstream exit at regular intervals. The determined erosion rate for a certain sample was also used for the period between the two last samples taken out when calculating the accumulated erosion.
- **Observing the material.** A digital camera was used in order to register the behavior.

3.3 Results

3.3.1 General

Three types of pre-compacted blocks made of Friedland clay have been available over the course of the testing program, see Table 3-1.

1. **Type 1**. The blocks were produced at a factory in Germany as a demonstration of the press. These blocks have rather high water content and also a high density. These blocks were used in Phase 2 of the Baclo project when testing the erosion properties of Friedland blocks.

2. **Type 2**. Before starting the large production of blocks at Bjuv, a small test series was done in order to study the quality of the production. No additional tests have been performed with these blocks.

3. **Type 3**. Blocks from the large scale production at Bjuv. The density of these blocks is low. Two erosion tests have been performed in Phase 3 of the project using blocks of this type.

Table 3-1. Properties of the different types of Friedland blocks produced.

Sample	Water ratio %	Bulk density kg/m³	Degree of saturation %	Void ratio e	Dry density kg/m³
Type 1. Friedland block, test series Phase 2	10.8	2,300	88.51	0.339	2,075
Type 2. Friedland block, test Bjuv april 2006	8.6	2,180	62.20	0.385	2,010
Type 3. Friedland block, production july 2006	6.3	1,940	33.26	0.526	1,820

3.3.2 Erosion

Two tests have been performed using the new Friedland blocks (Type 3 in Table 3-1). Both tests were done using 1% salt in the water but with different water flow rates, 0.01 l/min and 0.1 l/min. In Figure 3-2 the accumulated amount of eroded material from these two tests is plotted versus time. For comparison the results from the same type of tests from Phase 2 where Friedland blocks of Type 1 were used are also plotted. The duration of the new tests was increased in order to study their longer-term behavior.

In Figure 3-3 the results from all erosion tests performed with Friedland clay are presented. In the diagram the accumulated amount of eroded material is plotted vs. the accumulated water flow in logarithmic scales. The erosion properties of the new blocks are different from the earlier. This was very obvious in the test performed with the higher water flow rate. When applying a water flow rate of 0.1 l/min along the surface of the blocks, the erosion rate was about 4 times higher than observed using Type 1 blocks. In the test performed with the lower water flow rate, 0.01 l/min, the erosion rate was higher than in the earlier tests using a different block type but the difference was not as high as for the higher flow rate. The test duration in the new tests was 55 hours instead of 8 hours, see Figure 3-2. When evaluating the erosion rate after 8 hours, the value was about 65% higher compared with the old test but after 55 hours had the average erosion rate decreased. This depends on the tendency for erosion to decrease with time. Figure 3-4 shows a diagram where the average bentonite content in the discharged water is plotted versus different flow rates. Both results from the two latest tests, using Friedland blocks of Type 3 is shown and also the results from the earlier tests using Friedland blocks of Type 1.

Pictures and diagrams showing the applied and the measured flow from the two latest tests are shown in Appendix 18 and 19.

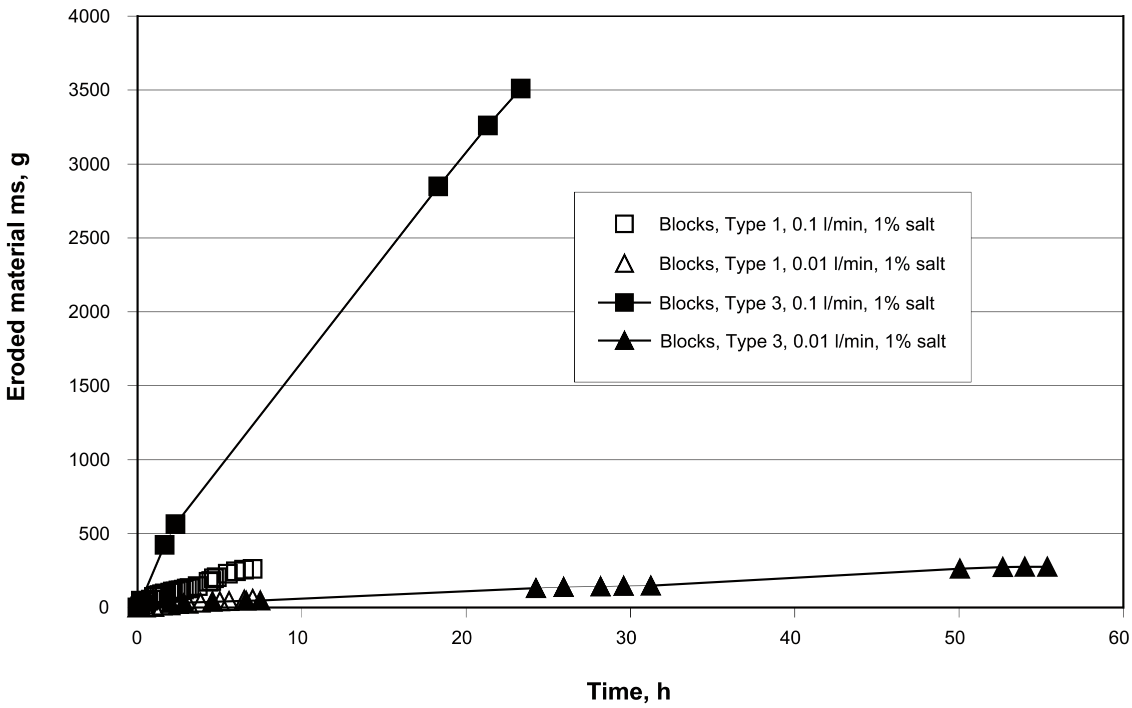


Figure 3-2. *The accumulated amount of eroded material plotted vs. time. The two test marked with black dots are from the latest tests using Friedland block Type 3, while the two tests with transparent dots are from the tests in Phase 2 using Friedland blocks of Type 1.*

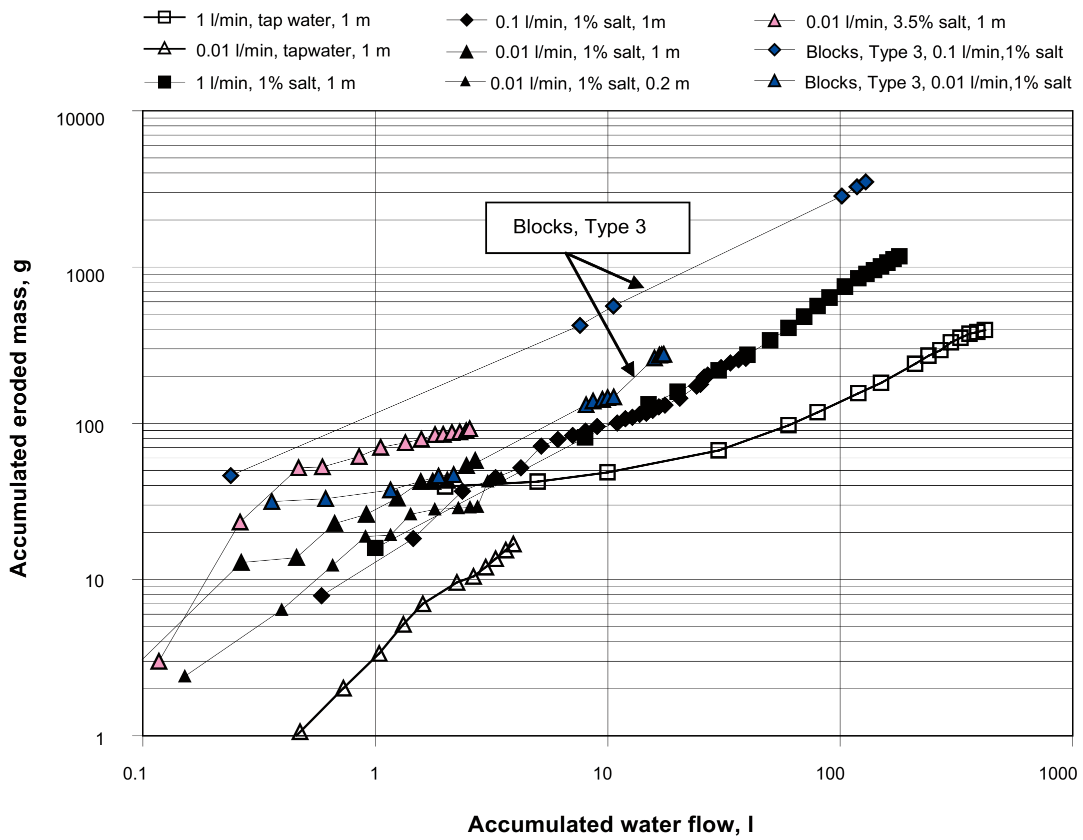


Figure 3-3. *Accumulated dry weight of eroded material plotted vs. the accumulated water flow in logarithmic scales.*

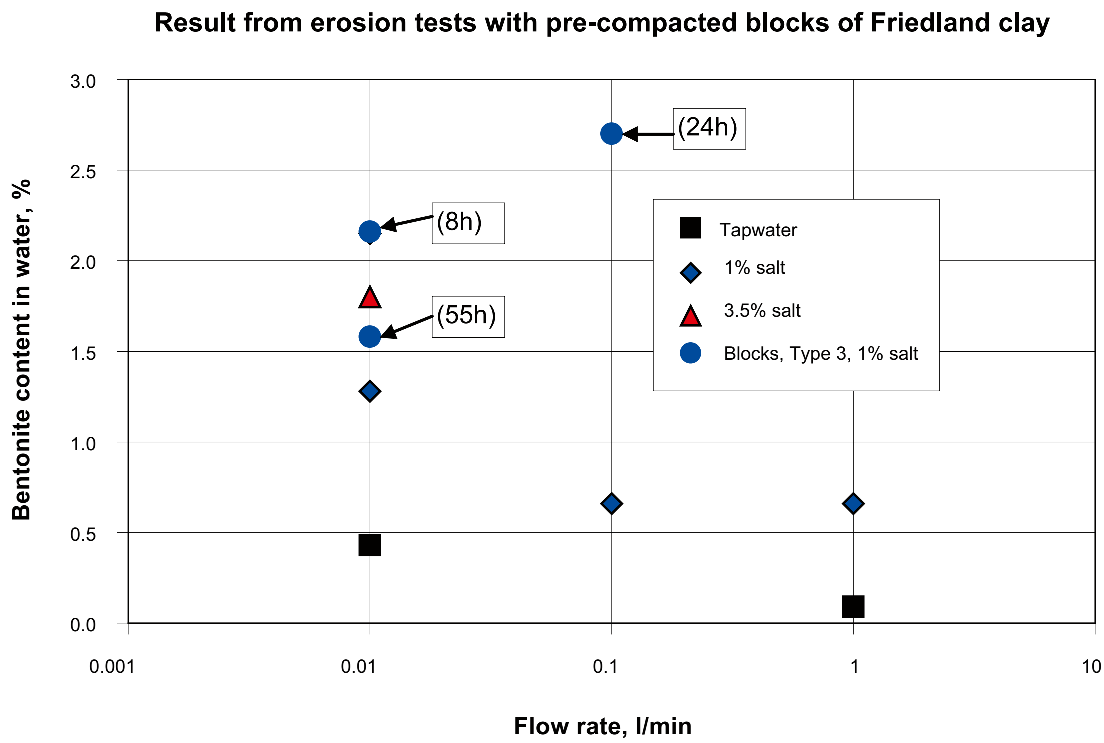


Figure 3-4. *Compilation of all erosion measurements with Friedland blocks in laboratory. The average bentonite content in samples taken from the discharging water plotted vs. different flow rates. The circular blue dots show the values from the latest tests using Type 3 Friedland blocks, while the other test results are from Baclo Phase 2 tests where Type 1 Friedland blocks were used.*

3.3.3 Long term behavior

All tests performed in Phase 2 (with Type 1 blocks) were operated for about 8 hours. There was a small tendency in these tests for the erosion rate to decrease with time. The two tests performed with the new blocks were run for 24 (0.1 l/min) and 55 hours (0.01 l/min). It was not possible to run the test with higher flow rate for longer times than in Phase 2 studies, because the water flow eroded so much bentonite that the water was eroding through to the bottom of test setup and was flowing on the steel plate. Erosion usually took place such that a central ditch was developed in the test setup. For both of the new, longer duration tests (0.01 and 0.11 l/min), a decrease in the erosion rate could be seen with increasing time.

3.4 Conclusions and comments

The results from the erosion tests on pre-compacted blocks can be summarized as follows:

- There is an influence of the salt content in the water on the measured erosion rates. Independent of the flow rate the bentonite content in the eroding water was 0.1–0.4% when using tap-water (two tests at different water flow rates). In the tests performed with 1% and 3.5% salt, the bentonite content was between 0.6 and 2.7% in all tests (7 tests at different water flow rates).
- There is an influence of the water flow rate on the bentonite content in the discharged water but it is rather small.
- The density of the blocks seems to influence the erosion rate. The test with the highest erosion rate, 2.7% bentonite content in the discharged water, was performed with the new "low density" blocks, a water flow rate of 0.1 l/min and a salt content of 1% in the water.
- There is a small tendency for the erosion rate to decrease with time.
- Although the number of tests performed has been limited, the test method seems representative of what might be encountered in the field. The repeatability of the tests has not been tested.

4 Influence of fine material mixed with bentonite pellets on the erosion properties (MX-80 pellets)

4.1 General

The erosion properties of bentonite pellets were initially investigated in Phase 2 of the Baclo project /Sandén et al. 2008/. The results from these tests were not entirely conclusive and some were difficult to explain. One explanation for the difficulty in interpretation was that when the tests where assembled (i.e. when the material, MX-80 pellets, was taken from a big bag and then poured into the test tube) there was a varying amount of fine material in the pellets. In order to investigate the influence of the fine material on the piping and erosion properties a number of further tests have been done. The same test equipment was used in this test series as in the earlier.

4.2 Test description

The test equipment was the same as was used in Phase 2 of the Baclo project. It consists of tubes made of Plexiglas so that the course of events could be followed from the outside and also photographed, Figure 4-1. The tubes had an inner diameter of 0.1 m and the length of each tube was 0.5 m. The tubes could be jointed end-to-end to produce test assemblies of any desired length.

At the outflow ends of the Plexiglas-tube a perforated plate was positioned in order to keep the pellet material in position during the test. At the other side of the tube a point inflow was applied. Different water types were used in order to examine the effects of the water composition, see chapter 2.

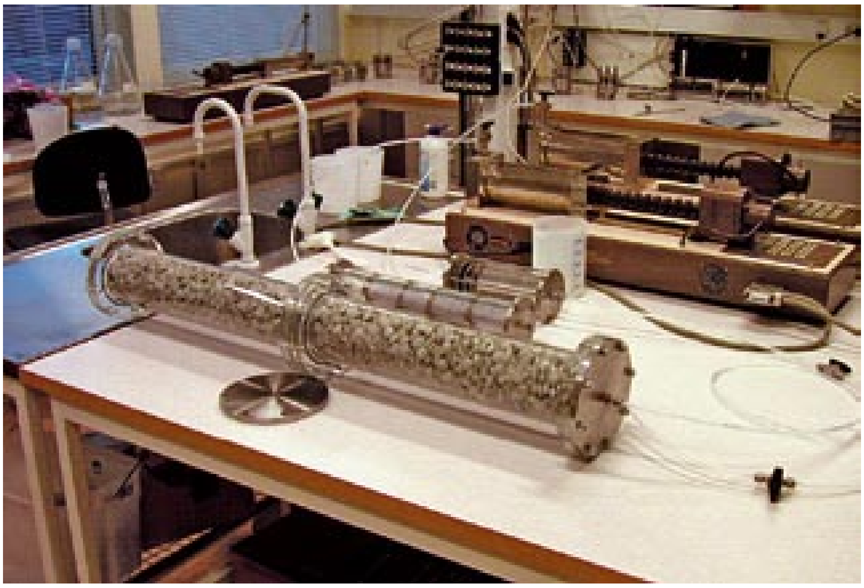


Figure 4-1. *Picture showing the test equipment. The picture shows a Plexiglas tube filled with Mx-80 pellets. A constant water flow was applied in one end and the discharging water was collected in the other end.*

Water flow and erosion measurements

The water flow and erosion measurements were controlled/measured in the same way as described in section 3.2. In addition, a separate pressure transducer was used to monitor possible water pressure built up in the system. The aim was to apply a constant inflow rate regardless of the resisting water pressure that was built up during the saturation of the pellet material.

4.3 Test matrix

In the earlier test series a number of parameters were varied: length of the test tubes (0.2, 1.0 and 3.0 m), water flow (0.001, 0.01, 0.1 and 1.0 l/min) and water type (0%, 1% and 3.5% salt). In this new test series the following parameters have been examined:

1. **Material**:
    - Pure Mx-80 pellets. The pellets were separated from the fine material also present in the pellet bags by sieving.
    - Mx-80 pellets mixed with powder. In a pellet filling (Mx-80 pellets) about 55% of the volume is occupied by the pellet. This means that theoretically the rest of the volume can be filled with bentonite powder. 1 kg pure pellets were mixed with 0.45 kg powder.

2. **Applied flows**:

The tests were performed with two different constant flow rates, 0.01 and 0.1 l/min

3. **Water types**. (See chapter 2).
    - 1% salt.
    - 3.5% salt.

The complete test matrix is shown in Table 4-1. The tests performed are marked with bold text. All tests were performed with 1 m test length.

Table 4-1. Test matrix for the piping and erosion tests.

Pellets MX-80						
Flow	Top water		1% Salt		3.5% Salt	
l/min	Pellets	Pellets+powder	Pellets	Pellets+powder	Pellets	Pellets+powder
0.001	A:111	A:121	A:211	A:221	A:311	A:321
0.01	A:112	A:122	**A:212**	**A:222**	**A:312**	**A:322**
0.1	A:113	A:123	**A:213**	**A:223**	**A:313**	**A:323**
1	A:114	A:124	A:214	A:224	A:314	A:324

4.4 Test results

4.4.1 General

In total eight tests were performed in this investigation. It was only possible to measure erosion in six of them. In two of the tests, A:312 and A:322, the one with the lowest water flow rate (0.01 l/min) and highest salt content (3.5%) in the water respectively, the bentonite swelled and sealed and due to the applied constant inflow rate and a substantial resistance to water input rapidly built up. When the water pressure exceeded the maximum pressure the pump could deliver (1 MPa) it was not possible to continue the experiments, see Figure 4-2, 4-3 and Appendix 5 and 7. The other six tests were performed as planned.

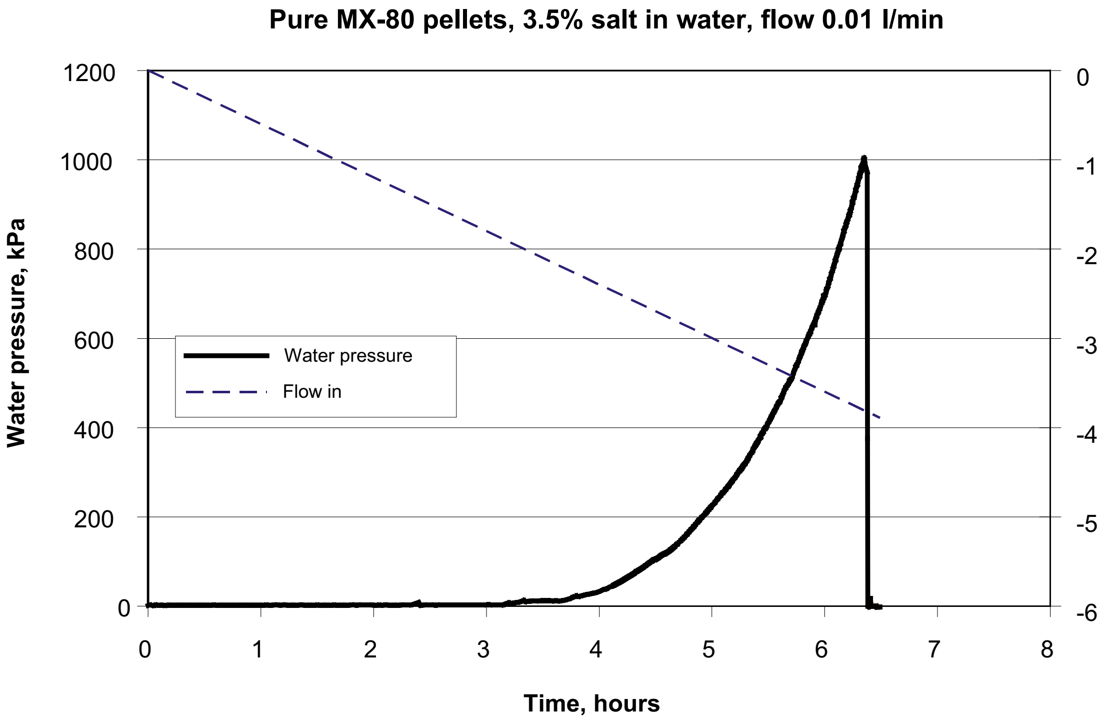


Figure 4-2. *The water inflow rate and the measured water pressure built up in test A:312. When the pressure reached 1 MPa the test was terminated.*

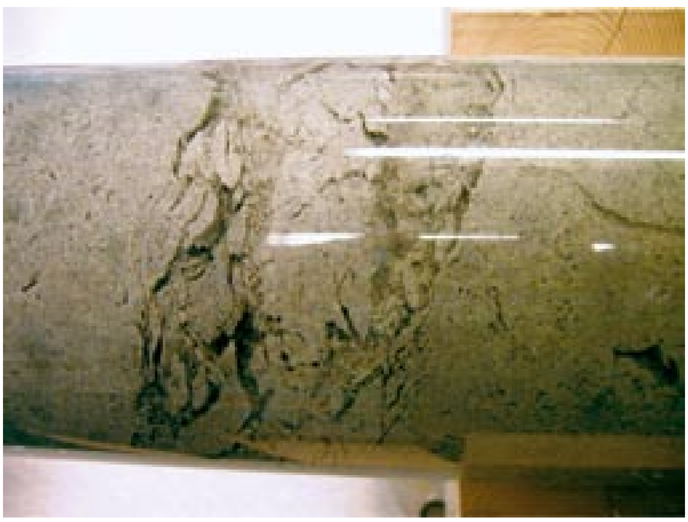


Figure 4-3. *Picture from the test A:312 (0.01 l/min and 3.5% salt in the water). The material seemed to separate and the water pressure was acting on a surface pushing the bentonite specimen forward.*

4.4.2 Erosion measurements

The results from the six tests where erosion was measured are easily predicted. In Figure 4-4 the accumulated amount of eroded material is plotted vs. time. During the first 5 to 10 hours of the tests the erosion rates were very high and the influence of fine material was obvious i.e. the erosion rate was higher if fine material was present in the pellet filling. After 5 to 10 hours, the erosion rate seemed to decrease with time and after about 24 hours the erosion rate was almost the same in all tests. The measured data can also be presented as the amount of eroded material plotted versus the accumulated water flow, see Figure 4-5.

Also the influence of the salt content in the water was clear (higher salt content caused higher erosion rate) during the first day of testing but after about one day the erosion rate was independent of the water type.

From the data plotted in Figure 4-4 the erosion rate i.e. the bentonite content in the discharged water, was evaluated and presented, see Figure 4-6. In that figure it is clear that the erosion rate changes with time.

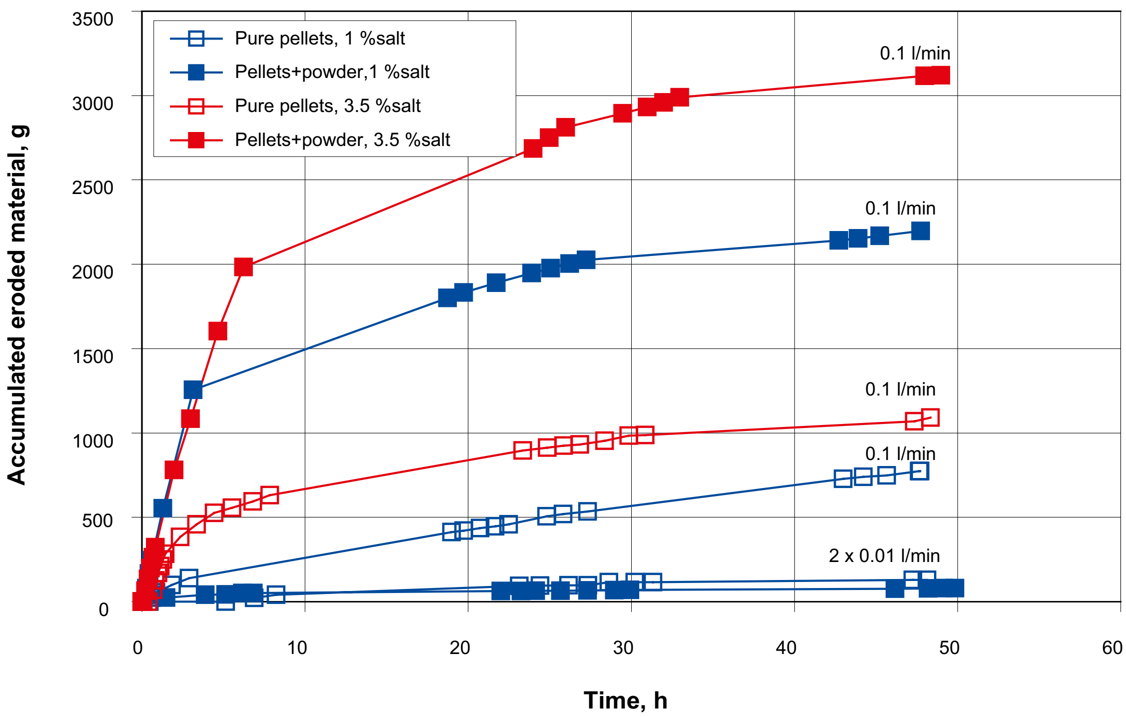


Figure 4-4. The accumulated amount of eroded material plotted vs. time for the six tests. In the beginning of the tests the influence of fine material and salt content in the water was strong but after about 24 hours the erosion rate almost was the same in all tests.

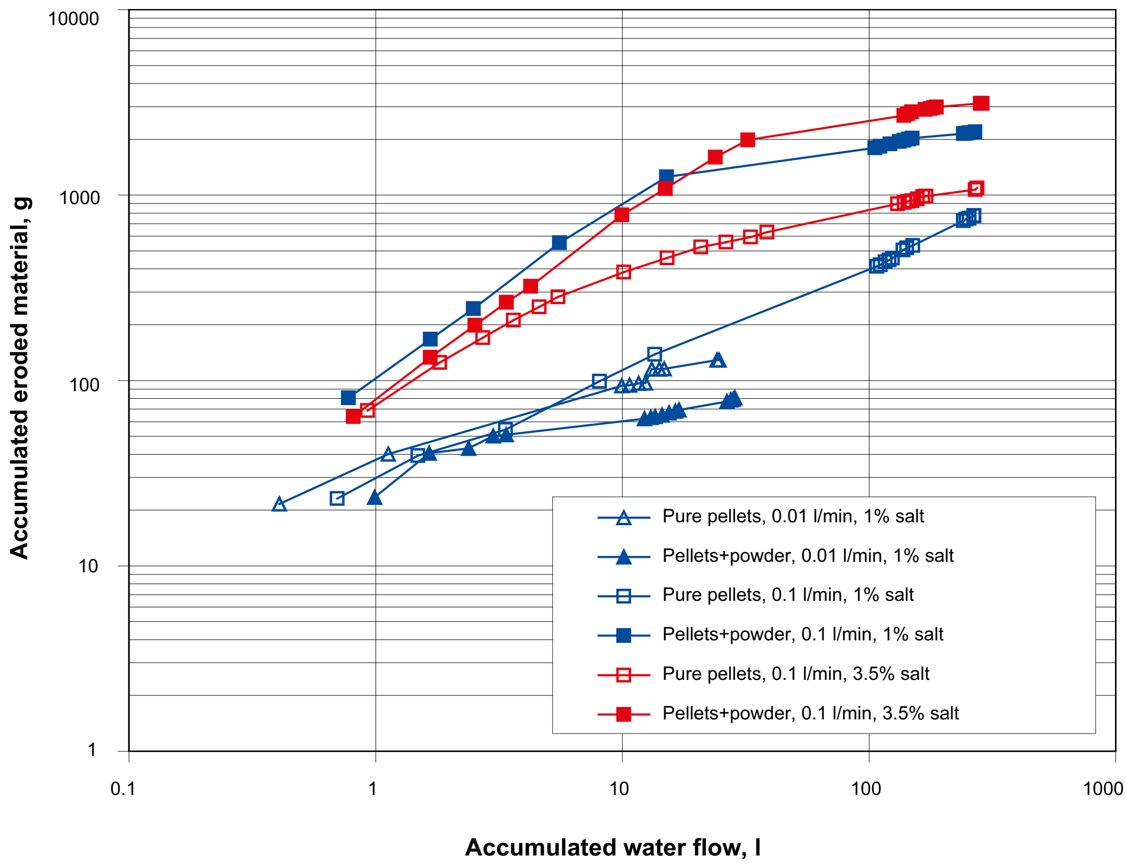


Figure 4-5. *The accumulated amount of eroded material plotted vs. the accumulated water flow in logarithmic scales.*

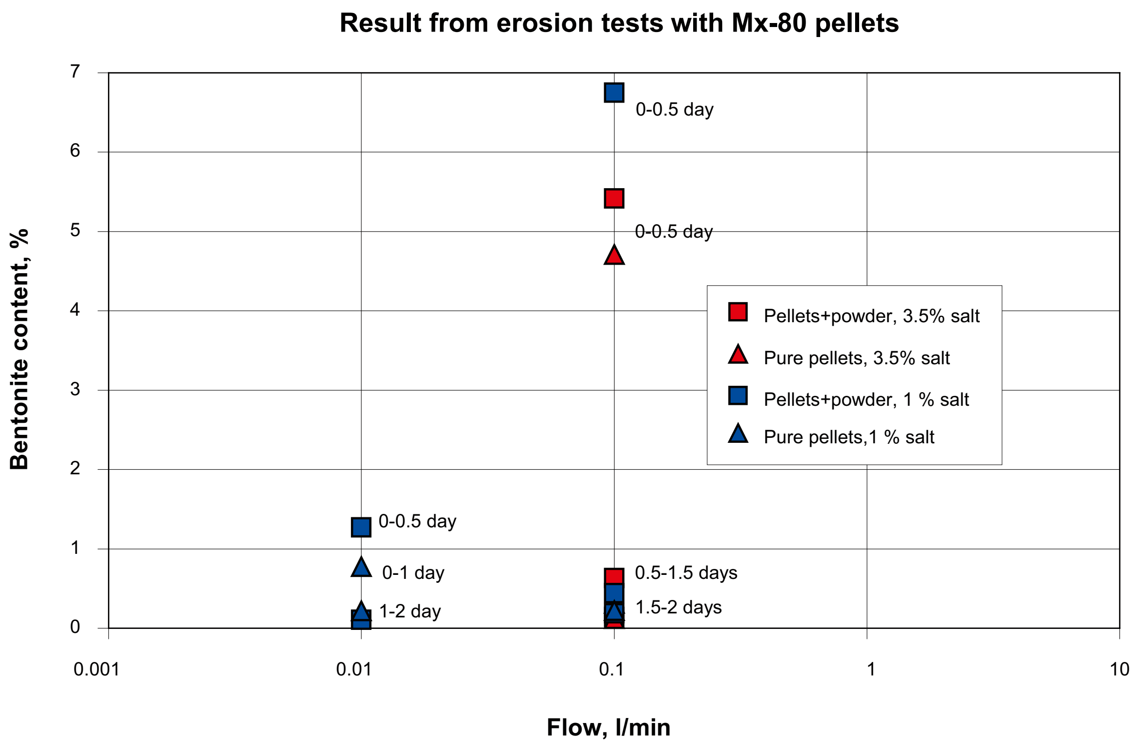


Figure 4-6. *The bentonite content in the discharged water (after different times) plotted vs. different water flow rates. The influence of time is very strong. After 1 day the bentonite content in the water is about 0.1–0.3% for all tests.*

4.4.3 Resistance to water input build up during test

A compilation of flow and pressure measurements during the tests is presented in Appendix 1-8 together with pictures from the tests. In none of the tests performed with the higher water inflow rate (0.1 l/min), did a strong degree of resistance to water input build up during the test. The resistance to inflow was monitored in the tests performed with the lower water flow rate, 0.01 l/min, see Figure 4-7. For the test parameter combination with low water flow rate, 0.01 l/min and 3.5% salt in the water rather high water pressures (up to 1,000 kPa when terminated) were reached and the experiments had to be terminated early in order to not destroy the test equipment, Appendix 5 and 7. For the same water flow rate but with a salt content of 1% in the water a few pressure peaks of 80–90 kPa were registered during the tests, Figure 4-7 and Appendix 1 and 3. It was not possible to register any difference in behaviour regarding the inflow resistance pressure for tests performed with pure pellet material pellets mixed with powder.

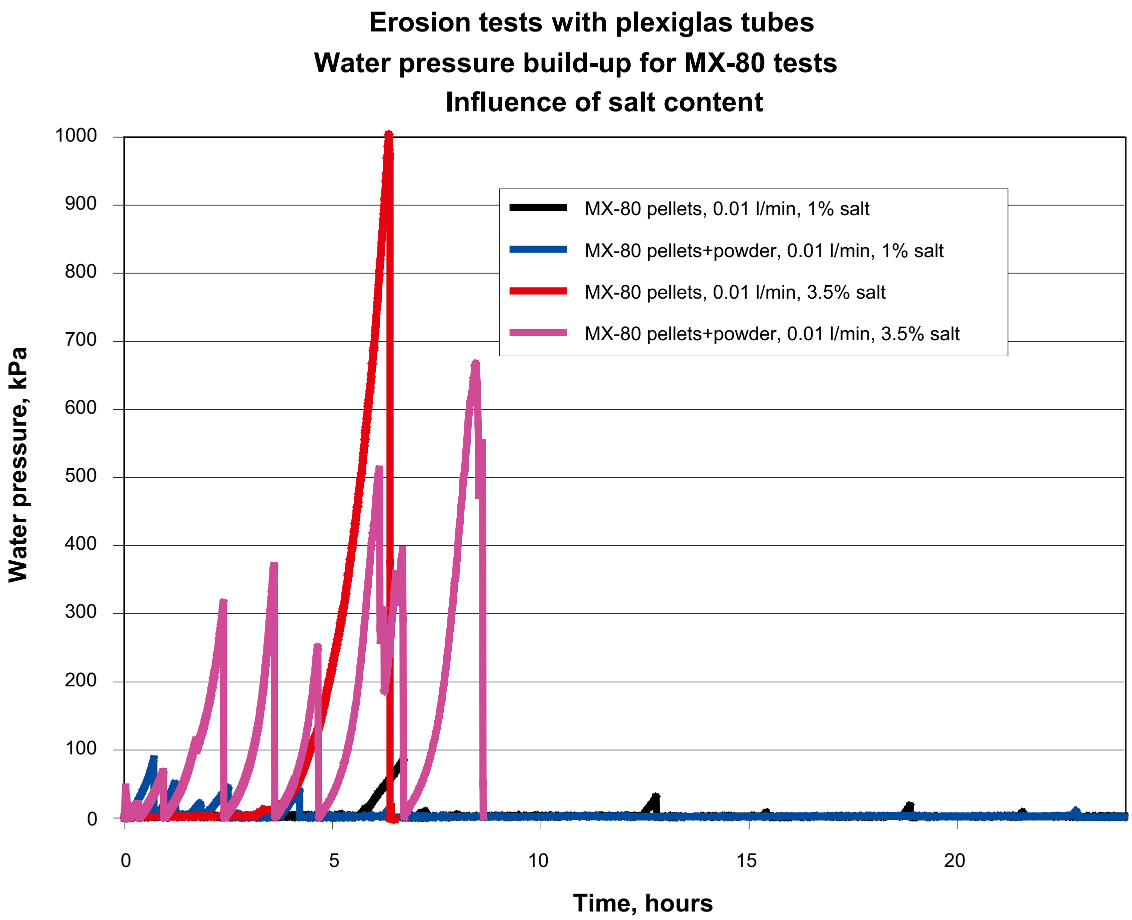


Figure 4-7. *The water pressure built up during tests plotted vs. time. The results are from tests performed with a constant water flow of 0.01 l/min and with different salt content in the water.*

4.4.4 Comparison to results of previous studies

The same kind of erosion tests were performed in Phase 2 of the Baclo project. These tests did not take into account the amount of fine material so the results were not entirely conclusive and some were difficult to interpret.

A comparison of the results from Phase 2 and Phase 3 is presented in Figure 4-8. The difference in results is probably due to differences in the test duration for the tests in Phase 2. This means that the erosion rate was in some cases only measured during the first phase of the test when the erosion rate was still high. The erosion rate in these earlier tests was also evaluated as an average during the test time. New work has been done in order to determine the erosion rate after 24–30 hours.

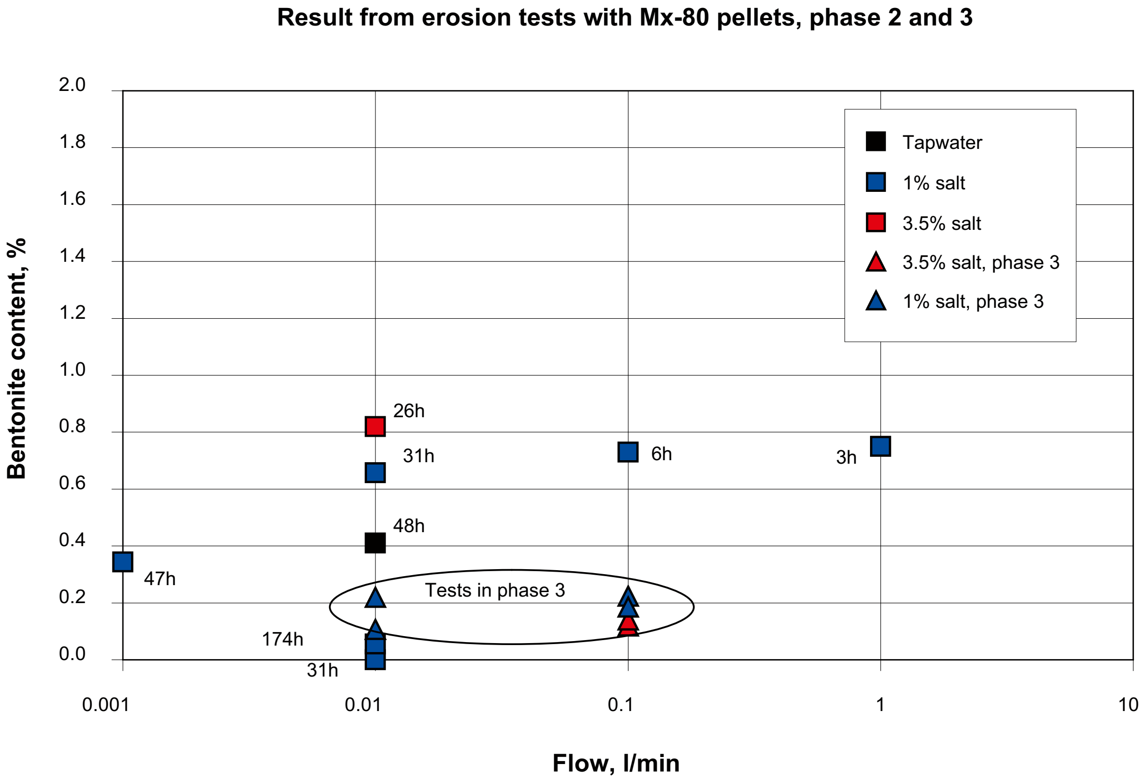


Figure 4-8. The bentonite content in the discharged water for the latest six tests and also for the earlier tests made in Phase 2 of the project plotted vs. the different flow rates. The bentonite content in the water for the test performed in Phase 3 was evaluated after about 24–30 hours test duration. It was not possible to do the same evaluation for all of the tests performed in Phase 2 of the project due to the different test durations. The test duration for each of these earlier tests is shown in the diagram.

4.5 Conclusions and comments

The results from the erosion tests on MX-80 pellets can be summarized as follows:

- The results from the tests show that the influence of fine material on the erosion rate is very strong in the beginning of the tests (if fine material was present the erosion rate increased) but after 24 hours the erosion rate was very similar and fairly low in all tests.
- The influence of the salt content in the water was also investigated. Due to very fast swelling and sealing in the tests with 3.5% salt with the lower water flow rate (0.01 l/min) high resistance to water flow built up (up to 1 MPa) and it was not possible to measure erosion in these two tests. The behavior probably depends on a combination of many factors such as salt content in water, water flow, grain size distribution and the size of the available voids. The main reason is however probably the geometry of the confinement. In the other two tests performed with 3.5% salt content and a water flow rate of 0.1 l/min, the erosion rate was very high during the first hours but after about 24 hours the erosion rate was the same as in the tests performed with 1% salt in the water.
- The bentonite content in the out flowing water was after 24 hours test duration between 0.1–0.2% for all tests performed in this series.

5 Investigation of piping and erosion properties of alternative “pellet” materials

5.1 General

A comparison of piping and erosion properties of a number of candidate backfill materials for use in filling of the slot between the blocks and rock (see Chapter 2) has been done. In addition some standard investigations to determine properties such as liquid limit and swelling capacity have been done on these materials. The following materials have been investigated:

1. **Cebogel QSE**. This is a commercial bentonite pellet product. The material is used in the ongoing field tests at Äspö. The pellets are extruded cylindrical rods with a diameter of 6.5 mm and a length of 5–20 mm.
2. **Minelco granules**. Tests are also ongoing at Äspö using Minelco, which is a Greece bentonite from Milos. The material is very inhomogeneous in granule size (55% is > than 4 mm and 99% > 1 mm).
3. **Friedland granules**. Mixed layer clay from Germany.
4. **MX-80**. The properties of the new candidate materials have been compared with data from tests with MX-80 pellet (Test A212 and A213 in Chapter 4).

5.2 Standard investigations

For all materials some standard properties were determined, see Table 5-1.

- **Water content**. The water content of the as-delivered Cebogel pellet and the Minelco material was rather high, 18–19% while the Friedland granules had rather low water content, about 7%.
- **Dry density of bulk filling**. In spite of the high water content of the Cebogel pellets and the Minelco material the dry density of the bulk filling using these materials was in the same range as for the MX-80 pellet. Also the dry Friedland material had a dry density very close to that of the other materials.
- **Liquid limit**. The Cebogel pellet and the MX-80 pellet have a very high liquid limit, 576 and 520% respectively. Both materials also have a high montmorillonite content, about 80%. The liquid limit of the Friedland clay is however much lower, about 132%.
- **Swelling capacity**. One gram of the dry test material is poured down very carefully into a glass measuring cylinder filled with de-ionized water. The volume occupied by the swelled clay is recorded after 24 hours to provide the volumetric swelling capacity. The swelling capacity depends on the montmorillonite content of the material. MX-80 has the highest swelling capacity of the tested materials and Friedland the lowest.

Table 5-1. Table showing some standard properties investigated for different materials.

Sample	Water ratio %	Bulk density of filling kg/m³	wL Liquid limit %	Swelling capacity ml
MX-80 pellets, typical value	11.3	1,038	520	20.0
Minelco, big bags at Äspö	18.8	1,159	334	9.7
CEBOGEL QSE	18.9	1,121	576	11.9
Friedland granules	7.1	1,118	132	8.7

5.3 Special measurements on Cebogel QSE

In addition to the standard investigation the swelling pressure and the hydraulic conductivity were determined for the Cebogel QSE pellets. The pellets filling tested had a dry density of 966 kg/m³. The specimen had a diameter of 101 mm and a height of 88 mm. The specimen was saturated with water having a salt content of 1% (Type 1). The swelling pressure was determined to be about 45 kPa and the hydraulic conductivity to 4.3 x 10^{-11}. Corresponding values for MX-80 pellets are 55–60 kPa and 2.1 x 10^{-10}, (Chapter 9, Figure 10-5 and Table 10-2).

5.4 Erosion measurements

5.4.1 General

Two tests with different water flow rates (0.01 and 0.1 l/min) were performed on each material using the 1% salt water. A compilation of the results is presented in Table 5-2.

The tests were performed in the same test equipment as used for the MX-80 material (see Chapter 4) i.e. Plexiglas tubes with an inner diameter of 0.1m and with a length of 1 m.

5.4.2 Water flow and erosion measurements

The water flow and erosion measurements were controlled/measured in the same way as described in section 3.2. In addition, a separate pressure transducer was monitoring possible water pressure built up. The aim was to apply a constant flow that remained constant independent of the resisting water pressure that was built up during the saturation of the pellet material

Table 5-2. Tests performed and some data from the experiments.

Material	Salt content NaCl/CaCl %	Applied flow rate l/min	w initial %	Dry density in tube kg/m³	Max. resisting water pressure kPa	Erosion measure-ment	Comments
MX-80 pellets	1%	0.01	11.3	958	85	Yes	
MX-80 pellets	1%	0.1	11.3	949	13	Yes	
Cebogel QSE	1%	0.01	18.9	956	175	Yes	
Cebogel QSE	1%	0.1	18.9	961	140	Yes	
Minelco (Äspö)	1%	0.01	18.8	1,010	600	Yes	Test was terminated in advance
Minelco (Äspö)	1%	0.1	18.8	1,022	470	No	Test was terminated in advance
Friedland	1%	0.01	7.1	996	500	No	Test was terminated in advance
Friedland	1%	0.1	7.1	996	500	No	Test was terminated in advance

5.4.3 Results

The behaviour of the materials differed considerably. For three of the tests it was not possible to measure any erosion. Specifically in both of the tests performed with Friedland granules and one of the tests with Minelco (0.1 l/min), the bentonite swelled and sealed and a high resistance to further water input developed (see section 5.5 and Appendix 12,13 and 14). The clay in these samples dispersed and formed a uniform low porosity plug, against which the water acted as solid surface pushing the material forward and developing considerable resistance since water supply was at a constant-rate, see Appendix 14. The other materials have very different behaviours regarding the development of resistance to water inflow. A compilation of the pressure measurements is provided in Chapter 5.1.3.

The erosion measurements showed that the Cebogel pellets seemed to have a lower erosion rate than MX-80 pellets. This is probably due to the fact that there is less fine material available in the Cebogel material but also on the higher initial water content, which results in pellets with a higher strength. In Figure 5-1 the accumulated amount of eroded material is plotted vs. time. The results can also be presented as the accumulated amount of eroded material plotted vs. the accumulated water flow in logarithmic scales, see Figure 5-2.

Figure 5-3 shows the bentonite content in the discharged water plotted vs. the different flow rates. The erosion rate was evaluated after 24 hours test duration.

The values are in the same order of magnitude for all materials but the erosion rate seems to be slightly lower for the Cebogel QSE material.

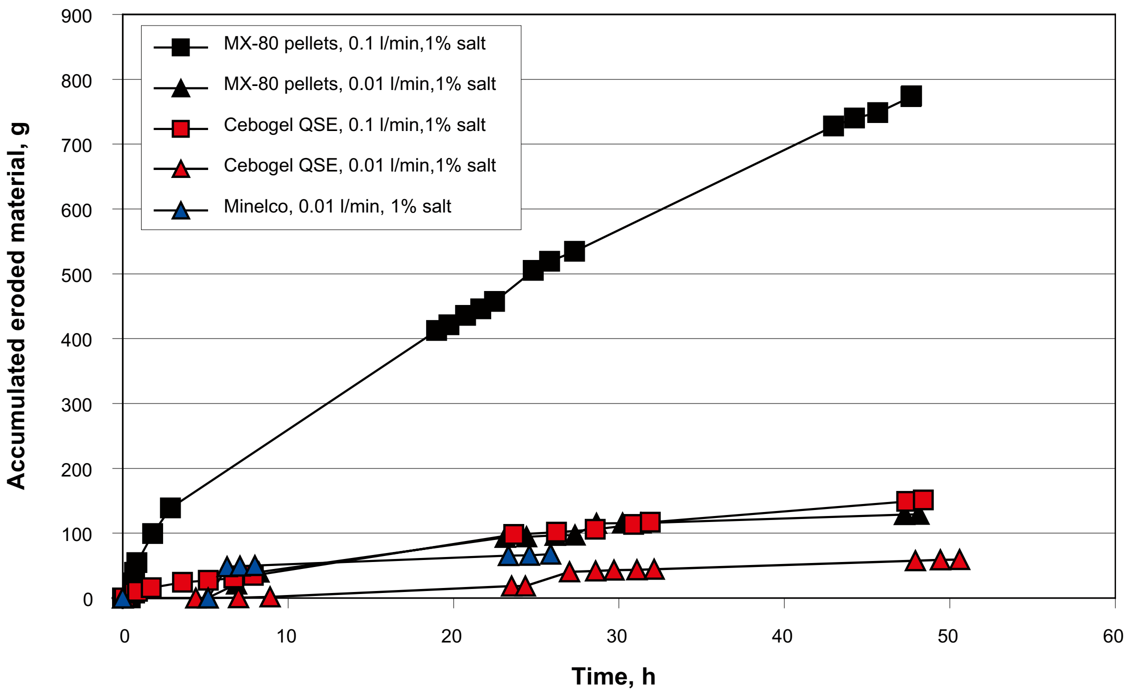


Figure 5-1. *The accumulated amount of eroded material plotted vs. time.*

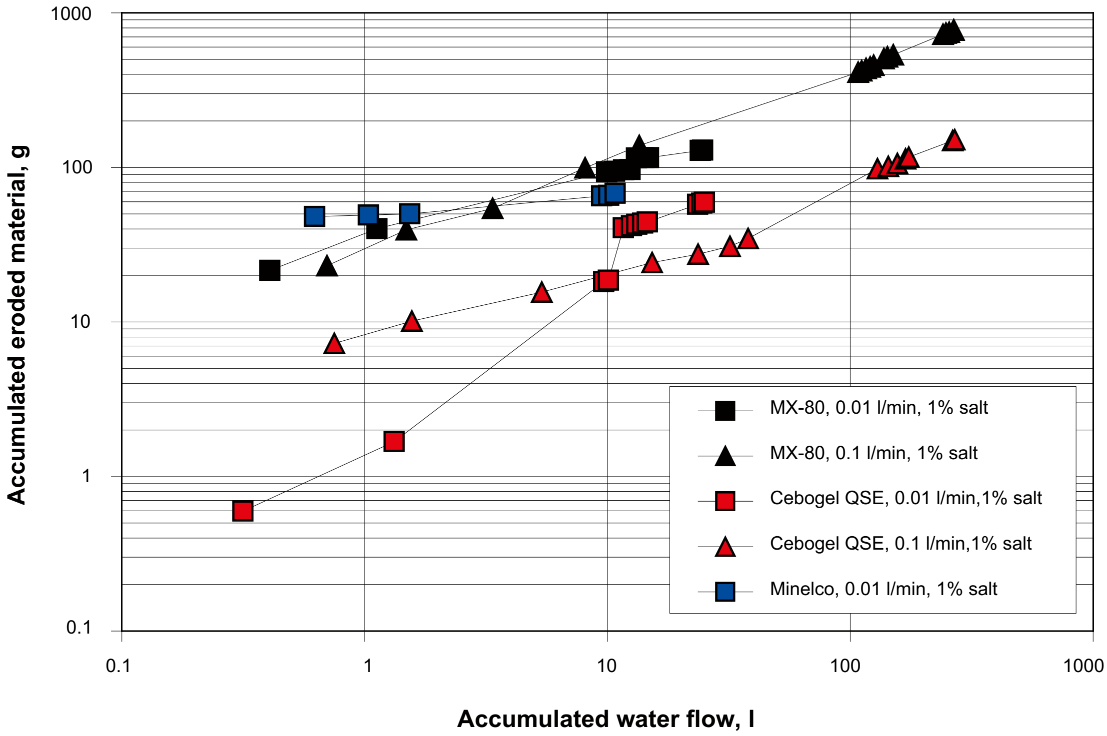


Figure 5-2. *The accumulated amount of eroded material plotted vs. the accumulated water flow in log scales.*

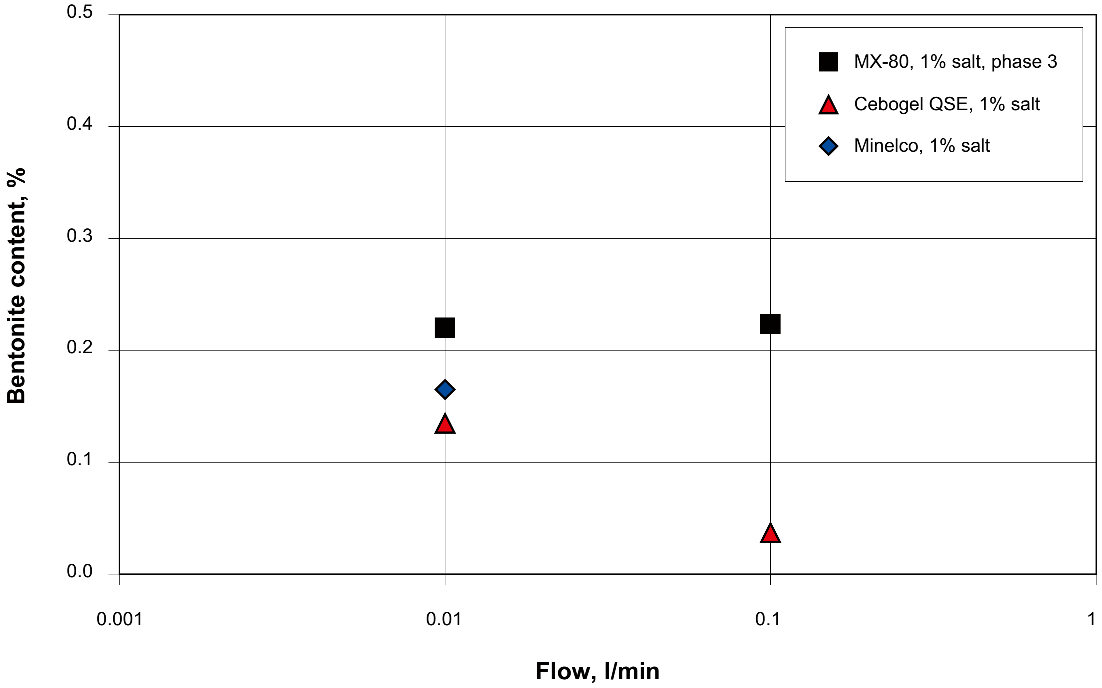


Figure 5-3. *The bentonite content in the discharged water in percentage plotted vs. the different water flow rates.*

5.5 Resistance to water inflow built up during testing.

Due to the applied constant rate of water input a counter pressure (resistance to further water inflow) was built up if the ability to transmit water through or past the specimens was low. The different materials examined in this study behaved very differently, this is summarized as follows:

- MX-80 pellets. Almost no water pressures were built up during the test time, just a few pressure peaks of 80–90 kPa were observed early in test. Almost all the water seemed to flow in one very obvious channel. (Appendix 1 and 2).

- Cebogel QSE. An almost constant water pressure of 140–180 kPa was observed during this test. The water seemed to flow into and through the voids between the pellets. No obvious channel could be seen, see Figure 5-5 and Appendix 9 and 10.

- Minelco. It was only possible to measure erosion in the test performed with the lower of the water flow rates examined. It was also necessary to terminate this test in advance of the target test duration because of the resistance to water inflow that built up. (Appendix 11 and 12).

- Friedland. High inflow resistance pressures were built up very quickly. The material sealed and the inflowing water could act uniformly against the essentially impermeable clay surface resulting in compressing the material forward in the tube, see Figure 5-6 and Appendix 13 and 14.

The MX-80 bentonite and the Cebogel material have the highest content of montmorillonite and were supposed to have the highest potential to swell and seal off the water flow. One explanation for the different behaviours observed could be the difference in grain size distribution between the materials:

- **MX-80 pellets**: Consists of "pillow" shaped pellets with the dimensions 18 x 18 x 8 mm. In addition there are a few percent fine materials. Dry density of filling about 932 kg/m^3.

- **Cebogel QSE**: Extruded cylindrical rods with a diameter of 6.5 mm and a length of 5–20 mm. Dry density of filling about 942 kg/m^3.

- **Minelco**: The material is very inhomogeneous (55% is > than 4 mm and 3% is < 1 mm). Dry density of filling about 975 kg/m^3.

- **Friedland granules**: Consists of broken fragments. The pieces are even-grained with a size of about 8 x 8 x 4 mm. Dry density of filling about 1,043 kg/m^3.

Due to the size of the MX-80 pellets, there are fewer voids but they are relatively large. In the Minelco and in the Friedland materials the numbers of voids are larger but they are rather small. This void size relationship depends on the sizes and distribution of the grains.

Due to the differences in the void distribution, the materials with more small voids will have an increased flow resistance. If the water pressure can act on a larger surface, the material will be compacted and the flow resistance will increase even more.

Another difference between the materials is the dry density of the fillings, see above. The Friedland filling has the highest dry density 1,043 kg/m^3 and the MX-80 filling the lowest dry density, 932 kg/m^3. This could probably also slightly influence the measurements.

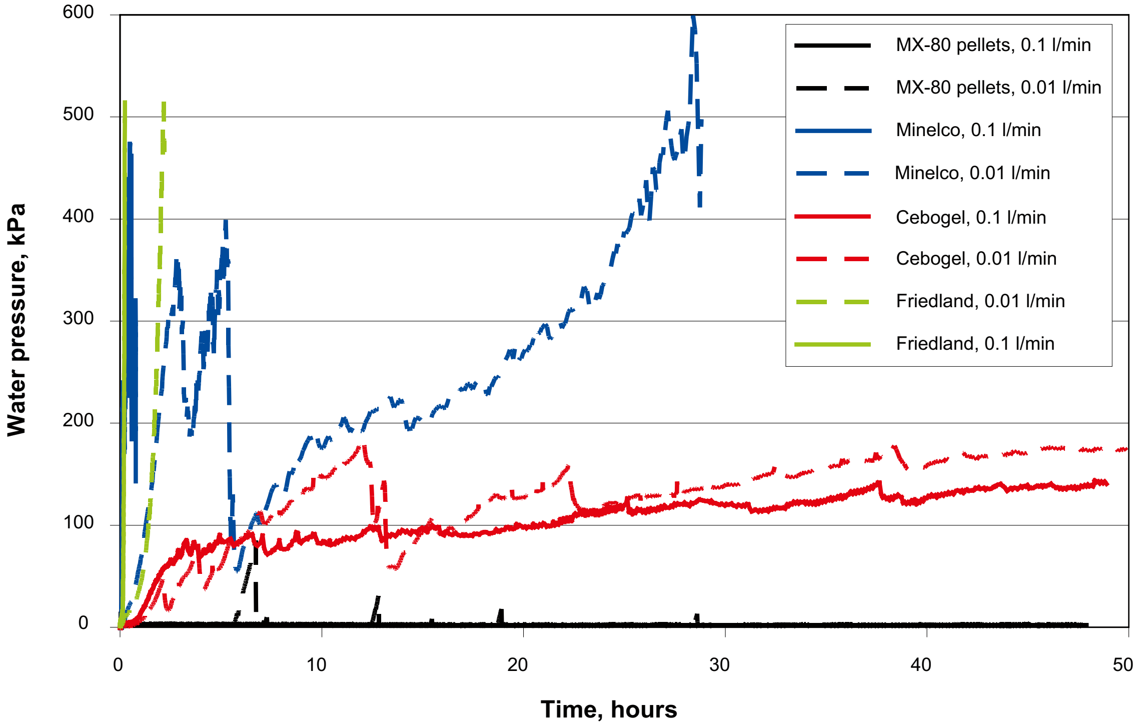


***Figure 5-4.** Diagram showing the resistance to water inflow built up during the test time for the different materials and applied water flows plotted vs. time. The behavior seems to be very different for the different materials.*

***Figure 5-5.** Picture from the test performed with Cebogel pellets, 0.1 l/min and 1% salt in the water. There is no main channel where all water is flowing, like in the tests with MX-80 pellets. The water seems to flow in the voids between the pellets, which can be one reason for the water pressure that was built up during the test.*

Figure 5-6. *Pictures from the test performed with Friedland granules, 0.1 l/min and 1% salt in the water. The material sealed and the water pressure could act on a surface pushing the material forward.*

5.6 Conclusions and comments

The results from the tests on different pellets/granules can be summarized as follows:

- The erosion rate can vary a lot during the first 24 hours depending on material and salt content in the water but will end up at almost the same level (0.1–0.3% bentonite in the out-flowing water). The erosion rate of the MX-80 material seems to be at the upper level and the Cebogel QSE material at the lower. This is probably the result of the lower initial water content of the MX-80 pellets, which makes them more brittle. The amount of loose material in the pellet filling is also larger for the MX-80 material.
- For some materials, Friedland granules and Minelco, high water counter pressure can be built up. This may affect the ability of the pellets to "store" water and thereby delay the time before water will exit the backfilled volume into adjacent open areas. Should this not occur the dry pellets could be pushed forward and water filled cavities be created. This phenomenon could probably also occur with the other materials if unfavorable conditions existed. The behavior probably depends mainly on the grain size distribution, the size of the available voids and the geometry of the confinement. With a large pellet size the voids are rather large and the water can flow in a channel that remains open for long time (MX-80). When the pellets are smaller the voids are smaller and flow resistance will be built up (Cebogel QSE). This situation may be desirable in some situations since the resistance makes the water flow into different areas and by doing so fill up a larger volume with water. If the material contains a large amount of fine materials the flow resistance may be too high and high pressures will be built up, moving the dry pellets forward (Minelco and Friedland).

6 Large slot tests

6.1 General

A test series using MX-80 pellets was done in Phase 2 of the Baclo project using this test equipment. Three tests were performed using different water inflow rates (0.01, 0.1 and 1 l/min) and a 1% salt content water was used.

The purpose of the earlier tests was mainly to check the stability of a large inclined volume of pellets when exposed to water inflow but also to study the bentonite erosion of the water leaking through the slope and measure the amount of material eroded. Another process of interest is the wetting of the pellets and successive water filling of the pore space between the pellets. In the new test series the same processes were studied but using another test material Cebogel QSE.

6.2 Test description

The test equipment consists of an artificial slot, 2 x 1 x 0.1 m, made of Plexiglas as shown in Figure 6-1. The slot is filled with pellets and a constant water inflow rate applied on the side of the slot (see the tube inlet on the picture in Figure 6-1). The picture provided as Figure 6-1 was taken 5 hours into the test performed with the lowest water inflow rate, 0.01 l/min, and only a small volume around the inflow point has been affected. The inflow point is positioned 0.5 m from the bottom and 0.3 m from the end of the slot. The water pressure required to keep a constant inflow rate was measured and the amount of eroded material determined.

Figure 6-1. *Picture showing the test equipment.*

6.2.1 Water flow and erosion measurements

The water flow and erosion measurements were controlled/measured in the same way as described in section 3.2. In addition a separate pressure transducer was registering possible water pressure built up. The aim was to apply a constant flow that remained constant independent of the resisting water pressure that was built up during the saturation of the pellet material.

6.3 Results

6.3.1 General

Three tests have been performed in this test series. All tests were done using Cebogel QSE pellets and with the inflow water containing 1% salt. The difference between the three tests was the applied constant water inflow rates (0.01, 0.1 and 1 l/min).

6.3.2 Wetting process

Two main factors seemed to affect the progress of the wetting; the material and the applied water inflow rate. A comparison of the old test results with MX-80 and the new test results with Cebogel QSE is shown in Table 6-1. Figure 6-2 to 6-4 show comparing pictures from the two test series and diagrams that illustrate the materials ability to store water (the difference between inflow and outflow). In Appendix 15-17 diagrams showing the water inflow and water pressure built up during test time are provided together with pictures from the tests.

Table 6-1. Table comparing the wetting process between the two tested materials at different applied water flow rates.

Applied water flow rate	MX-80	Cebogel QSE
0.01 l/min	Mainly the regions above the inflow point were wetted. Below the inflow point large volumes were dry. Water was flowing on the slope. The first water flow out of the slope was observed after about 50 hours. The pellets volume stored 30 liters before water flow out.	The area around the inflow point was wetted almost symmetrical. The test was terminated after 54 hours in order to preserve the test equipment (some cracks could be seen in the Plexiglas at some points). No water had been lost at this time. The pellets volume had stored 32 liters at test stop.
0.1 l/min	Only the pellets below the inflow point were affected. The first water was observed after 3 hours. The water was flowing in a channel. The pellet filled volume stored 18 liters before outflow.	The wetting started in the lower part but almost the whole pellet filling was wet before any outflow occurred. The first water was observed after 11 hours. The water was flowing down the slope. The pellets stored 66 liters before outflow began.
1 l/min	Only a small part of the pellets below the inflow point was affected. The first water outflow was observed after 20 minutes. Water was flowing in a channel. The pellets volume stored 20 liters before outflow began.	The wetting started in the lower part but almost the whole pellet volume was wet before any outflow occurred. The first water outflow was observed after 20 minutes, but the outflow quantity was smaller than for the Cebogel than for MX-80 (90 l/3h compared to 150 l/3h). The pellet volume stored 20 liters before outflow.

In Figure 6-2 it can be seen that there was an obvious difference in behavior between the MX-80 and Cebogel materials. The MX-80 only wet in an upwards direction and there was a flow of water along the slope, essentially sealing off the lower regions of the test. The Cebogel QSE wet almost symmetrical around the inflow point. The wetting front is marked in Figure 6-2. This test was terminated before any outflow occurred in order to protect the test equipment (the swelling pressure from the bentonite caused some small cracks in the Plexiglas close to the fixing screws).

The diagram provided in Figure 6-2 shows the total inflow provided and the difference between inflow and outflow for the MX-80 and Cebogel materials. The open void volume available (macro voids between granules) was about 66 liters for both tests and the total water volume needed in order to get full water saturation was about 71 liters for the test with Cebogel QSE and about 79 liters for the test with MX-80. This figure shows the amount of water held by the test and shows the clear development of preferential flow paths 48 hours after tests start for both materials. Once these pathways developed the majority of the inflowing water moved rapidly to the front face of the pellets and out of the system.

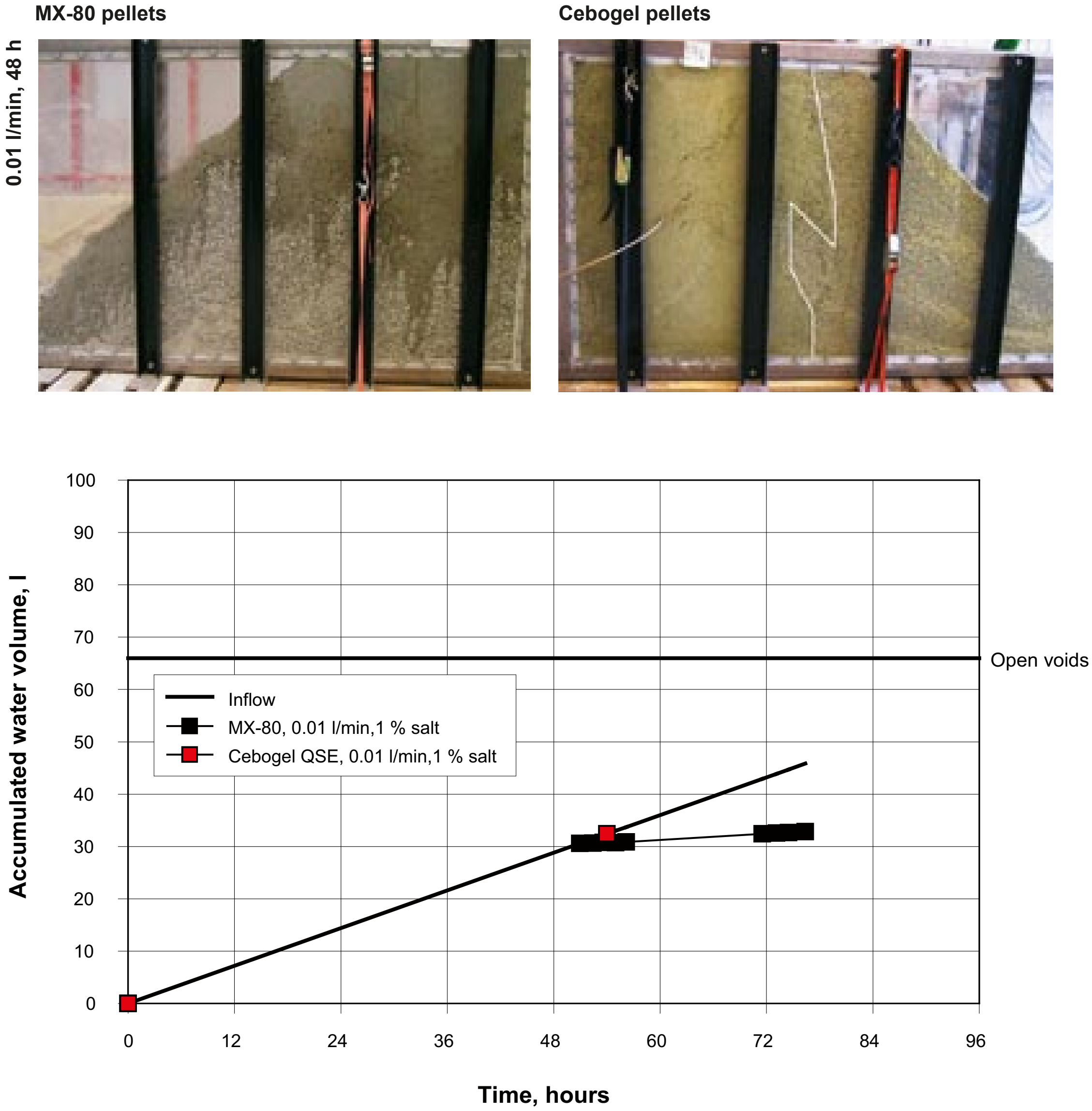


***Figure 6-2. Upper:** Pictures from the two tests performed with a water inflow rate of 0.01 l/min taken after 48 hours. **Lower**: The total inflow and the difference between inflow and outflow plotted vs. time.*

At inflow rate of 0.1 l/ there was an obvious difference in behavior between the two materials. The MX-80 material wet below the inflow point and after initial water breakthrough to the front of the test, flow was via a clearly defined channel. The wetting of the Cebogel started at the below the inflow point but before breakthrough almost the whole volume was wetted. A small "dry" island is marked in the photo in Figure 6-3. Once nearly full wetting was achieved and outflow began there was little further water storage by the test and water moved directly out from the system. The plot of total inflow and the difference between inflow and outflow is also provided in Figure 6-3. The open void volume available was about 66 liters for both materials and the total water volume needed in order to get saturation about 71 liters for the test with Cebogel QSE and about 79 liters for the test with MX-80. The Cebogel QSE material absorbed almost 77 liters during the test time i.e. more than the accessible volume. This higher volume is as the result of the swelling of the material. It was observed that the slope was moved about 0.1 m during the test time as the result of clay swelling (the originally position of the slope is marked on the photo provided in Figure 6-3). This expansion of the test explains the higher storage of the system than the original volume would have allowed.

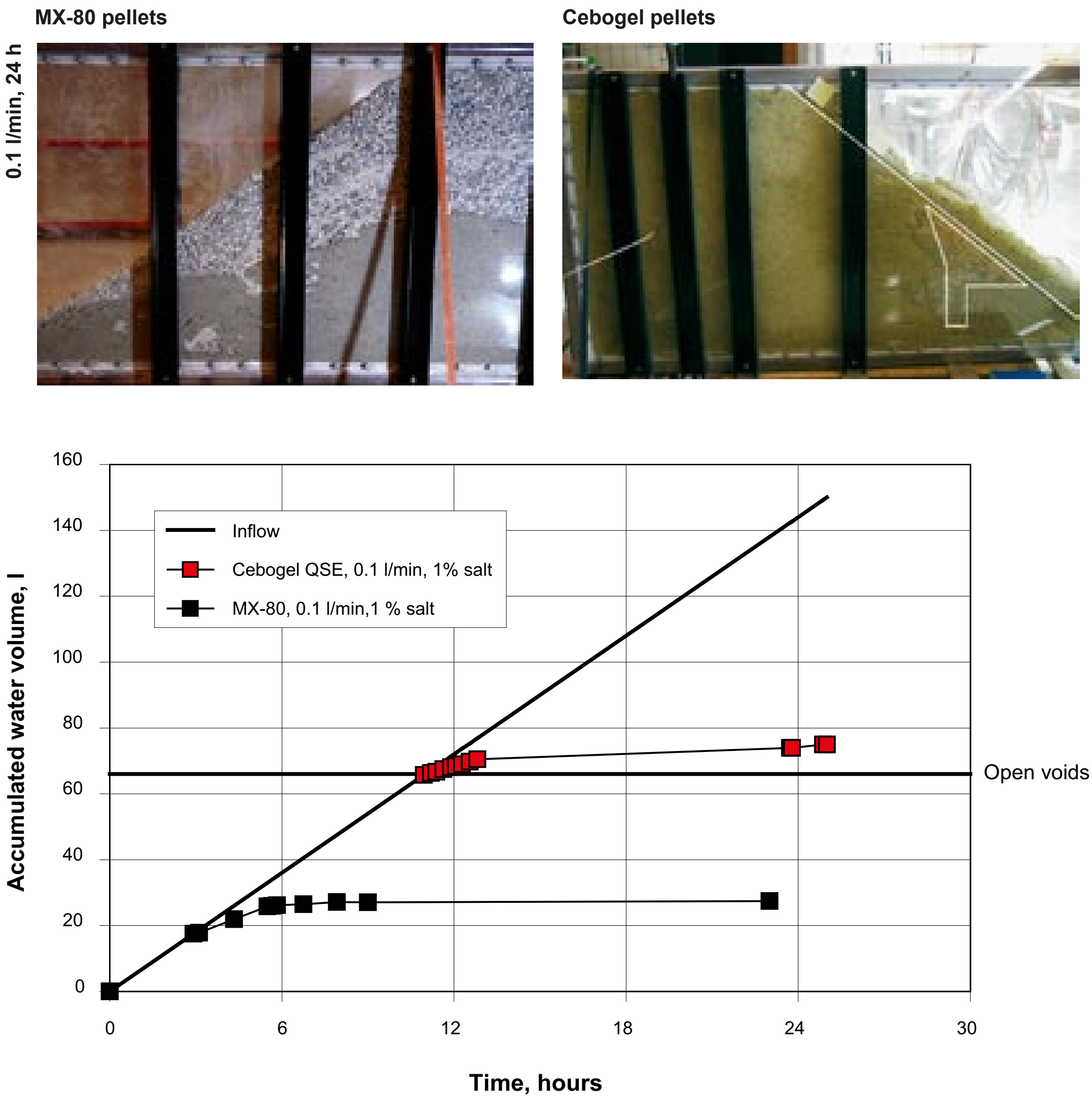


***Figure 6-3. Upper**: Pictures from the two tests performed with a water inflow rate of 0.1 l/min taken after 24 hours. **Lower**: The total inflow and the difference between inflow and outflow for the two tests plotted vs. time.*

At an inflow rate of 1 l/ there was an obvious difference in behavior between the two materials. Water outflow occurred within minutes of the test being started and only a small part of the lower region of the MX-80 filled test was wet after three hours despite the high volume of water supplied. The patterns of water uptake after approximately 3 hours are shown in Figure 6-4. The time to water breakthrough was almost the same in both tests (about 20 minutes) but the Cebogel QSE material continued to absorb a discernible amount of water after breakthrough occurred. The plot provided in Figure 6-4 showing the total inflow and the difference between inflow and outflow for the two tests is very informative. The open void volume available was about 66 liters for both materials and the total water volume needed in order to get saturation is about 71 liters for the test with Cebogel QSE and about 79 liters for the test with MX-80. The Cebogel QSE material had achieved essentially full saturation within approximately 1.5 hours and continued to absorb water. Over 90 liters of water uptake were recorded during for the Cebogel during the test more than the accessible volume. This additional water volume is the result of swelling of the material towards the open upper and downstream directions, which increased the systems ability to hold water. It was observed that the slope was moved about 0.1 m during the test time (the originally position of the slope is marked on the photo supplied in Figure 6-4).

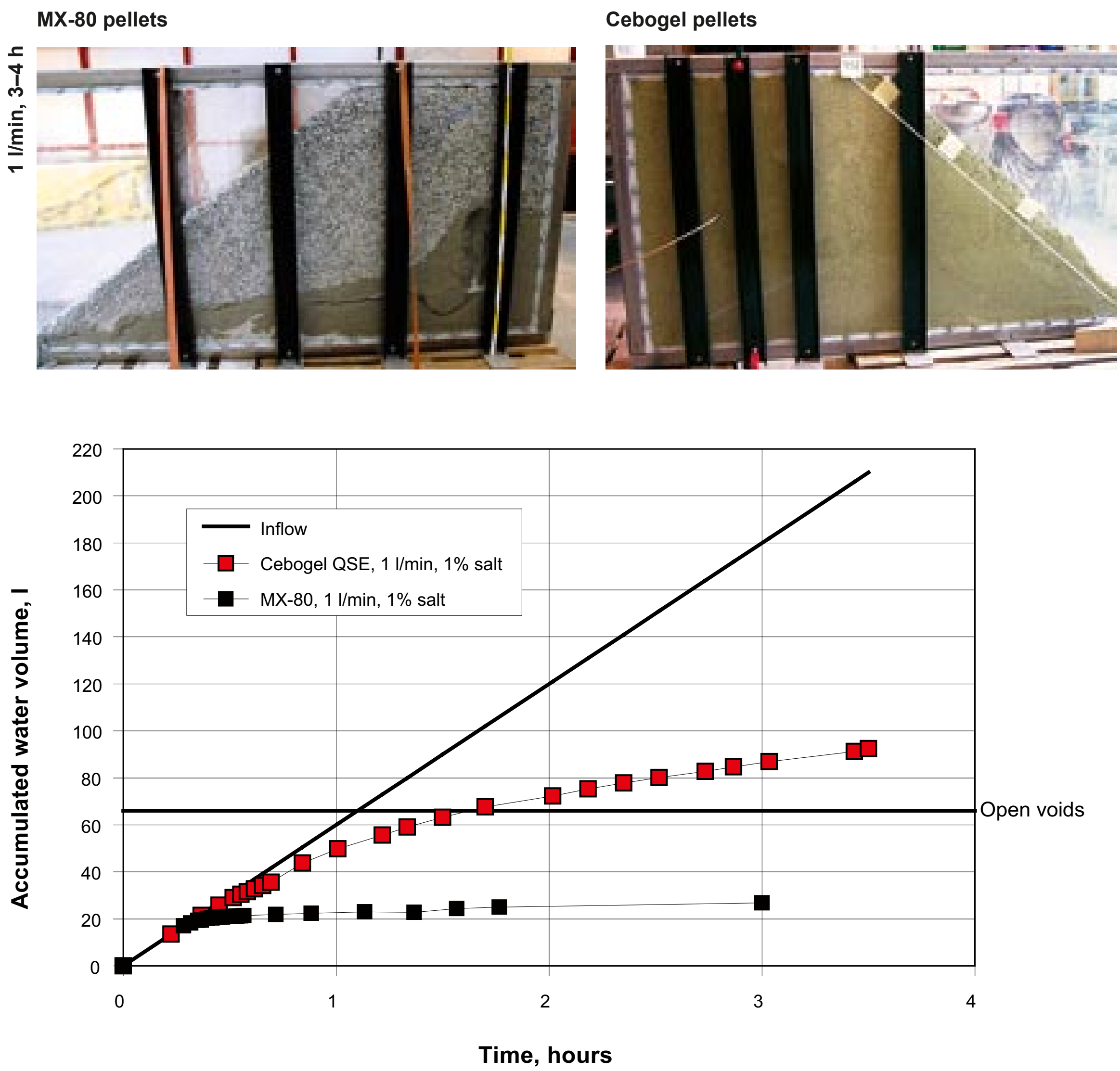


***Figure 6-4.** **Upper:** Picture from the two tests performed with a water inflow rate of 1 l/min taken after 3–4 hours. **Lower**: The total inflow and the difference between inflow and outflow for the two tests plotted vs. time.*

6.3.3 Erosion

It was only possible to measure erosion in two of the three tests performed. In the test with the lowest water inflow rate, a high swelling pressure/total pressure was built up and in order to not destroy the test equipment (some cracks could be observed on the Plexiglas close to some of the fastening screws) the test was terminated after 54 hours. At that time no water had exited from the pellet filling and so no erosion had occurred.

The erosion measurements in the two other tests showed that the Cebogel pellets seemed to have a lower erosion rate than MX-80 pellets, in agreement with the results from the tube tests in Chapter 5. In Figure 6-5 the accumulated dry weight of eroded material is plotted vs. time. The result can also be presented as the accumulated dry weight of eroded material plotted vs. the accumulated water flow in logarithmic scales, see Figure 6-6.

The diagram in Figure 6-7 shows the bentonite content in the discharged water plotted vs. the different flow rates. The erosion rate plotted in the diagram was evaluated at the end of the test after the initial higher erosion rate had ceased and more stable conditions existed. The steady state erosion rate was found to be lower for the Cebogel QSE pellets than for MX-80 pellets.

Also in these tests a substantial resistance to water inflow built up during the test time, see Appendix 15-17. The pressure was between 30 kPa (0.01 l/min) up to 250 kPa (1 l/min).

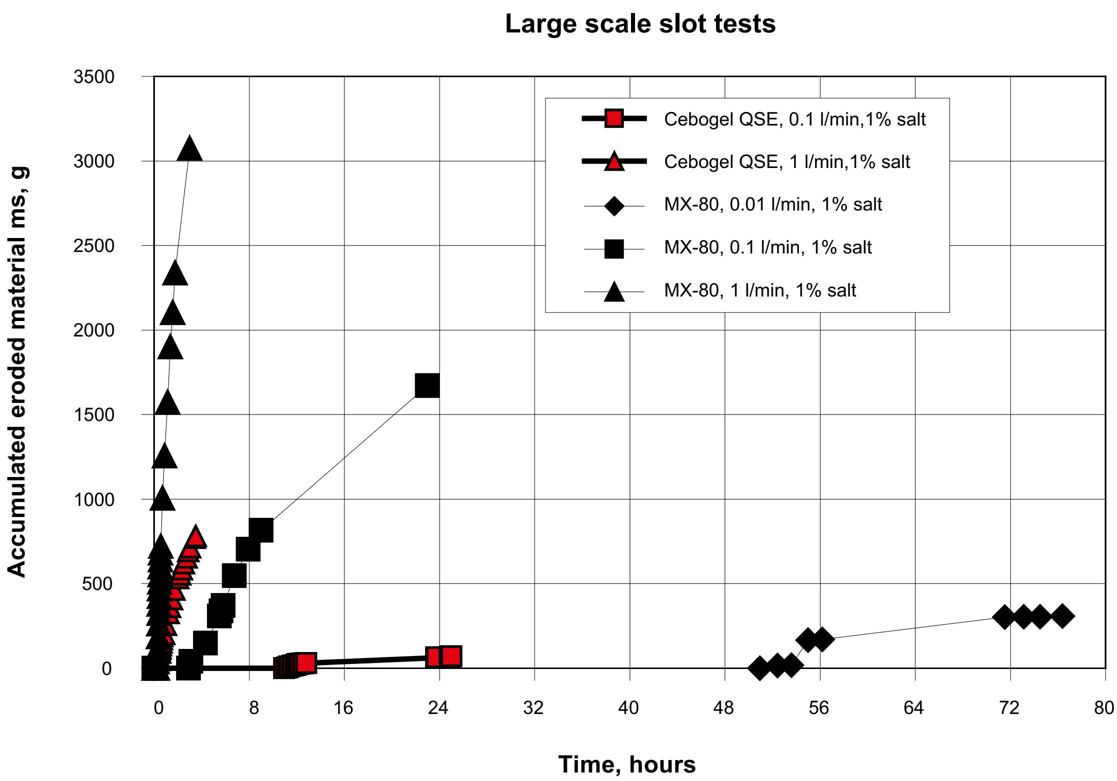


Figure 6-5. The accumulated dry weight of eroded material plotted vs. time. Both the new test results (Cebogel QSE) and the old test results (MX-80) are shown.

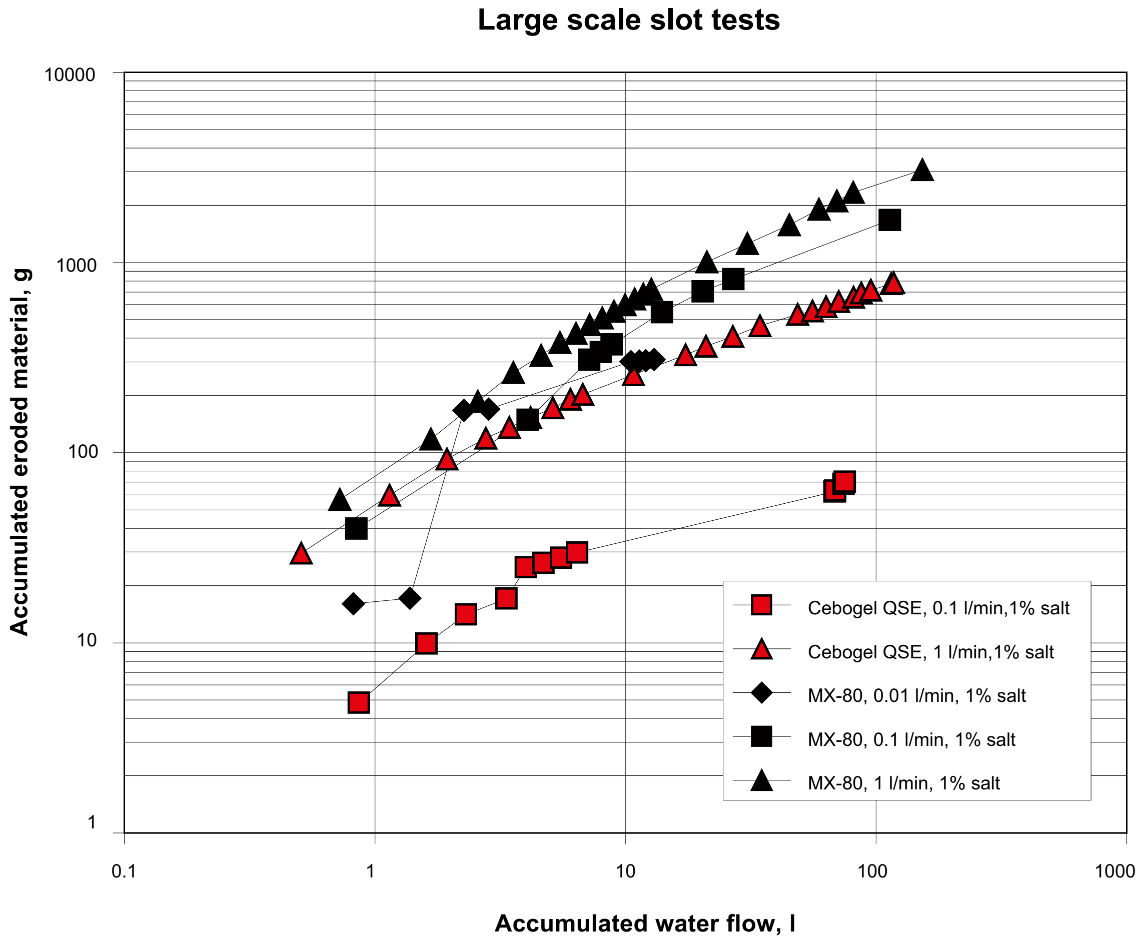


Figure 6-6. *The accumulated dry weight of eroded material plotted vs. the accumulated water flow. Both the new test results (Cebogel QSE) and the old test results (MX-80) are shown.*

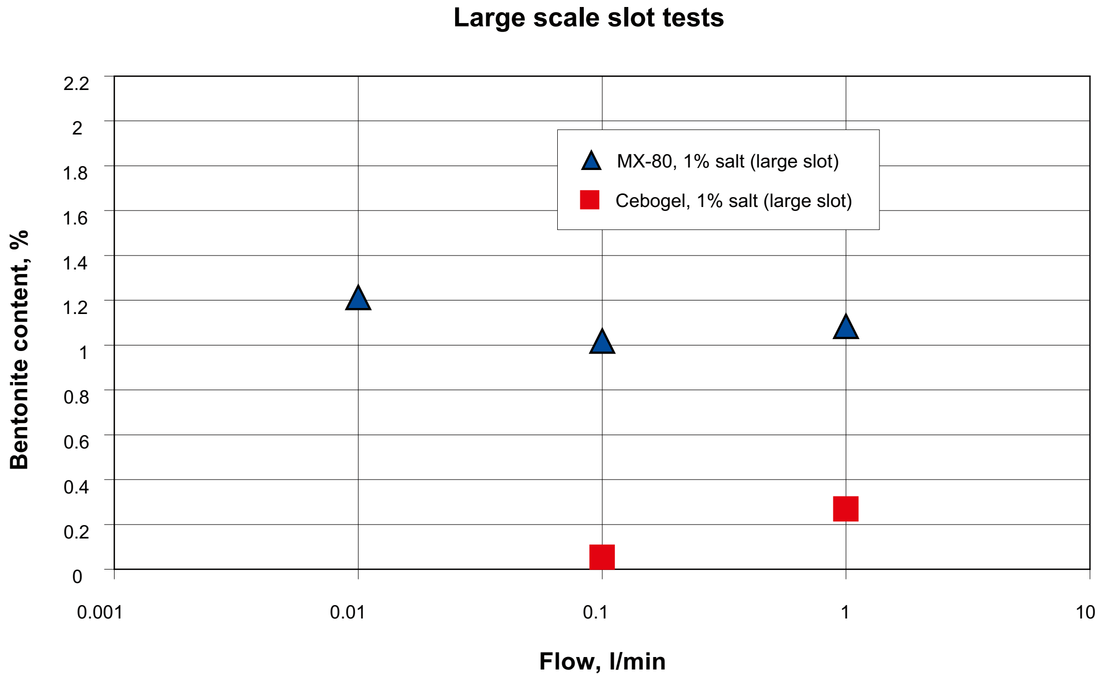


Figure 6-7. *The dry weight of eroded bentonite in percentage in the discharged water plotted vs. the different water flow rates. In the diagram is both the new test results (Cebogel QSE) and the old test results (MX-80) shown.*

6.4 Conclusions and comments

The results from the large slot tests can be summarized as follows:

- **The stability of the slope during water inflow**. There were no observations of a total collapse of the pellets filling. The slope swelled however in some of the tests and material had rolled downwards the slope.
- **Erosion measurements**. The erosion rate was measured also in these tests. The erosion rate was higher for the MX-80 pellets, 1–1.2%, compared to the results from the tube tests, 0.2–0.3%. The difference depends probably on that the amount of fine material was larger in the slot tests. The erosion rate of the Cebogel QSE material was in the same order of magnitude as in the tube tests.
- **The wetting process**. The materials ability to store water was also studied. All tests with MX-80 pellets resulted in a partial wetting of the pellets filling was wetted and then the water flow via a single channel not affecting the still dry parts of the assembly. The tests with Cebogel had different results. Almost all material were wet before breakthrough (0.011/min and 0.1 l/min) and for the highest inflow rate (1 l/min) the wetting proceeded after the breakthrough, resulting in an almost completely wet pellet filling after three hours of testing. The reason for this difference is probably the size of the voids which is smaller for the Cebogel pellets, resulting in a higher flow resistance which makes the water flow in different directions, see section 6.3.

7 Modeling of the erosion

7.1 General

As illustrated in Figure 7-1 a pellet-filled slot will be present between the rock surface and the backfill blocks and the wall in the deposition tunnel. A similar gap will exist between the buffer blocks and the wall in the deposition holes. This means that all water that leaks in from the rock first comes into contact with a pellet filling material. Since these pellet filled volumes have a rather low density and initially placed with a substantial large pore size it is unlikely that it will be able to completely prevent piping and potentially erosion in the channels that are formed in the pellets during the initial water inflow period. It should be noticed that this piping and erosion period is likely only to be of concern during the period when backfilling operations are ongoing and considerable gradients and volumes into which water can drain will exist. Once backfilling is completed and bulkheads that will prevent ongoing piping are installed this water movement process will be reduced and the clay will eventually be able to swell and close these features.

It takes either a very high swelling pressure or an equally high water pressure in the backfill to stop water inflow. This means that the inflow will not be stopped until either the backfill is highly water saturated (which takes years) or the tunnel plug in the end of the deposition tunnel is sealed and the water pressure gradient is transferred to the plug. The latter cannot take place until all open voids are filled with water and a water pressure established inside the plug.

The conclusion drawn from these tests is that there will be ongoing water inflow and erosion into the tunnel until the entire empty space in the pellets filling is filled with water. When the plug is sealed there will be no leakage of water out of the tunnel so there will be only internal erosion. Since the empty volume in the pellets filling is known and equal to the total water inflow that can cause erosion the maximum erosion that can take place can be calculated provided that the erosion rate is known.

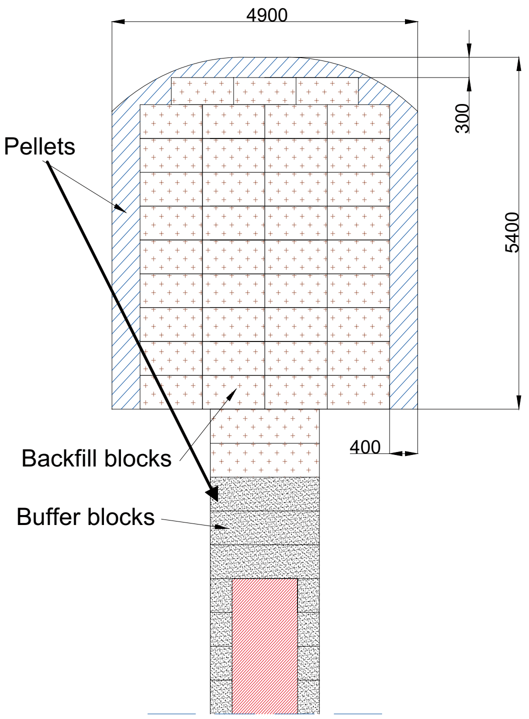


***Figure 7-1.** The rock surface in both the deposition tunnel and the deposition holes is in direct contact with pellets filling.*

80% block filling yields the total volume of pellets filling:

$V_{pellets}$ = 300 • 0.2 • 25 m^3= 1,500 m^3

50% open space in the pellets filling yields the total volume that needs to be filled with water:

V_{space} = 750 m^3

The most extreme case that yields the largest erosion is that all water inflow into the entire tunnel comes in at one point. Measurements have shown that the erosion is between 1 and 10 g per litre of eroding water (at least in the beginning). With this rough estimation the consequence of erosion will be the following:

Erosion 1–10 g/l in 750 m^3 eroding water yields 750–7,500 kg eroded backfill.

If the inflow rate is 1 l/min it will take 1.43 years to fill the tunnel and stop the erosion.

Although this is an extreme scenario the example shows that the consequences of internal erosion can be severe for the backfill and that a better understanding and an improved model of the erosion is desirable in order to find the limits.

7.2 Preliminary model

All results from the reported erosion tests are plotted in Figure 7-2 with the accumulated dry mass of eroded material as a function of the accumulated water flow in double logarithmic diagrams. The diagrams clearly show that there seems to be a fairly linear relation and that most relations have similar inclination.

A model can be derived from these test results assuming linear relation in such a double logarithmic diagram:

$$m_s = \beta \bullet (m_w)^{\alpha} \quad (7\text{-}1)$$

where

m_s= accumulated mass of eroded bentonite (g)

m_w= accumulated mass of eroding water (g)

β = 0.02–2.0 = parameter defined by the level of erosion at a certain accumulated water flow

α = 0.65 = parameter defined by the inclination of the straight line relation

α = 0.65 yields a rather strong decrease in erosion rate with time and accumulated water flow. Constant flow rate corresponding to α = 1.0 is also illustrated in the figure.

The model can also be used to determine the expected erosion rate:

The water flow rate can be expressed according to Equation 7-2.

$$q_w=\delta m_w/\delta t =(at\ constant\ rate)=m_w/t \quad (7\text{-}2)$$

Differentiation of Equation 7-1 yields the rate of erosion as function of the accumulated mass of eroding water:

$$\delta m_s/\delta m_w=\beta \cdot\alpha\cdot (m_w)^{\alpha-1} \quad (7\text{-}3)$$

Insert $\delta m_w=q_w\delta t$ and $m_w=q_wt$ in Equation 7-1:

$$\delta m_s/\delta m_w=\beta \cdot\alpha \cdot(q_w\cdot t)^{\alpha-1} \quad (7\text{-}4)$$

$$\delta m_s/\delta t=q_w\cdot\beta \cdot\alpha \cdot(q_w\cdot t)^{\alpha-1} \quad (7\text{-}5)$$

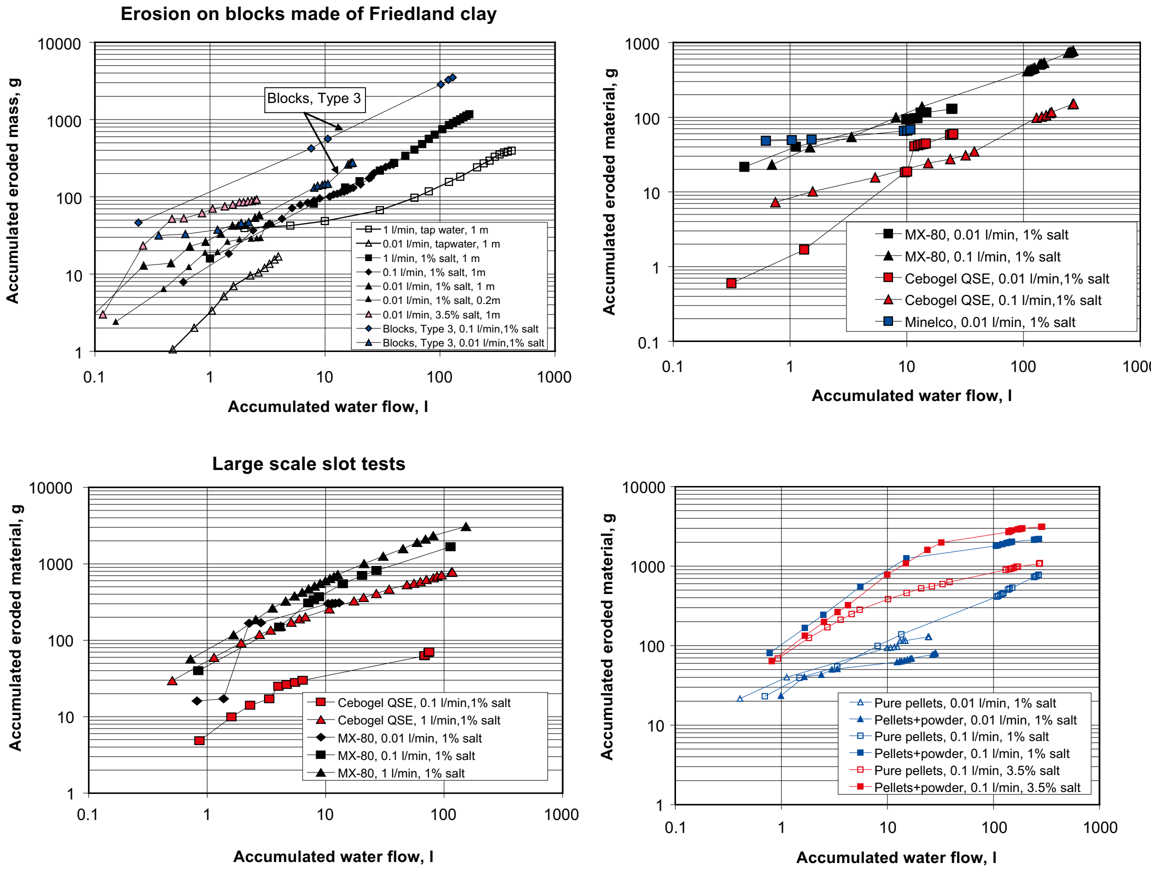


Figure 7-2. *Results of erosion tests plotted as accumulated dry mass of eroded material as a function of accumulated water flow in double logarithmic diagrams (diagrams of larger size are available, see Figure 3-3, 4-5 and 6-6).* ***Upper left:*** *Friedland clay blocks.* ***Upper right:*** *Tube tests of different pellet materials.* ***Lower left:*** *Slot tests of different pellet materials.* ***Lower right:*** *Tube tests of pellets mixed with 50% powder.*

Figure 7-3 shows all results plotted in one diagram. All data is limited by two lines with the inclination corresponding to $\alpha = 0.65$ and the erosion level corresponding to $\beta = 0.02$ (lower line) and $\beta = 2.0$.

Equations 7-4 and 7-5 thus yield the rate of erosion as function of time at constant flow rate:

$$q_{mv} = \delta m_s/\delta m_w = \beta \cdot \alpha \cdot (q_w \cdot t)^{\alpha-1} \qquad (7\text{-}4b)$$

$$q_{mt} = \delta m_s/\delta t = q_w \cdot \beta \cdot \alpha \cdot (q_w \cdot t)^{\alpha-1} \qquad (7\text{-}5b)$$

where

q_{mv} = erosion rate (grams dry backfill per ml eroding water) at time t

q_{mt} = erosion rate (grams dry backfill per second) at time t

q_w = water flow rate (grams eroding water per second)

t = time (s)

β = 0.02–2

α = 0.65

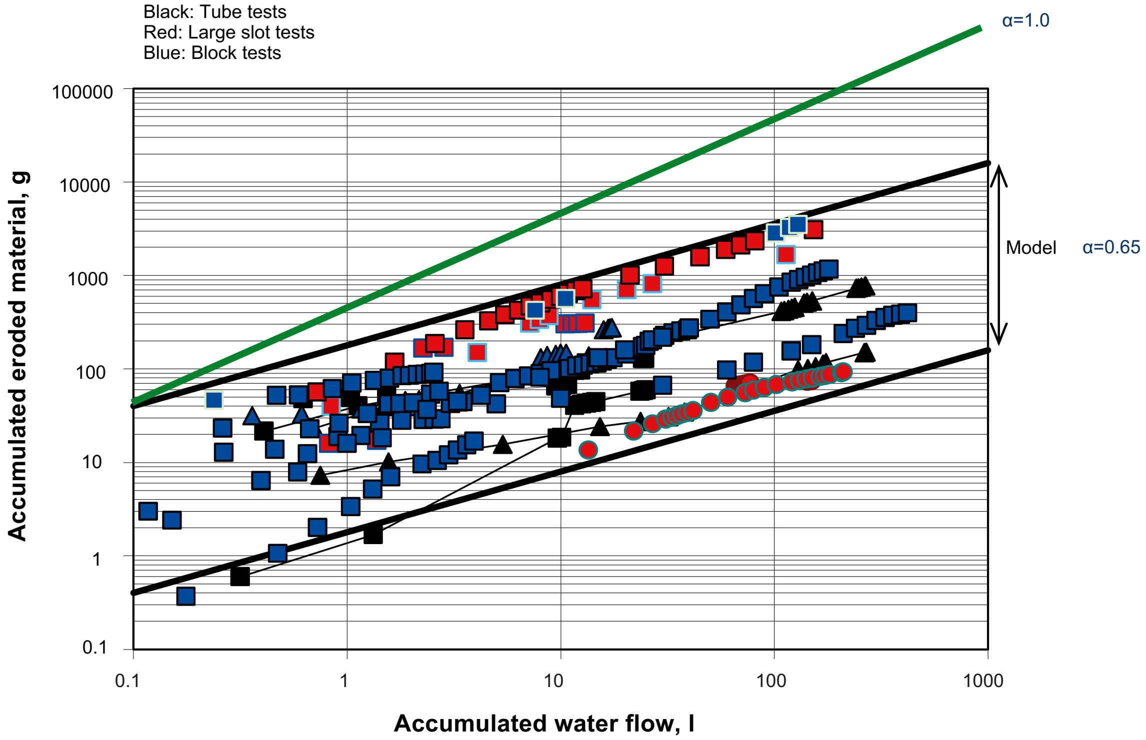


Figure 7-3. *All erosion results plotted in one diagram. The lower boundary line corresponds to β = 0.02 and the upper β = 2.0. The inclination of the boundary lines corresponding to α = 0.65 is motivated by the figure. α = 1.0 (corresponding to constant erosion rate) is also illustrated.*

7.3 Application of the new model

The new model can now be applied to the same extreme scenario (Chapter 7.1).

750 m^3 (= $7.5 \cdot 10^8$ g) eroding water yields according to Equation 7-1

$m_s = \beta \cdot (m_w)^{\alpha}$

$m_s = (0.02\text{–}2) \cdot (7.5 \cdot 10^8)^{0.65}$ = 11.7–1,170 kg

The total expected mass of eroded backfill will with this model be only between 11.7 and 1,170 kg which is 1.5–15% of the erosion estimated when a constant erosion rate of 1–10 g/l was assumed.

The rate of erosion at different times can also be estimated with equation 7-5. If the inflow rate is 1 l/min the total time will be 1.43 years:

q_w = 1 l/min = 16.7 g/s

t = 1.43 years = $4.5 \cdot 10^7$ s

Erosion rate after 1 hour: q_{mv} = 0.28–28 g/l (or q_{mt} = 0.28–28 g/min)

Erosion rate after 1.43 years: q_{mv} = 0.01–1.0 g/l (or q_{mt} = 0.01–1.0 g/min)

Although the erosion rate is similar after one hour (0.28–28 g/l) to what was assumed in the original example (1–10 g/l) it decreases with time so much that the total erosion is 7–70 times lower when the new model is used.

7.4 Conclusions and comments

A simplified erosion model based on the results of erosion tests has been suggested. It assumes a linear relation between accumulated eroded material and accumulated water flow in a double logarithmic diagram. It includes two parameters: α that corresponds to the inclination of the linear relation and β that determines the level of the accumulated erosion. Application of the model on an extreme case showed that the expected total mass of eroded material was reduced 7–70 times compared to what could be expected if a constant erosion rate of 1–10 g/l was assumed. Some observations and comments:

- α is little affected by the test material or conditions and is according to the measurements, a constant with the value 0.65.
- β must be measured and is dependant on the material type, the salt content, the water content, the pellet grain size distribution and the geometry etc.
- The model is preliminary but may be a way to put limits on the erosion that occurs.
- All tests have made on bentonite with low water content (10–17%) but the erosion seems to decrease with increasing water content.
- Since tests have so far only been made with short duration (less than a week) and with rather short flow paths, long term tests and tests in long tubes are needed in order to verify that the results can be extrapolated to actual field conditions.

8 Displacement of blocks during the installation phase

8.1 General

The reference concept for backfilling of deposition tunnels is to use compacted blocks. After emplacement of the blocks in the deposition drifts and for a period prior to installation of the pellet fill, they may be exposed to inflowing water from the surrounding rock. A process that could occur is water entry into the slots between the blocks, generating a swelling pressure that can move the surrounding blocks. This kind of process will be studied in large field tests, but in order to understand the process a pre-study have been performed in the laboratory. The tests were focused on the influence of the initial slot widths between the blocks, on the forces between the blocks and the possible displacement of the blocks.

8.2 Test description

Cylindrical block specimens with a diameter of 50 mm and a height of 25 mm were compacted in the laboratory with a pressure of 25 MPa. The materials were compacted at water contents close to the optimum to achieve maximum density at the selected load (determined earlier in the Baclo project /Johannesson and Nilsson 2006/, see Table 8-1.

Two types of tests were done in two different test setups, see Figure 8-1:

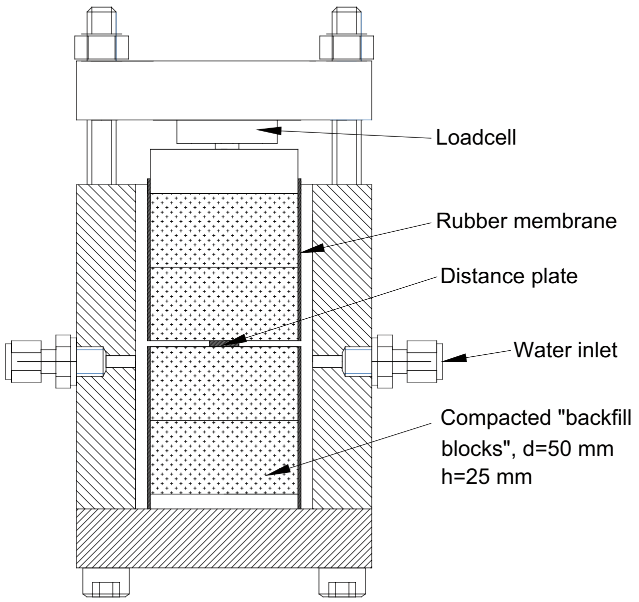
1. Measurement of the displacement between two blocks when a slot between two blocks is exposed to water in an unconfined condition.
2. Measurement of the force caused by the swelling bentonite when a slot between two blocks is exposed to water in a confined condition.

Figure 8-1 shows schematic drawings of the test equipment used in the tests. The equipment to the left was used for measuring the force achieved at confined conditions and the equipment to the right for measuring the displacement at unconfined conditions. In both test types the samples were covered with a rubber membrane that exposed only the slot to incoming water. The water level in the outer slot was kept constant about half-way up on the uppermost block.

In both test types, compacted blocks were placed on top of each other, with small distance plates between, setting the decided slot width. In order to separate the swelling of the whole block from the swelling in the slot, the outer periphery of the specimens were covered with a rubber membrane. This means that only the slot had access to water. The test equipment used for measuring the displacement (to the right in Figure 8-1), was equipped with a dead weight, acting on the uppermost block. The weight was set to give a pressure of 50 kPa. This weight simulates the friction and the average overload of backfill blocks above in an actual repository simulation.

Table 8-1. Table showing the initial date on static compaction of backfill blocks.

Material	Compaction pressure MPa	Water ratio %	Dry density kg/m^3
Friedland	25	9	2,000
Asha 230	25	16.7	1,695
Mixture (3) 30/70	25	7.2	2,150



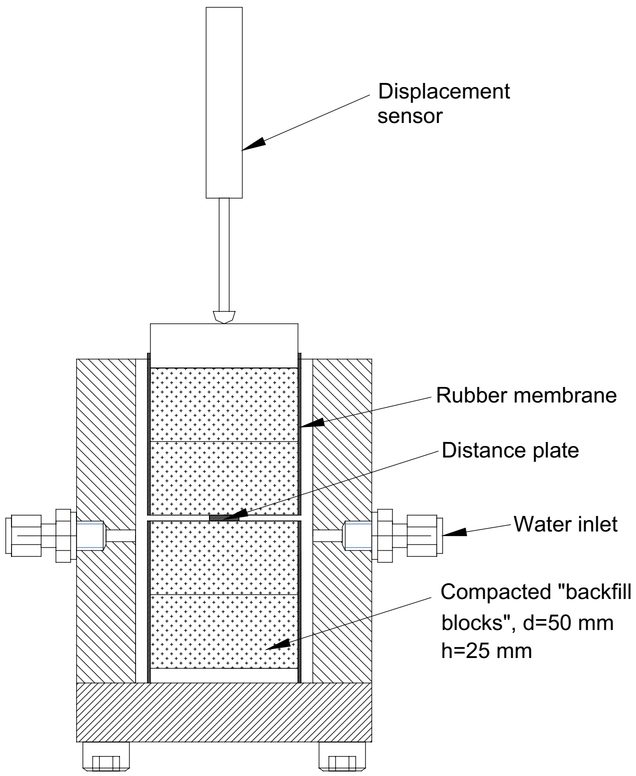


Figure 8-1. *Schematic drawing of the test equipment used.*

8.3 Test matrix

Three candidate backfill materials were tested: Friedland clay, Asha 230 and the Mixture 30/70 (30% bentonite and 70% crushed rock), see chapter 2. The complete test matrix for these tests is shown in Table 8-2. The tests performed are marked with green squares. Two tests were done using Friedland material where no initial slot was present between the block samples. These two tests were performed with 1% salt solution as the inflow water.

Table 8-2. Table showing the test matrix.

Displacement of backfill blocks. Friedland						
Slot width mm	Tap water Force	Displacement	1% salt Force	Displacement	3.5% salt Force	Displacement
0	E:110	E:120	E:210	E:220	E:310	E:320
0.5	E:111	E:121	E:211	E:221	E:311	E:321
2	E:112	E:122	E:212	E:222	E:312	E:322
5	E:113	E:123	E:213	E:223	E:313	E:323

Displacement of backfill blocks. Asha 230						
Slot width mm	Tap water Force	Displacement	1% salt Force	Displacement	3.5% salt Force	Displacement
0	E:110	E:120	E:210	E:220	E:310	E:320
0.5	E:111	E:121	E:211	E:221	E:311	E:321
2	E:112	E:122	E:212	E:222	E:312	E:322
5	E:113	E:123	E:213	E:223	E:313	E:323

Displacement of backfill blocks. 30/70 BallastB / Deponit C-A-N						
Slot width mm	Tap water Force	Displacement	1% salt Force	Displacement	3.5% salt Force	Displacement
0	E:110	E:120	E:210	E:220	E:310	E:320
0.5	E:111	E:121	E:211	E:221	E:311	E:321
2	E:112	E:122	E:212	E:222	E:312	E:322
5	E:113	E:123	E:213	E:223	E:313	E:323

8.4 Results

8.4.1 General

The technique of using a rubber membrane (as shown in the picture in Figure 8-2) in order to only give the slot between the blocks access to water was successful. The test duration was set to be about 1 week (two tests with Asha 230, displacement tests, were run for two weeks).

Figure 8-2 shows one of the Friedland specimens before test start and after terminating of the test. The picture to the left shows the lower blocks standing on a steel pedestal and covered with rubber membrane. The O-ring ensures that no water leaks in under the bottom block, which would strongly influence the results. The photo on the right was taken after termination of the test. It was obvious that the blocks also had swelled radial during the test period.

In the unconfined tests measuring the displacement a dead weight of 50 kPa was applied on the top of the piston simulating the weight of the overburden.

In the tests measuring the force the results are presented as load and not as a pressure, since the "active surface" between the blocks not is fully known. A measured load of 1 kN corresponds to a pressure of 509 kPa if acting on the whole block surface.

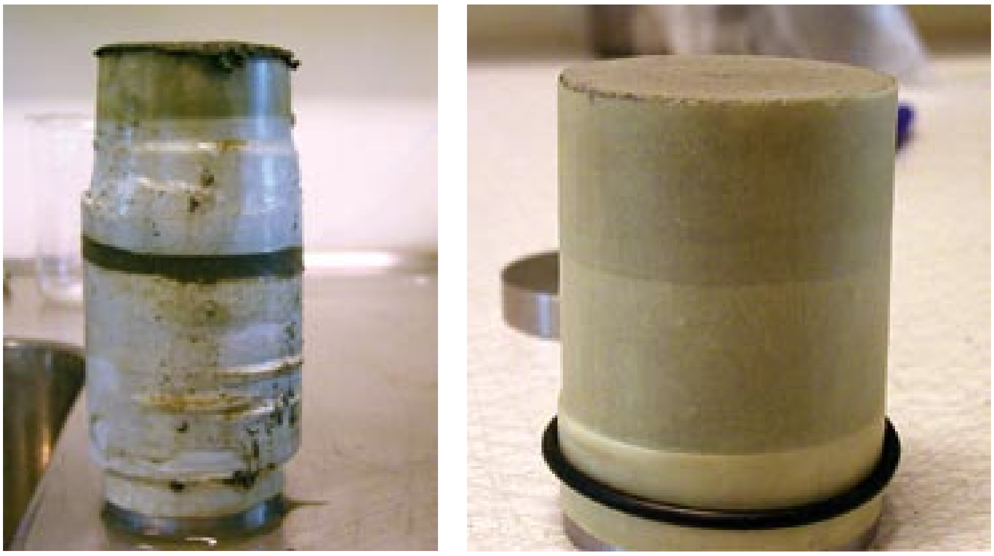


Figure 8-2. Picture showing a Friedland specimen before (left) and after (right) testing.

8.4.2 Influence of initial slot width

In Figure 8-3 and 8-4 the results from the unconfined tests with Friedland blocks are shown. In these figures the displacements of the specimens are plotted vs. time. They show very distinctly that the initial slot width between the blocks strongly influences the displacement that occurs. With a small initial slot between the blocks, 0–0.5 mm, the displacement started immediately after the bentonite got access to water. The total displacement with these small gaps was about 7 mm after one week, independent of the water type (1% salt and 3.5% salt). When the initial slot was increased to 5 mm it took almost 2 days before any displacement at all and after 1 week was the total displacement about 2 mm.

The results from the unconfined tests with Friedland block are very consistent when compared with the corresponding confined tests where the force was measured. Figures 8-5 and 8-6 show the results from these tests. For small initial slots, the forces built up due to the swelling of the bentonite were considerable higher, 5–6 times, when compared with the specimens having an initial slot of 5 mm.

8.4.3 Influence of salt content in the water

The results from the tests with Friedland blocks provided as Figure 8-3 to 8-6 indicate that the influence of the initial slot width is stronger than the influence of the salt content in the water. The results were similar irrespective of whether the tests were performed with 1% or 3.5% salt in the water.

In Figure 8-7 and 8-8 the results from tests with the same initial slot width (2 mm) are presented. Tests were done with all three materials and also different salt content in the water. The influence of the salt content in the water is very small for these materials. One of the tests with Friedland blocks used potable water and in the displacement test it was observed that the swelling of this specimen was somewhat higher than in the tests performed with same material but with salt in the water (1% or 3.5%), see Figure 8-7. The displacement tests showed that the swelling potential of the Friedland and the Asha 230 is higher than for the 30/70 mixture. The measured displacement was negative for the 30/70 material. The displacement was in the same order as the initial slot width i.e. 2 mm. When the slot surfaces were exposed to water there have probably been a softening of the material and the distance plates have sunk into the specimens. The corresponding confined tests with the 30/70 mixture yielded no swelling-induced force, see Figure 8-8. The tests with Friedland clay showed a peak upwards force within one day of the test starting. After the initial increase of the measured force, it decreased to a level of about 0.2–0.3 kN while the tests with Asha 230 ended with a force between 1 and 1.4 kN. The difference in the forces measured can be attributed to the swelling clay content differences in these materials.

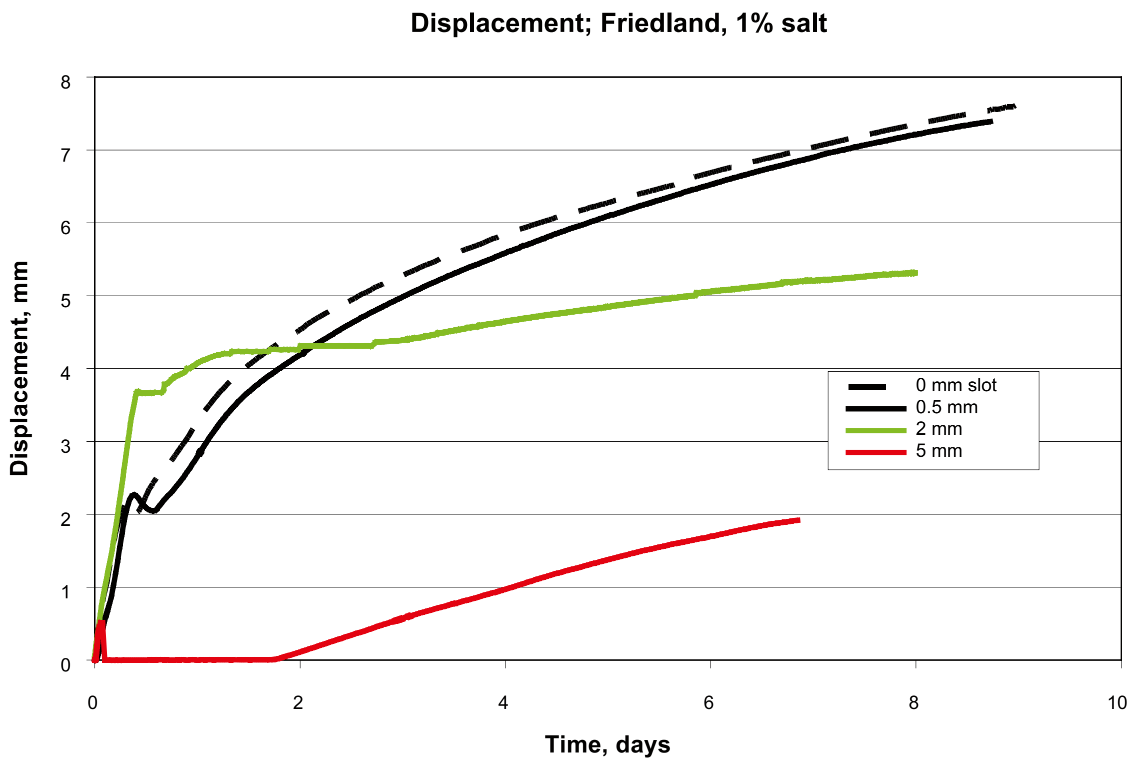


Figure 8-3. The results from the unconfined tests where displacement was measured (1% salt solution) plotted vs. time.

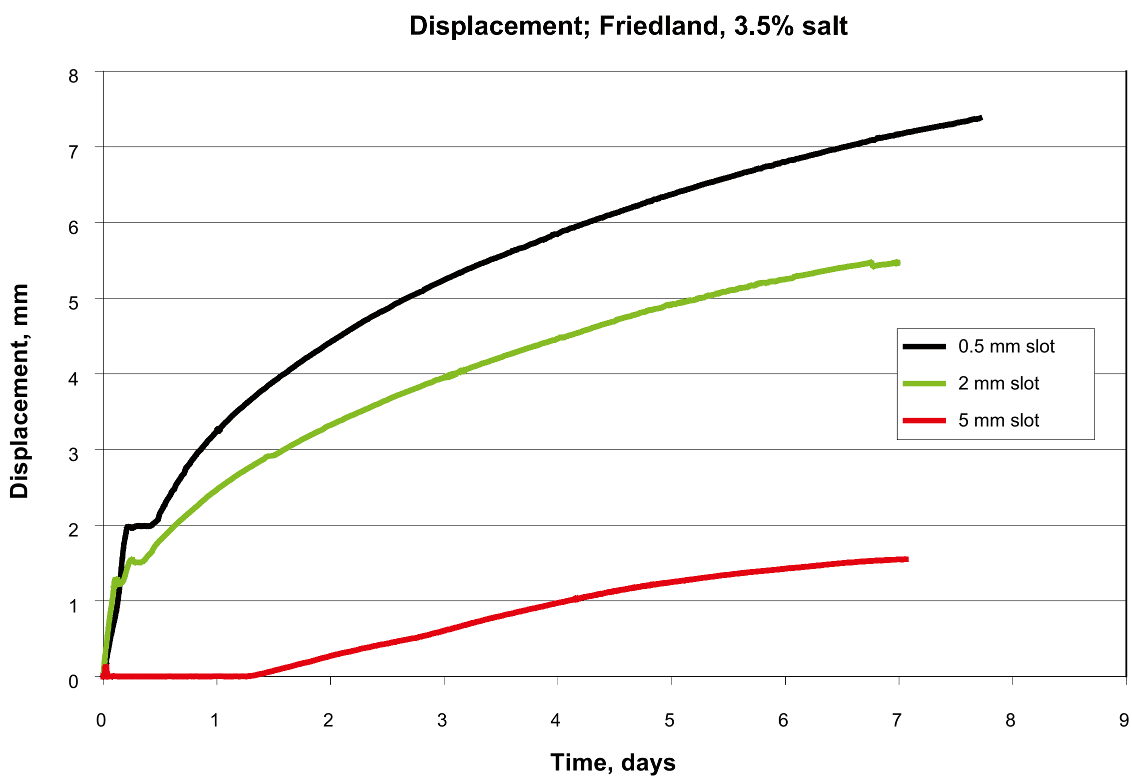


Figure 8-4. The results from the unconfined tests where displacement was measured (3.5% salt solution) plotted vs. time.

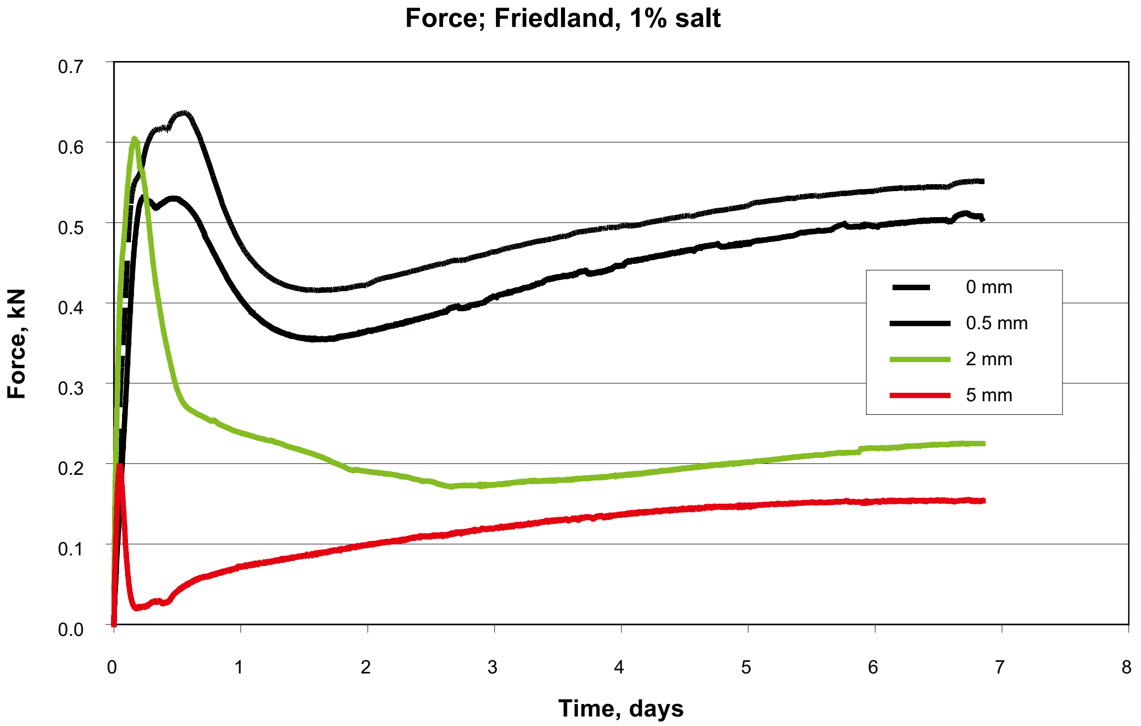


Figure 8-5. The results from the confined tests where force was measured (1% salt solution) plotted vs. time.

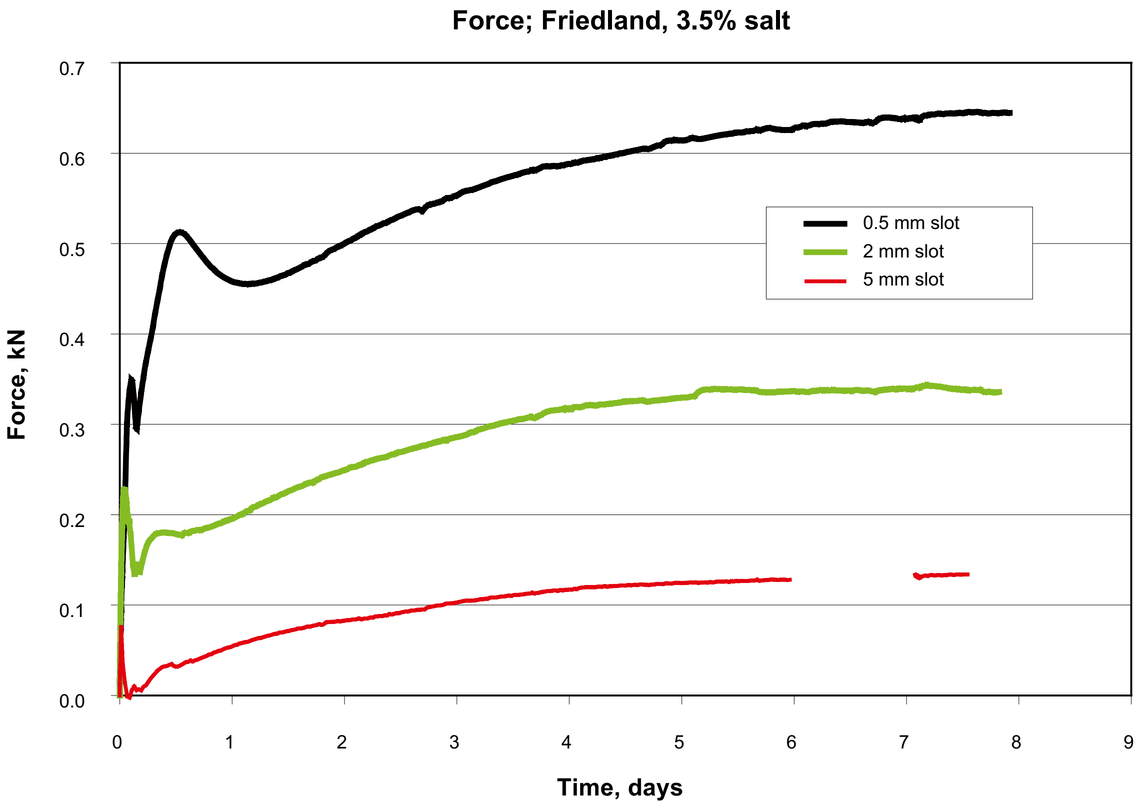


***Figure 8-6.** The results from the confined tests where force was measured (3.5% salt solution) plotted vs. time.*

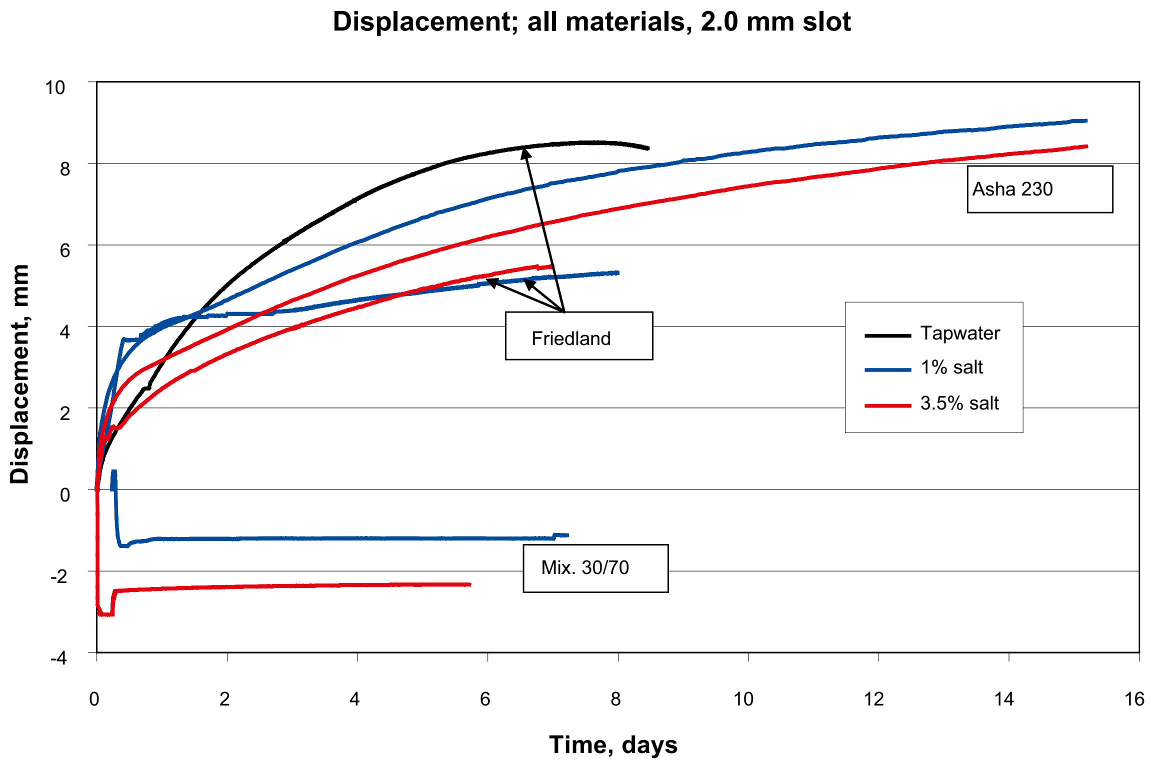


Figure 8-7. The results from unconfined tests measuring displacement with time.

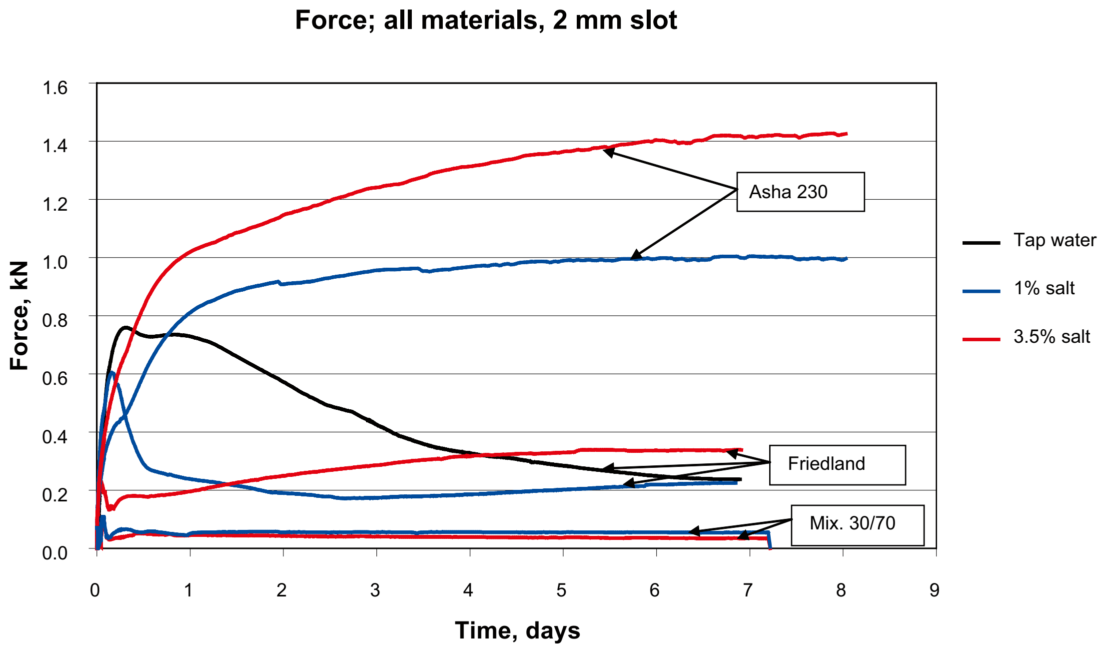


***Figure 8-8.** The results from the confined tests measuring the force. The tests are performed with different materials, different waters and with an initial slot of 2 mm.*

8.5 Conclusions and comments

These tests were done with three materials which could be used for manufacturing of backfill blocks, Asha 230B, Friedland and Mixture 30/70. The aim of this test series was to investigate how different initial slot widths between the blocks after emplacement may affect the displacement and forces between blocks when water comes in contact with the slots. Some conclusions from the test series are as follows:

1. **Scale effects**. The tests described in this chapter were done at bench-scale which means that the mass and dimensions of full-sized blocks probably will result in different magnitudes of displacement than were measured here. The processes described are likely relevant and significant to a field application but care should be used when evaluating the magnitudes of displacements measured.
2. **Influence of initial slot width**. The tests showed clearly that the initial slot width between the blocks influences the displacement very strongly under unconfined conditions. With a small initial slot between the blocks 0–0.5 mm, the displacement started immediately when the bentonite got access to water. The total displacement with these small gaps was about 7 mm after one week, independent of the water type (1% salt and 3.5% salt). When the initial slot was increased to 5 mm it took almost 2 days before any displacement took place and after 1 week the total displacement was about 2 mm. The results from the tests with Friedland blocks were consistent when compared with the corresponding tests at confined conditions where instead of displacement the force was measured. When the initial slot was small, the force that was build up due to the swelling of the bentonite was considerable higher, 5–6 times, than in the tests with specimens having an initial slot of 5 mm.
3. **Influence of salt content**. The results from these tests indicate that the influence of the initial slot width was stronger than the influence of the salt content in the water. The results were similar irrespective of whether the tests were performed with 1% or 3.5% salt in the water.
4. **Influence of material**. Asha 230 B has the highest montmorillonite content and by that also reacts stronger when exposed to water i.e. the displacements are larger and the forces built up higher than for the other two tested materials. The Friedland blocks were almost as sensitive as the Asha blocks regarding displacement but the measurements of forces that were built up during the test time was lower. The reaction from the blocks made of the Mixture 30/70 when exposed for water in the slot between them was very small both regarding displacement and forces built up.

9 Plug tightness required in order to stop erosion of backfill materials

9.1 General

After plugging a disposal drift there may be water leakage from the plugged section past the plug either between the in-situ cast plug and the rock or in fractures in the rock. This test series was intended to check the ability of the bentonite pellets to seal these leakage paths. The parameters varied are the aperture of the slot (leakage way), the water flow rate and also for one test, the salt content in the water.

9.2 Test description

The erosion tests were performed in specially designed equipment as shown in Figure 9-1. The test chamber was filled with pellets. The dry density of the filling was about 980 kg/m^3. The top of the test apparatus was equipped with a special flange, simulating a slot or a fracture in the rock. The slot width could be set to a desired value by using different shims/steel parallels. The slot width was after mounting controlled with a thickness gauge. The slot width varied somewhat after assembling the equipment. The aperture was slightly smaller (~ 50 micron) in the middle between the shims, which may have affected the results for the tests performed with the smallest slot widths. The lid is very stiff and at the maximum applied pressure was the bending calculated to be negligible, i.e. the aperture was constant during the test time.

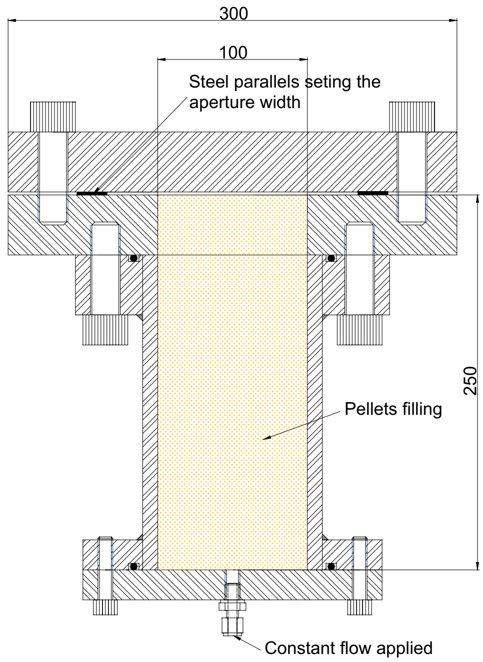


***Figure 9-1. Left:** Picture from the laboratory showing the assembled equipment just before test start.*
***Right**: Schematic drawing of the test equipment.*

The tests were started by applying a constant water flow from the bottom. In order to avoid a very rapid pressure increase, a gas volume of about 0.6 liter was included in the pressurizing system. The achieved water pressure was measured during the test. When a water pressure of 1 MPa was reached, if possible, the constant flow was transformed to a pressure ramp with a pressure increase rate of 1 MPa/h. The maximum pressure allowed was 5 MPa.

The following was measured/controlled during each test:

1. Water flow into the system (was set to a decided value on the microprocessor controlled pump).
2. Achieved water pressure. A separate transducer registered the water pressure.

9.3 Test matrix

All experiments of this type were done using MX-80 pellets, mostly with 1% salt in the water. In order to study the influence of the salt content the test series was complemented with one test with 3.5% salt in the water. The tests were performed with two different water flow rates, 0.01 l/min and 0.1 l/min.

9.4 Result

A compilation of all tests is shown in Table 9-1. The first test was done with a low water flow rate (0.01 l/min) and a rather small aperture of the artificial “fracture” (0.05 mm). As shown in Figures 9-2 and 9-3, the pellets sealed the fractures and could also withstand 5 MPa water pressure.

In Figure 9-2 it can be seen that after about three hours the water pressure had increased to 1 MPa and the applied constant flow was then changed to a pressure ramp of 1 MPa/h up to a maximum of 5 MPa.

The picture provided as Figure 9-3 shows the fracture after removal of the upper lid. The eight thin plates are the parallels setting the aperture width. Bentonite has been transported out into the fracture and sealed the flow paths.

In the next two tests the aperture was increased too 100 and 150 um respectively. The results of these two tests were important to the question of sealing of joints and cracks. In both of these specimens they sealed and could withstand 5 MPa hydraulic head, but the sealing did not take place in the artificial fracture but in the pellets filled part. The upper part of the pellets filling was dry and the pellets had been compressed by hydration of materials underlying them, see Figure 9-4.

Table 9-1. Compilation of the configuration and results.

Test	Flow rate l/min	Water type	Dry bulk density kg/m^3	Intended slot width mm	Measured slot width mm	Remark
B:212-0.050	0.01	1% salt	955	0.050	0–0.050	Sealed
B:212-0.100	0.01	1% salt	942	0.100	0.050–0.100	Sealed
B:212-0.150	0.01	1% salt	950	0.150	0.100–0.150	Sealed
B:212-0.300	0.01	1% salt	944	0.300	0.200–0.300	Did not seal
B:212-1	0.01	1% salt	929	1.000	0.900–1.00	Did not seal
B:213-0.050	0.1	1% salt	952	0.050	0–0.050	Sealed
B:213-0.150	0.1	1% salt	966	0.150	0.100–0.150	Sealed
B:213-1	0.1	1% salt	931	1.000	0.900–1.00	Did not seal
B:312-0.150	0.01	3.5% salt	931	0.150	0.100–0.150	Sealed

The picture provided as Figure 9-4 shows the fracture after removal of the upper lid. The eight thin plates are the parallels setting the aperture width. The specimen sealed and could withstand 5 MPa. The sealing has however taken place in the pellets filling. The picture shows that the uppermost pellets have been compressed upwards against the fracture.

The following test was made with an aperture width of 1 mm, still a water inflow of 0.01 l/min and 1% salt in the water. There was no tendency during the test time, almost 8 hours that the bentonite could seal this fracture (see the diagram in Appendix 27). A new test was done with the same parameters but the aperture of the fracture was set to 300 um. A small water pressure was built up, about 90 kPa at the maximum, but the specimen could not seal. A new test series was done where the water inflow rate was increased to 0.1 l/min. Also for this flow the maximum aperture that the pellets could seal was 150 um. A complementing test was done using water with a salt content of 3.5%. The slot width was set to 50 um and the applied flow was 0.01 l/min. The result from this test was very similar to the results from Test 212-100 and Test 212-150 i.e. the specimen sealed but the sealing took place in the pellet fill.

After termination of each test the water content was determined at six levels in each sample. The results from these measurements are presented in the diagram in Figure 9-5. In three of the tests the sealing took place in the pellets filling. These three tests have water contents around 15% closest to the slot.

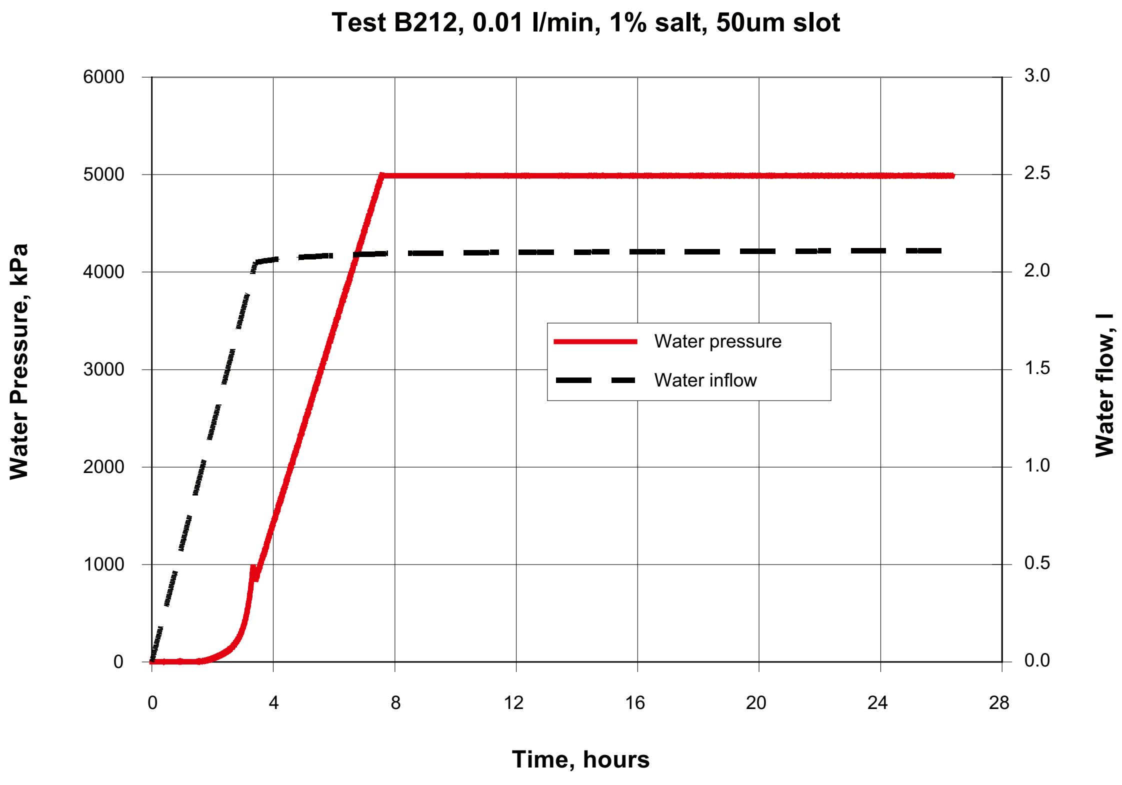


Figure 9-2. Results from the test performed with a water flow rate of 0.01 l/min and an aperture of the fracture of 50 um. The water pressure and the accumulated water flow is plotted vs. time.

Figure 9-3. *Test performed with 0.01 l/min, 50 um aperture and 1% salt in the water.*

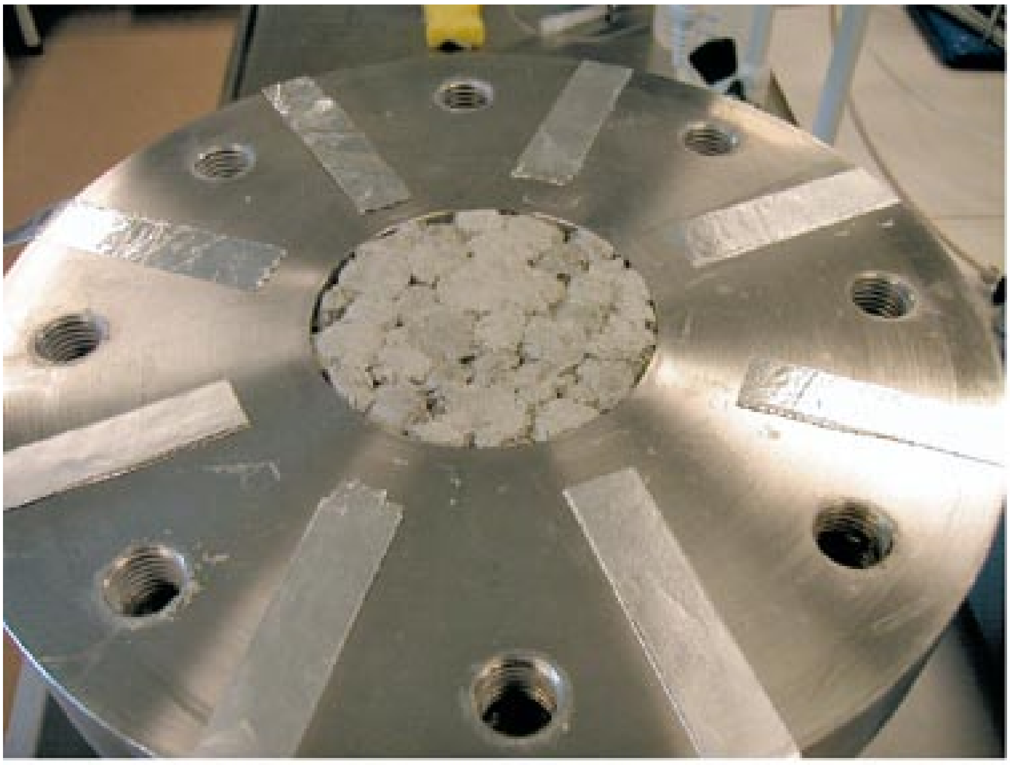


Figure 9-4. *Test performed with 0.01 l/min, 100 um aperture and 1% salt in the water.*

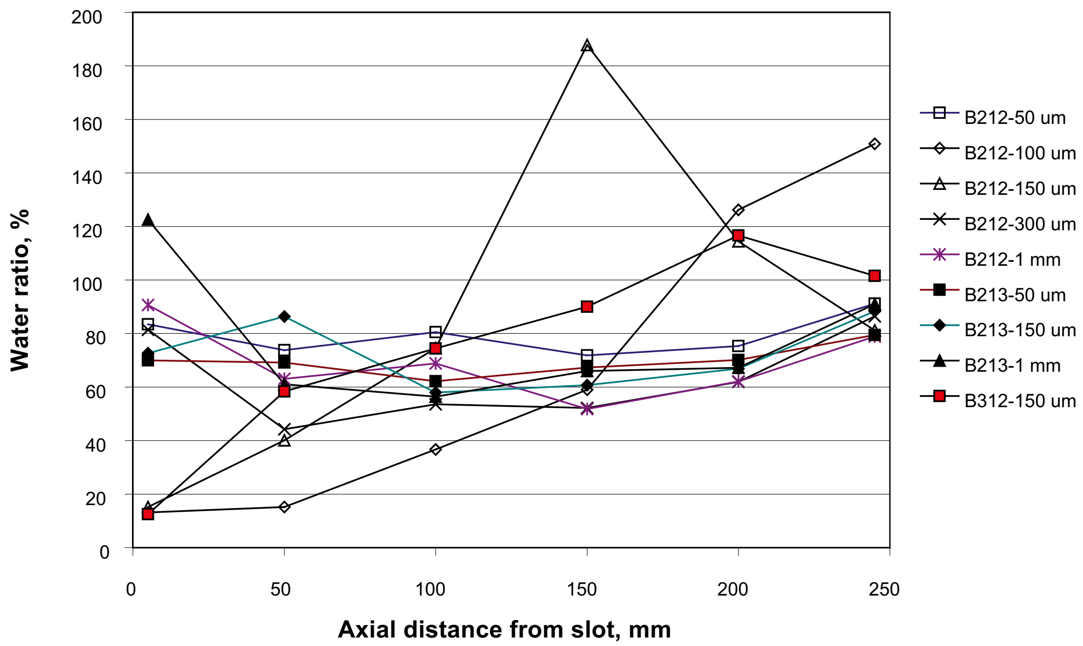


Figure 9-5. *Water content distribution in the pellets filling after termination. The water content is plotted vs. the axial distance from the slot.*

9.5 Conclusions and comments

The diagram in Figure 9-6 shows a compilation of all test results. Detailed results from all tests are presented in Appendix 23-31. The tests indicated that the maximum slot width that the MX-80 pellets can seal for at these flow rates and under these conditions is 0.15 mm. The total number of tests done is limited and the results should be seen more as an indication of the capability for this material to seal a fracture and not as an exact limit.

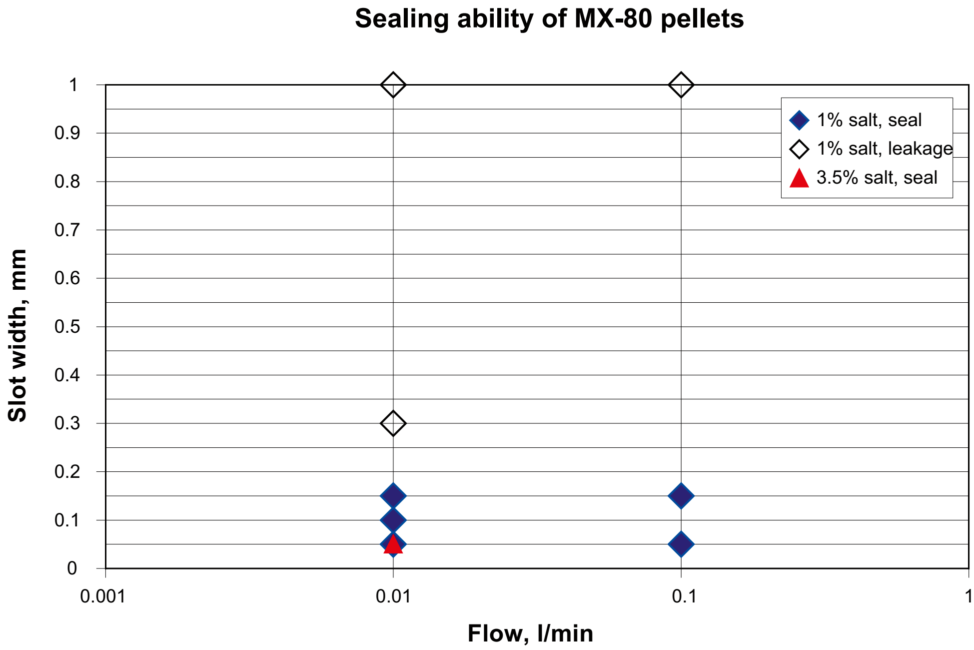


Figure 9-6. *Compilation of the test results. The different slot widths are plotted vs. different water flow rates. The tests indicate that the maximum slot width that the MX-80 material could seal was 0.15 mm for the tested flow rates.*

10 Self healing ability of some backfill materials

10.1 General

The aim of these tests was to study the healing ability of the backfill materials after piping. A pre test had been done earlier with 30/70 within the Baclo project /Sandén et al. 2008/. The healing ability of this material seemed to be very low.

In this test series four materials have been tested: Asha 230, Friedland, the mixture of 30/70 (Deponit–CA-N/Ballast B) and also MX-80 pellets.

10.2 Test description

The tests were performed in oedometers where specimens with an outer diameter of 50 mm and a height of 50 mm could be tested (the tests with MX-80 pellets were performed in a similar piece of equipment, but having an inner diameter of 101 mm and a specimen height of 85 mm). Each material, except the MX-80 pellets, was compacted to two different densities. The higher density corresponds to an average dry density of the backfill material in a cross section /Johannesson et al.2006/. Piping will however probably occur at the outermost parts of the deposition tunnel where the backfill has swollen and the density is lower. Based on this density gradation, the lower density condition was chosen for inclusion in the test matrix. The chosen density of the pellets specimens corresponds to the bulk density of the filling after pouring the pellets into the vessel without any additional compaction. Both of these conditions are therefore conservative and represent the least dense conditions anticipated to occur.

Saturation of samples

After preparation of the specimens they were placed in oedometers, Figure 10-1, and contacted to water via the steel filters placed on both sides of the samples. Tubes were connected to the oedometers in one end and to burettes in the other end. The burettes were set to provide a water pressure of about 1 meter during the saturation time. The saturation time lasted for about 1.5 to 2 months. During this time no measurements were done except for in the oedometers with pellets, where the swelling pressure was measured.

Measuring of hydraulic conductivity

When the specimens were saturated, the hydraulic conductivity was determined by applying a water pressure in the bottom of the oedometer and measuring the volume of the discharged water on the other side per unit time. The applied pressure was different for the different materials (see Table 10-2), and there was no backpressure applied during the measurement of the hydraulic conductivity. When the measurements were finished, the lids of the oedometers were removed and a hole, d= 5mm (10 mm for one of the pellets samples), was drilled through the center of each specimen. The lids were then re-mounted and the specimens were again provided with passive access to water (a small through flow in the drilled hole was done in order to avoid the problem with air pockets and then a source of water was connected to the specimen, providing the specimen with whatever water it wanted to take in). After a certain time of healing, about three weeks, the hydraulic conductivity was measured again with the same method as previous.

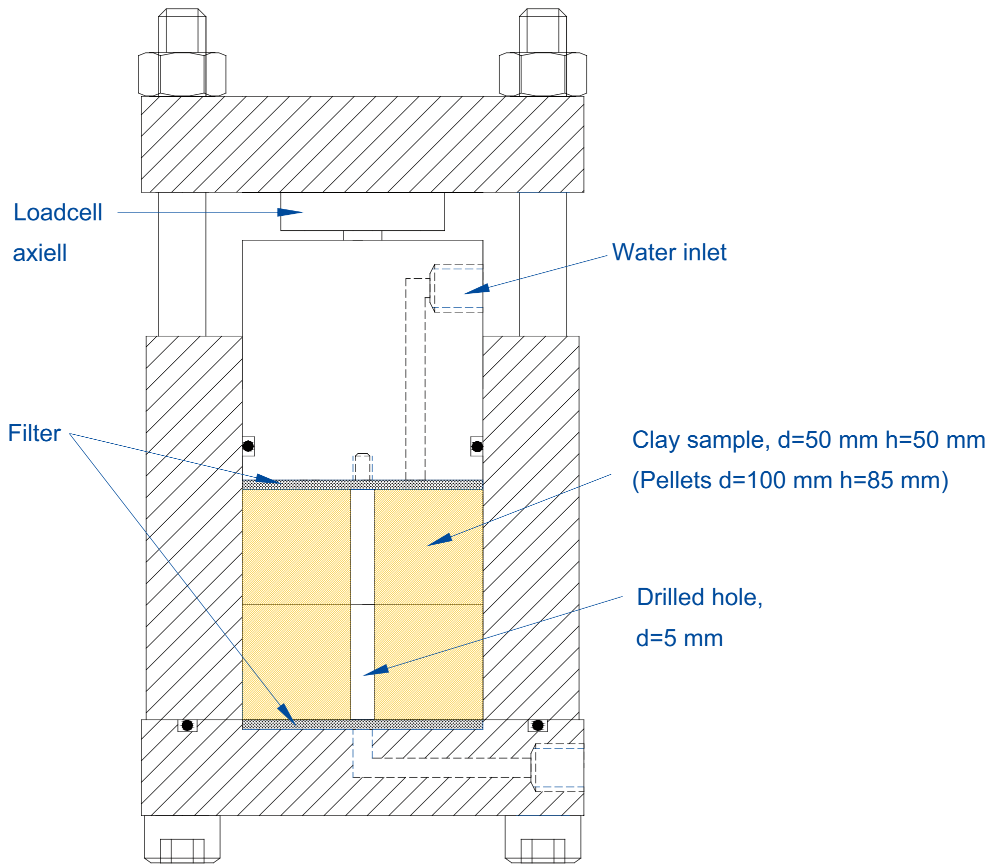


Figure 10-1. *Schematic drawing of the test equipment used in self-healing tests. In the tests with MX-80 pellets a larger test cell was used (inner diameter= 101 mm, height= 85 mm).*

10.3 Test matrix

The test matrix is shown in Table 10-1. The performed tests are marked with colored boxes. Test number SH103, MX-80 pellets and 3.5% salt in the water, was doubled. The only difference between the two specimens was the diameter of the drilled hole which was 5 mm and 10 mm respectively.

Table 10-1. Table showing the test matrix for the self healing tests.

Water type	Pellets, Mx-80	Asha 230		Friedland		Mixture 30/70	
	950 g/cm³	1,540 g/cm³	1,440 g/cm³	1,780 g/cm³	1,680 g/cm³	1,900 g/cm³	1,800 g/cm³
Tapwater	SH101	SH201	SH301	SH401	SH501	SH601	SH701
1% salt	SH102	SH202	SH302	SH402	SH502	SH602	SH702
3.5% salt	SH103	SH203	SH303	SH403	SH503	SH603	SH703

10.4 Results

10.4.1 General

All materials tested, except the 30/70 mixture, showed some self healing ability. The time dependence of the healing ability was not tested in this investigation (all specimens had a healing time of 3 weeks). The influence of salt in the water could only be seen in the tests with MX-80 pellets and the 30/70 mixture. This depends on the low clay density in these specimens. The loss of material caused by the drilling of the central hole was about 1% of the specimen's weight.

A compilation of the test data is presented in Table 10-2.

Table 10-2. Data from the self healing tests.

Material	Calc.dry density/ sat. density kg/m³	Measured sat.density kg/m³	Water	Applied water pr. kPa	H.K. before drilling m/s	Healing time	H.K. after healing m/s	Remark
MX-80 pellets	980/1,627	1,595	1% salt	20	2.1×10^{-11}	3 weeks	7.7×10^{-11}	5 mm hole
MX-80 pellets	980/1,627	1,595	3.5% salt	20	9.6×10^{-11}	3 weeks	1.3×10^{-8}	10 mm hole
MX-80 pellets	980/1,627	1,562	3.5% salt	20	1.2×10^{-10}	3 weeks	5.4×10^{-9}	5 mm hole
Asha 230	1,440/1,922	1,927	3.5% salt	500	2.8×10^{-13}	3 weeks	3.3×10^{-13}	5 mm hole
Asha 230	1,540/1,986	1,945	1% salt	500	9.7×10^{-14}	3 weeks	1.5×10^{-13}	5 mm hole
Asha 230	1,540/1,986	1,987	3.5% salt	500	1.3×10^{-13}	3 weeks	1.4×10^{-13}	5 mm hole
Friedland	1,680/2,076	2,064	3.5% salt	500	3.2×10^{-12}	3 weeks	1.4×10^{-10}	5 mm hole
Friedland	1,780/2,140	2,120	Tapwater	500	1.0×10^{-12}	3 weeks	1.2×10^{-12}	5 mm hole
Friedland	1,780/2,140	2,114	1% salt	500	1.2×10^{-12}	3 weeks	1.6×10^{-12}	5 mm hole
Friedland	1,780/2,140	2,130	3.5% salt	500	1.2×10^{-12}	3 weeks	2.2×10^{-12}	5 mm hole
Mix.30/70	1,800/2,153	2,100	3.5% salt	20	1.1×10^{-10}	3 weeks	2.6×10^{-7}	5 mm hole
Mix.30/70	1,900/2,217	2,151	1% salt	20	8.7×10^{-12}	3 weeks	4.2×10^{-9}	5 mm hole
Mix.30/70	1,900 / 2,217	2,164	3.5% salt	20	9.5×10^{-11}	3 weeks	6.4×10^{-8}	5 mm hole

10.4.2 MX-80 pellets

The swelling pressure was only measured in the tests performed with MX-80 pellets, Figure 10-4. After 35-36 days a water pressure of 20 kPa was applied in the bottom of the specimens in order to measure the hydraulic conductivity. 55–56 days after the start of testing the chambers were opened and a hole was drilled through the middle of the specimen. Following creation of the hole, the cell was closed and the specimen was allowed access to water. After three weeks of healing the hydraulic conductivity was measured again.

The measured values are quite similar, but there seems to be a somewhat higher swelling pressure for the specimen saturated with 1% salt in the water than for the other two tests saturated with 3.5% salt in the water which is to be expected for a system having lower salinity pore water provided to it.

The dry density of the pellet fills tested was very low compared to the other materials examined in this investigation. This is also the explanation for the strong influence of the salt content in the water on the healing ability. The specimen saturated with 1% salt in the water had healed the drilled hole after three weeks but for the other two specimens saturated with water with a salt content of 3.5%, there was a strong increase in the measured hydraulic conductivity. At termination of the tests all three specimens had the drilled hole still clearly visible but it was filled with a gel with noticeable lower density than the surroundings, see Figure 10-2. The water contents were determined at three levels in each specimen; close to the drilled hole and at the extreme perimeter, see Figure 10-3. The test performed with 1% salt in the water the specimen had homogenized best while in the test performed with 3.5% salt in the water and a 10 mm drilled hole there was still a large difference in water content in the different areas of these specimens.

Figure 10-2. *Picture from specimen SH103 (10 mm hole in MX-80 pellets) at the termination of the test. The drilled hole can still be seen very clearly. The hole is filled with gel with a higher water content than the surroundings.*

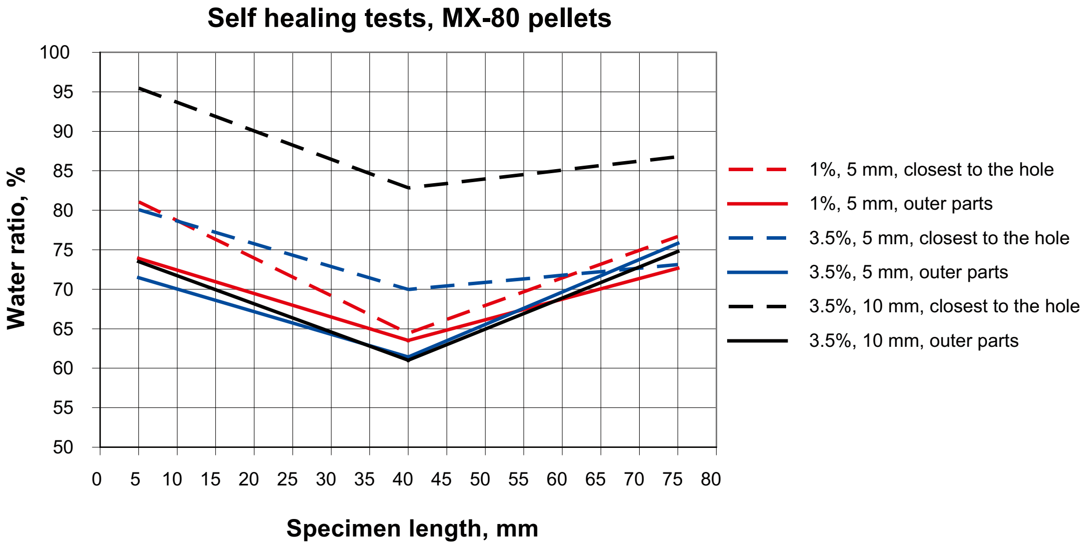


Figure 10-3. *Water content distribution measured in the three tests performed with MX-80 pellets. (Note the difference in water content between the outer parts and the parts around the pre-drilled hole for the specimens saturated with the higher salt content water (3.5%)).*

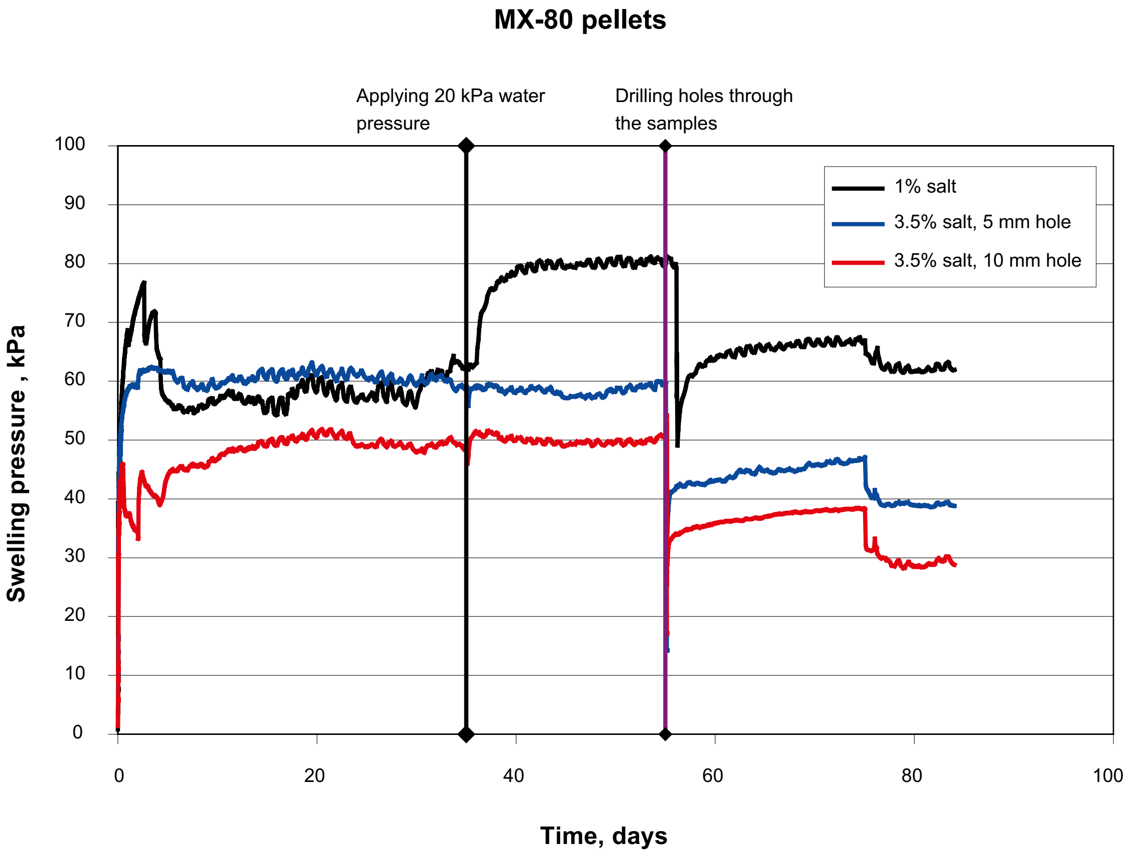


Figure 10-4. *Development of swelling pressure of MX-80 pellets with time.*

10.4.3 Asha 230

This material had healed so well that it was not possible to measure any difference in hydraulic conductivity before drilling of the hole and after three weeks of healing, Figure 10-5. Determination of the water content distribution in the specimens, Figure 10-6, shows however that there still are differences, a few percentage units, between the central parts and the outer parts of the specimens. These differences are however too small to discernibly influence the hydraulic conductivity.

Figure 10-5. *Picture from specimen SH203 at the termination of the test. The drilled hole has healed completely.*

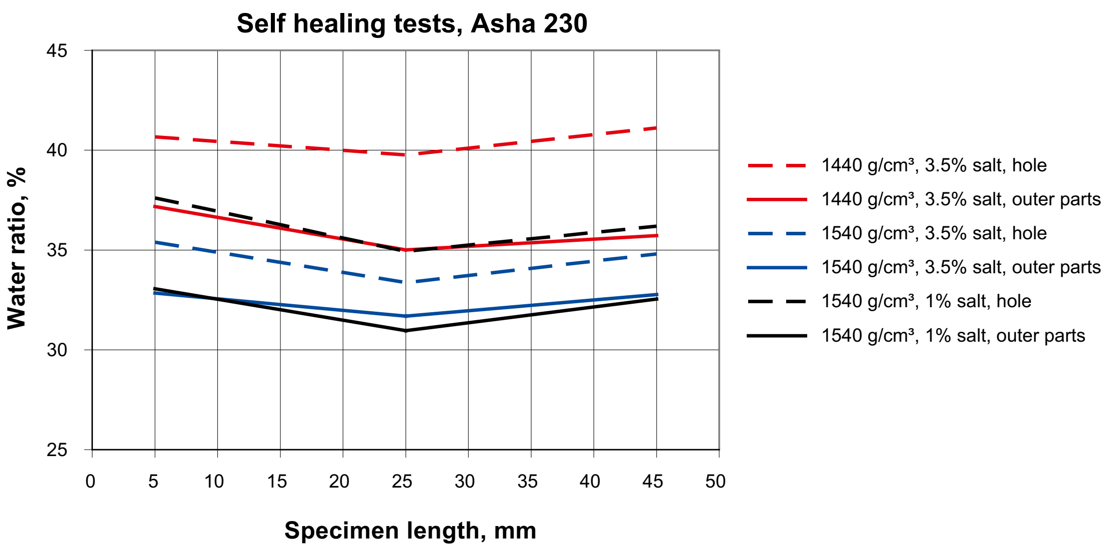


Figure 10-6. *Water content distribution in the three tests performed with Asha 230. There is still a small difference in water content between the central parts and the outer parts. This difference is however too small to influence the hydraulic conductivity more than marginally.*

10.4.4 Friedland

The specimens had extensively healed and it was difficult to see any traces of the drilled hole, Figure 10-7 (small mark from the filter disc can be seen in the centre of the sample and should not be mixed up with the drilled hole). The specimen with the lower density had a distinct increase in the hydraulic conductivity measured after the healing while it for the three specimens with higher density was not possible to measure any changes in hydraulic conductivity before and after healing of the drilled hole has taken place. The difference in water content between the outer parts and the volume around the pre-drilled hole was very clear for the specimens saturated with pot water and water with a salinity of 1%.

Figure 10-7. *Picture from specimen SH403 (Friedland) at the termination of the test.*

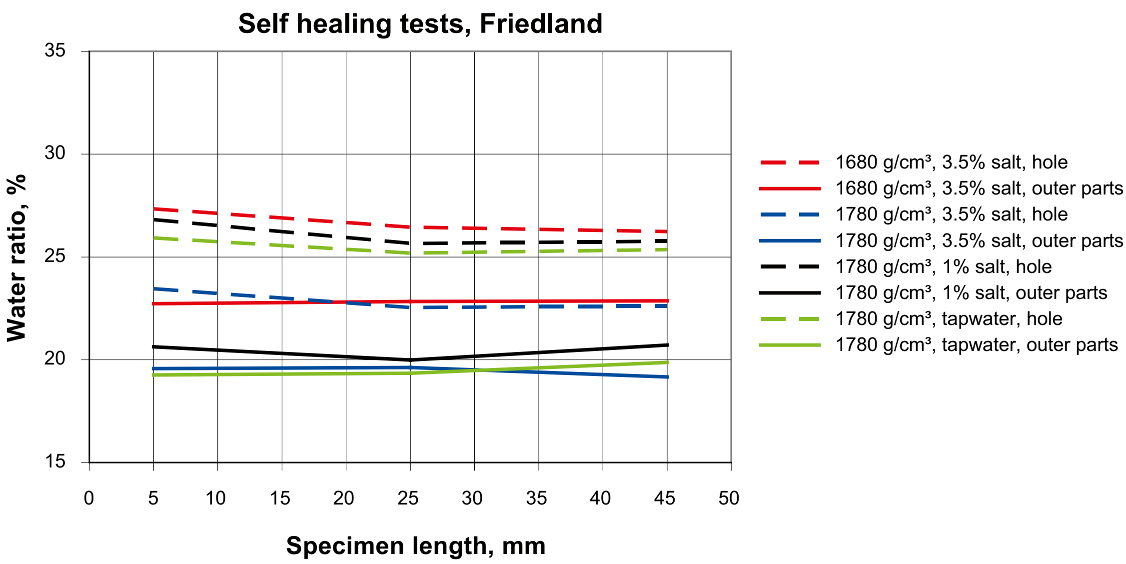


Figure 10-8. *Diagram showing the water content determination for the three tests performed with Friedland clay.*

10.4.5 Mixture 30/70

It was not possible to detect any healing at all in any of the tests performed with the 30/70 mixture. The hole was still open after termination of the tests, Figure 10-9. The water content in these specimens was only determined as an average along the whole specimen, because of the difficulty to recover representative samples, see Figure 10-10. The values show however that the water content in the specimens tested with 3.5% salt in the water, were lower in the central parts than in the other parts contrary to the specimens of other materials. This could be an indication on that the fine material close to the drilled hole have eroded away when the hydraulic conductivity was measured the second time.

A similar test has been performed earlier within the Baclo project and is described in a report /Sandén at al. 2008/. The result from this test was the same as these new results.

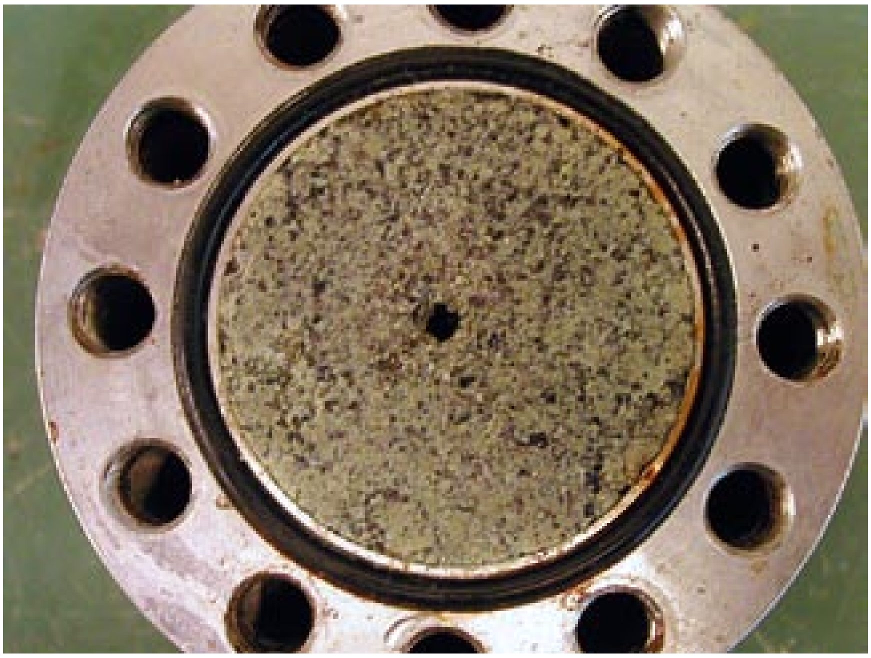


Figure 10-9. *Picture from specimen SH603 (30/70 mixture) at termination of the test. The drilled hole is still open. No healing had occurred in any of the 30/70 samples.*

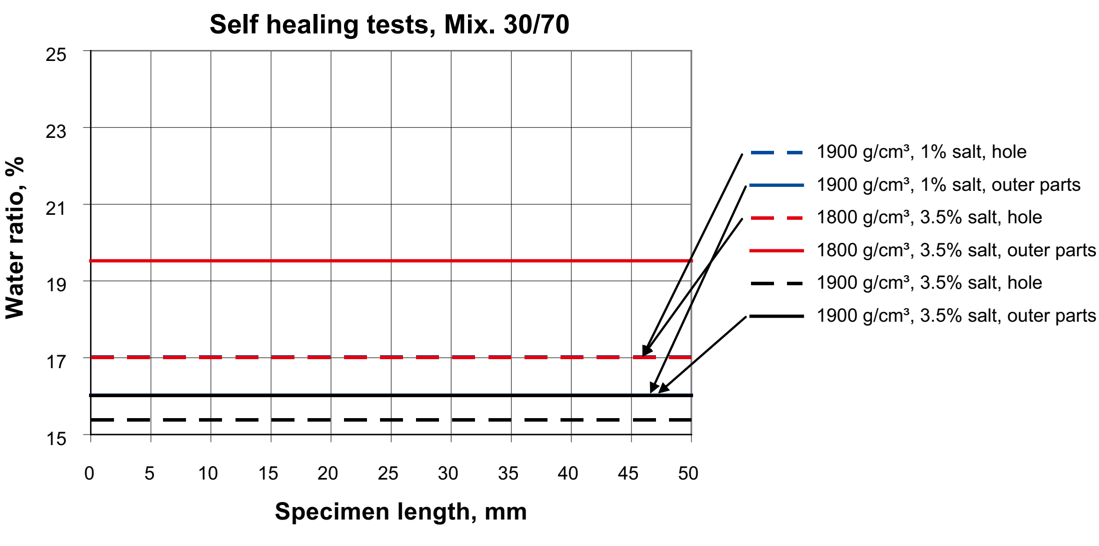


Figure 10-10. *The water content in the three tests performed with Mixture 30/70.*

10.5 Conclusions and comments

The diagram in Figure 10-11 shows the measured hydraulic conductivity before drilling the central hole and after three weeks of healing. The hydraulic conductivity, measured before drilling of the central hole and after three weeks of healing for each specimen, is plotted versus the dry density. Each sample is represented by two dots, one showing the hydraulic conductivity before drilling the hole and one showing the hydraulic conductivity after three weeks healing time. In all cases the hydraulic conductivity after self-sealing is equal to or higher than for the intact specimens and so to provide for ease of figure reading the same symbol has been used for each material tested.

The method used for determining the self healing ability of the materials is not a standard method as no standards for determining such behaviour exist. The results are consistent and the ability to the various materials examined to self-heal can be summarized as follows:

- **Asha 230**. The specimens had essentially healed completely and it was not possible to measure any difference in hydraulic conductivity before drilling the hole and after three weeks of healing.
- **Friedland**. The specimens had largely healed and no visual traces of the drilled hole could be seen. The specimen with the lower density and the highest salt content had however a distinct increase in hydraulic conductivity measured after the healing time when compared to the value determined before drilling.
- **Mixture 30/70**. It was not possible in any of the tests with this material to detect any healing at all.
- **MX-80 pellets**. The drilled holes were filled with gel, but the density of this material was noticeable lower than the surroundings. The specimen saturated with water with 1% salt had partially healed although a distinct increase in hydraulic conductivity was observed. The specimen saturated with water with a salt content of 3.5% had however hardly healed at all. The explanation for this is the rather low density of a pellet filling in combination with the high salt content.

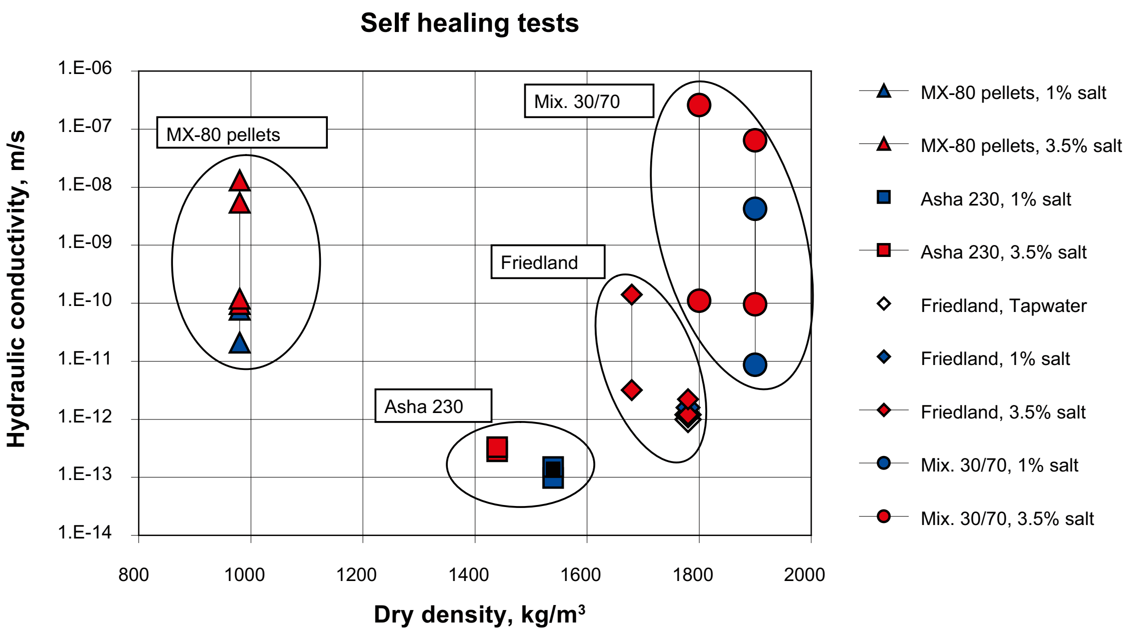


Figure 10-11. *Compilation of self healing test results.*

11 Relative humidity induced swelling and cracking of backfill blocks

11.1 General

The backfill blocks can absorb water from the atmosphere after emplacement (depending on local humidity conditions). This may cause swelling and cracking of the blocks. The swelling and cracking of the blocks may affect the ability to stack blocks in a stable manner and thereby influence the ability to fill the tunnel with the required number of blocks. The issue is also investigated in the KBS-3H project regarding the buffer material and the plan was to use the same test equipment for backfill specimens in a number of tests /Sandén et al. 2007/.

11.2 Experimental set-up

11.2.1 General

The specimens were compacted with a uniaxial compaction pressure of 25 MPa. After compaction they were exposed to a high relative humidity from a free water surface. The water uptake and swelling (volume expansion) were measured continuously and the cracking of the surfaces studied.

Different initial water contents of the specimens were chosen for the different materials due to the different optimum water contents for compaction of the materials. Three identical specimens were made for each material and water content;

- one specimen was used to determine the water absorption rate (no suffix),
- one specimen was used for studying the swelling/volume expansion and the cracking (suffix -V),
- one reference specimen was used for measurement of the initially obtained density and water content (suffix -E).

A second batch of specimens, one each of the highest and lowest water contents within each material group, were made in order to study the water absorption rate of specimens stored at a constant temperature of 10°C (suffix -T10).

The Asha and Friedland specimens were compacted in a mould with diameter d = 50 mm to a height of about 40 mm. Each specimen was subsequently sawn to the desired height h = 30 mm. The 30/70 specimens were compacted directly to a height of 30 mm, because the material is unsuitable for sawing.

At the end of testing each specimen was divided into three disks: closest to the water surface, middle and top (furthest from water). One half of each disk was used to determine the water content and the other half to determine the density. The density was calculated from a volume determined by weighing the specimens above and submerged into paraffin oil. Due to the nature of the 30/70 material these specimens could only be divided into two disks.

11.2.2 Test equipment

Determination of the water absorption rate. The prepared specimens were suspended in a special vessel (jar made of acrylic plastic with a tight lid) and shown in Figure 11-1. The specimen was covered with a rubber membrane and two O-rings to prevent the specimen from slipping. The bottom of the vessel was filled with de-ionised water. Only the base of each specimen was exposed to the air above the water's surface. The specimen was hung in a rod, which was led through the lid. This design makes it possible to weigh the specimen during the water uptake. A washer was mounted on the upper part of the rod, above the lid, in order to seal off the hole when no weighing was made. The distance between the exposed bentonite surface and the water surface was held constant during the test period. The specimens were weighed at selected intervals and after each weighing the amount of absorbed water could be calculated and hence the water absorption rate determined.

Swelling/volume expansion and cracking. These specimens were placed in a cage on a fine net over a free water surface (Figure 11-2) in the same type of vessel made of acrylic plastic as described above. The specimens were weighed (in their vessels) and taken out and measured with a slide calliper at preselected intervals. The surfaces were observed for evidence of cracking.

The height and diameter of each specimen were measured at two locations (Figure 11-3). The heights were measured from the bottom of the specimen holder to the top of the specimen on the opposite sides of the specimen. The diameters were measured a few millimetres from the bottom of the specimen and a few millimetres from the top. The results are displayed as the average of each measurement pair.

11.3 Results

11.3.1 General

In the diagrams the legends of the specimens refer to the names in Table 11-1. In all diagrams the shapes of the marks (■, ♦, ▲) denote the material (Asha, Friedland, 30/70) and the colours (purple, light green, dark green, red, light blue, dark blue) denote the initial water contents (7%, 10%, 15%, 17%, 20%, 24%).

Initial and final water contents and bulk densities are presented for all specimens in Appendix 32 and 33. The tests operated for 86–88 days and the samples are not assumed to have reached steady state or equilibrium.

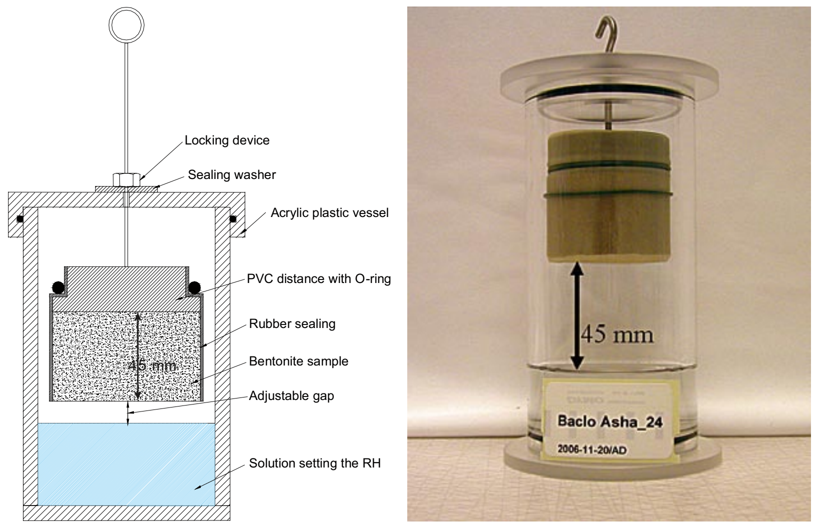


Figure 11-1. *Schematic view showing the test equipment to the left and the equipment used for measuring water absorption rate to the right.*

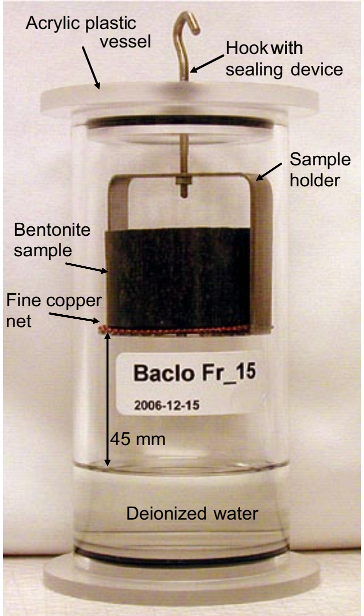


Figure 11-2. *Equipment used for measuring swelling and studying cracking.*

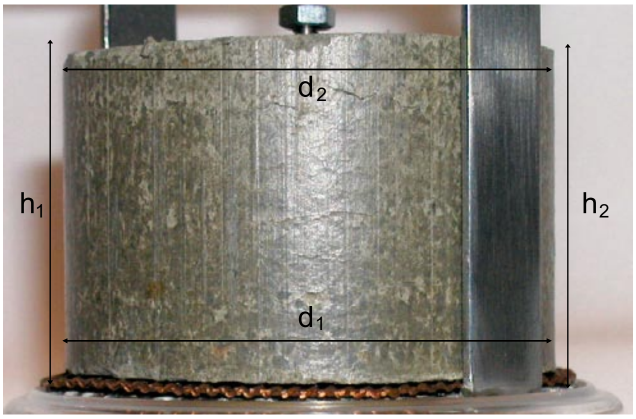


Figure 11-3. *Schematic view of specimen height and diameter measurement locations.*

11.3.2 Test matrix

The test matrix, with specimen names, is shown in Table 11-1.

Table 11-1. Table showing the test matrix and specimen names.

w initial (%)	30/70 (Bentonite/Ballast)	Friedland	Asha 230
7	30/70_7		
10	30/70_10	Fr_10	
15	30/70_15	Fr_15	
17			Asha_17
20	30/70_20	Fr_20	Asha_20
24		Fr_24[1]	Asha_24

1 Compacted at lower pressure than 25 MPa.

11.3.3 Water absorption

Figure 11-4 and Figure 11-5 show the cumulative mass of water absorbed and the corresponding water absorption rate for the specimens that were only weighed. In Appendix 34 the water absorption for all specimens is shown as increase in mass. When calculating the absorption rate (see Figure 11-5) it was assumed that the area through which the absorption takes place remained constant during the test. Accounting for the change in area only showed marginal changes for the materials with the highest absorption rate.

In the diagrams the initial weight at time zero corresponds to the specimens' weight directly after compaction and before they were placed in the vessels and water was added. Most of the specimens decreased approximately 0.1 g in weight from compaction to the start of the test. However, the driest specimens of the Asha and Friedland materials increased in weight. The specimens placed at 10°C decreased the most from the compaction to the start of the test. The decrease was between 0.2 g and 0.5 g for these specimens.

In Figure 11-4 it is seen that for each of the materials the absorption rate is higher the lower initial water content. It is also seen that the 30/70 specimen with the highest initial water content, 30/70_20, decreased in weight during the test period. In general, the absorption rate is higher in the Asha material than in the other materials and the absorption is almost the same for Fr_24 and 30/70_10, i.e. Friedland with initial water content of 24% and 30/70 with initial water content of 10%.

The initial and final water contents of the specimens shown in Figure 11-4 are shown in Figure 11-6. The 30/70 specimens were only divided into two parts and not three parts as was the case for the other materials.

The final water contents were measured but could also be calculated from the initial values and the changes in mass measured during the test period, i.e. Figure 11-4. The calculated final water contents were for the majority of the specimens less than 0.5% higher than the measured water contents. For all specimens the calculated values were between 0.5% lower and 1.6% higher than the measured water contents (see Appendix 35).

In Figure 11-7 the water absorption for specimens placed at 10°C are shown with specimens placed at room temperature. The 10°C specimens follow the same trends as those at room temperature with the exception of 30/70_20-T10, which after about four weeks started absorbing water and was approaching its initial mass at termination.

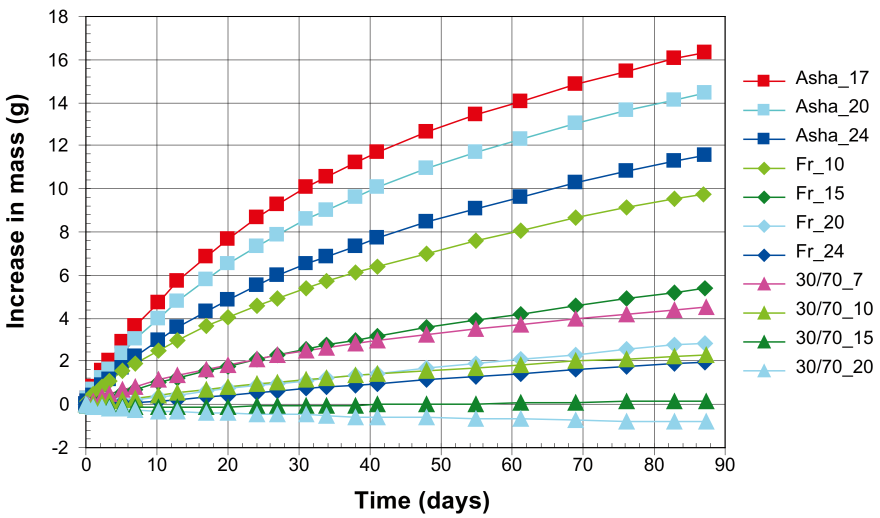


Figure 11-4. *Water absorption for one of the test series.*

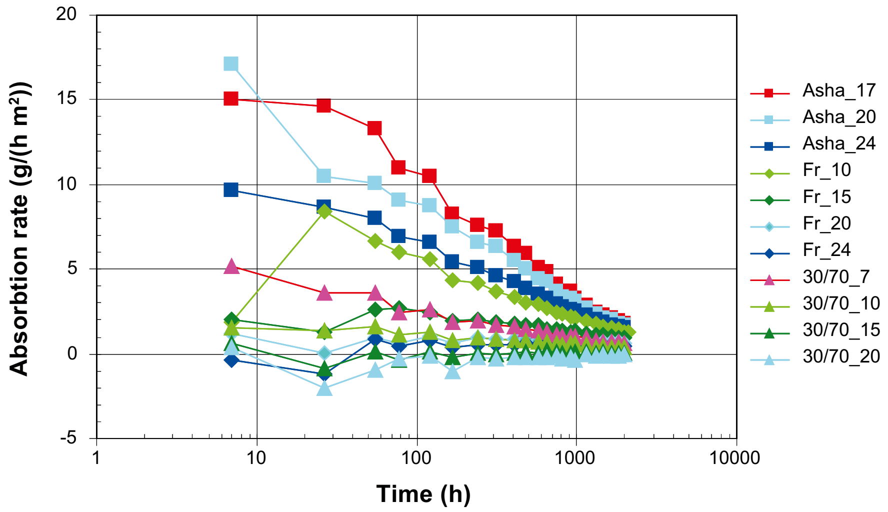


Figure 11-5. Water absorption rate for the specimens presented in Figure 11-4.

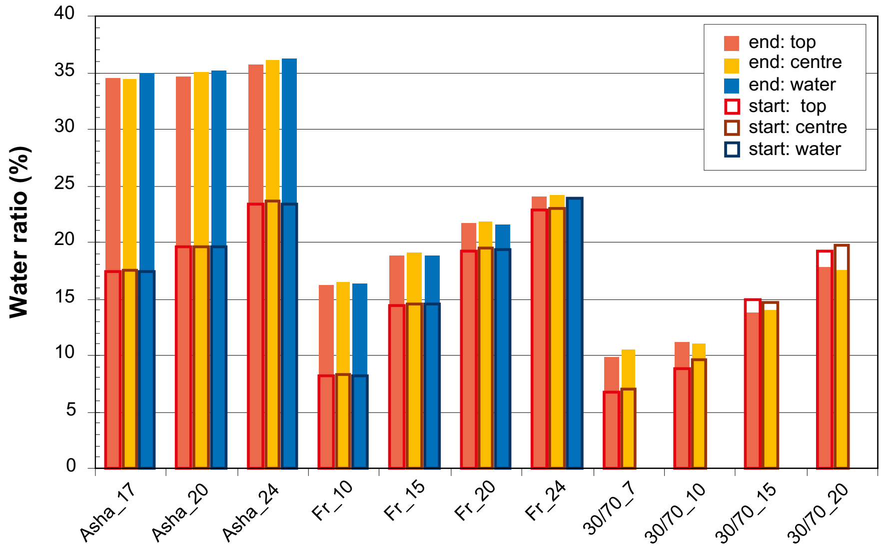


Figure 11-6. Measured water contents at start and at the end of the test for one of the test series.

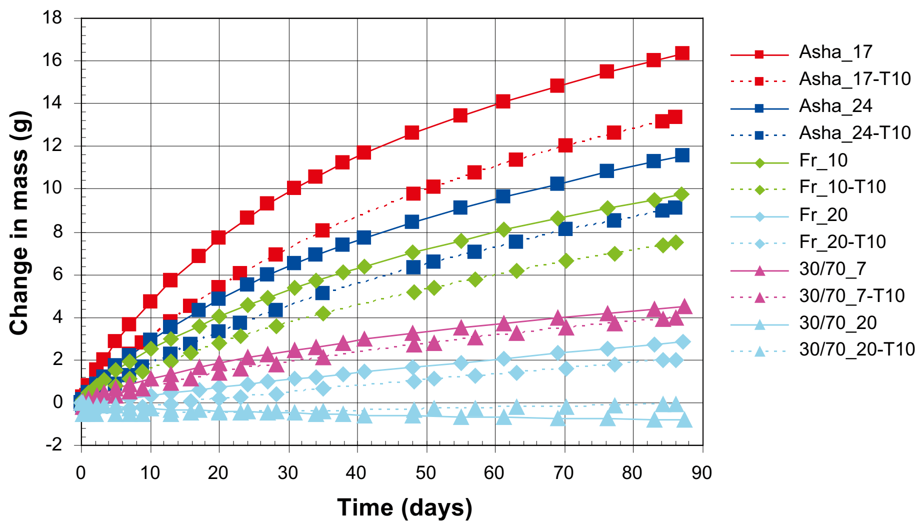


Figure 11-7. Water absorption for test series at 10°C and at room temperature.

11.3.4 Swelling/volume expansion

Figure 11-8 and 11-9 show the changes in height and diameter during the test period. The height and diameter at time zero correspond to measurements of the specimens before water was added to the vessel.

The increase in specimen height and diameter follows the same trend as the increase in mass in Figure 11-4 in that the swelling is larger for each material the lower initial water content. Some of the specimens decreased in height and diameter, which is consistent with the decrease in mass observed (specimens 30/70_15 and 30/70_20). However, other specimens also decreased in height; 30/70_10 and Fr_24. This is consistent with the results from the change in mass for these specific specimens, used for studying the volume expansion (see Appendix 34). In general the change in mass of the specimens used for studying volume expansion was 0.4 to 1.4 g, less than the change in mass resulting from the specimens only used to study the water absorption rate, see Appendix 34.

The final height and diameter were measured and could also be calculated from the initial values added to the changes shown in Figure 11-8 and 11-9. The difference in height between the calculated and measured values was between 0.2 and –0.6 mm (see Appendix 35). For the specimens showing small total change in height this difference is relatively large. However, since the curves showing measured changes versus time are rather smooth, i.e. no large scatter, the difference might originate from the mounting or dismantling. The difference between calculated and measured diameter is less than the corresponding values for the height.

Figure 11-10 shows the densities before and at the end of the tests. The Asha material was very crumbly especially the one with the lowest initial water content which tended to break before the density was determined.

The change in dimensions at 10°C was not determined during the test. However, the final densities were determined of all specimens and the final density of specimens placed at 10°C and the specimens placed at room temperature are shown together in Figure 11-11. Observe that final densities of Asha_17 and 30/70_7 were not obtained. In general, the final densities seem to be almost the same and independent of the temperature.

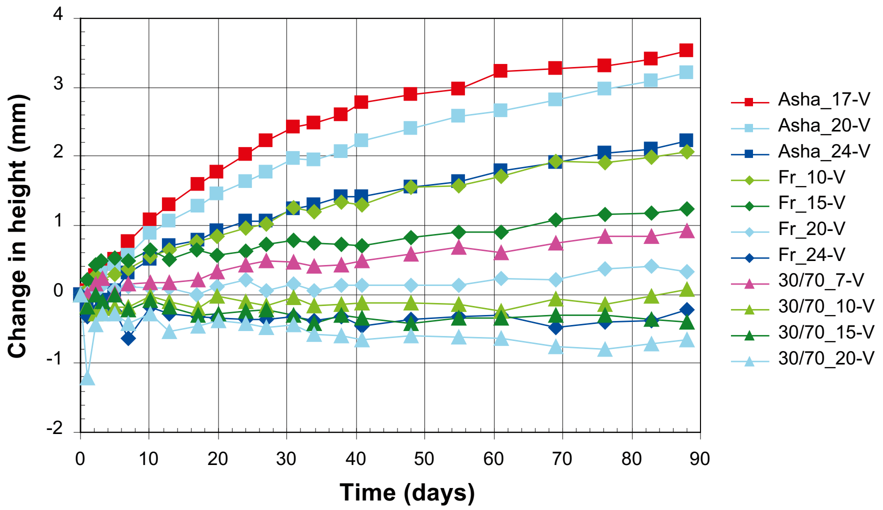


Figure 11-8. Change in specimen height as result of water adsorption. (The diagram shows the average of the measurements taken at each time.)

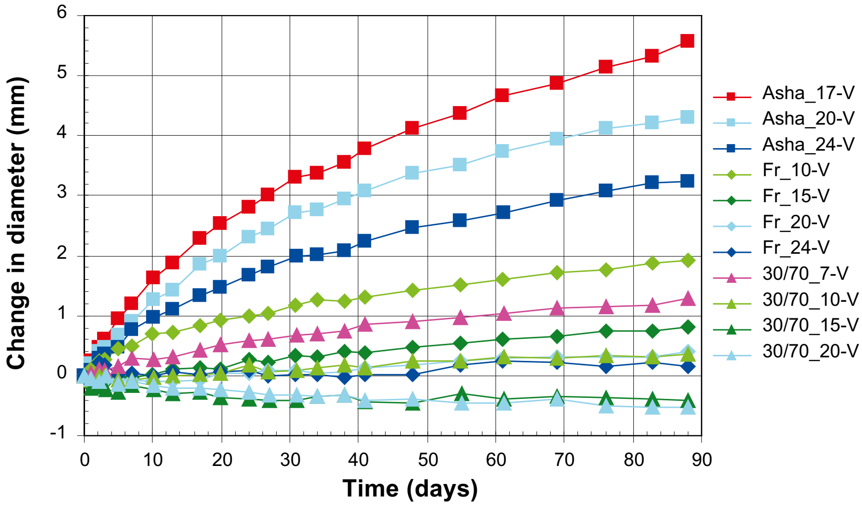


Figure 11-9. *Change in specimen diameter as result of water uptake. (The diagram shows the average of the measurements taken at each time.)*

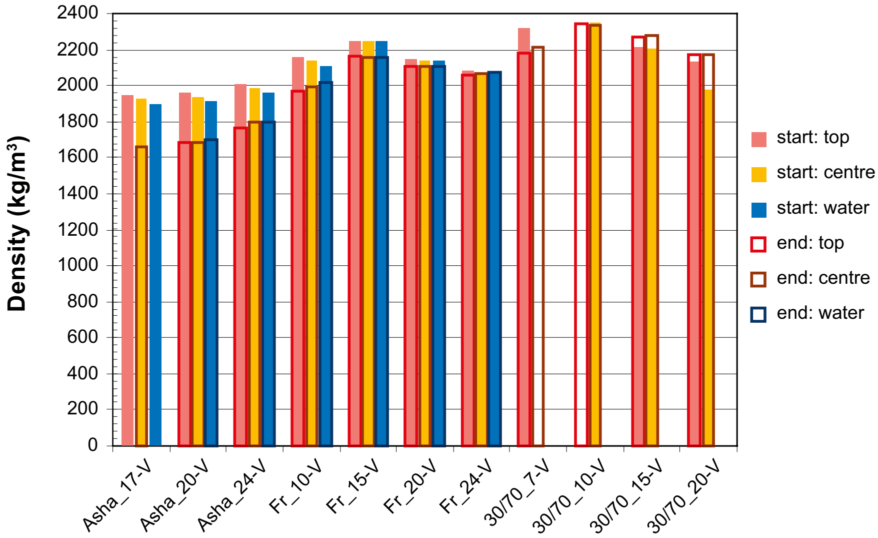


Figure 11-10. *Initial densities compared with the corresponding densities at the end of the test for one of the test series.*

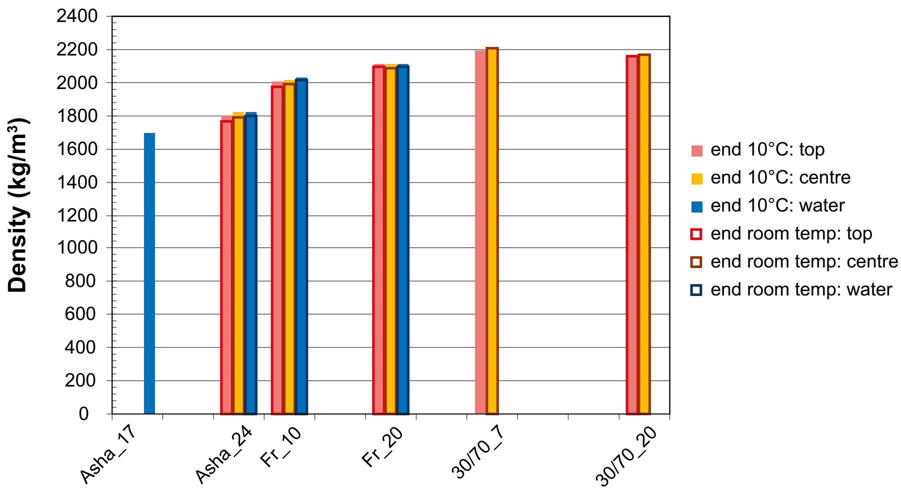


Figure 11-11. *Final densities from test series with specimens at 10°C and at room temperature.*

11.3.5 Cracking

Cracking of the specimens was observed and summarised in Table 11-2. A cross in this table means that no cracks were observed. A light blue square with a number means that cracking was observed but the time for the start of cracking is uncertain. Some photos of cracking are shown in Appendix 36-38.

Cracking on the surface towards the water surface was observed mainly on the following specimens: Fr_10-V, Fr_15-V and Asha_17-V, 20-V and 24-V. The cracking was most frequent along the circular edge of the surface towards the water.

Table 11-2 Observed cracking.

Material Namn	30/70 circumfer-ential	water surface	Friedland circumfer-ential	water surface	Asha circumfer-ential	water surface
7	X	X				
7-V	X	X				
10	X	X	2	X		
10-V	X	X		2		
15	X	X	X	X		
15-V		X		2		
17					2	X
17-V						3
20	2	1	X	X	2	2
20-V	1	1	2	X		2
24			2	X	X	2
24-V			1	X		2

	Not in the test matrix, see Table 11-1
X	No visible cracks
	Uncertain when the cracking started: 1. Possibly from compacting; 2. Visible at end of test; 3. Sample was destroyed when removed from equipment
	Cracking was visible within 3 weeks after start of test
	Cracking was visible within 6 weeks after start of test
	Cracking was visible within 7 weeks after start of test
	Cracking was visible within 8 weeks after start of test
	Cracking was visible within 11 weeks after start of test

Regarding the circumferential surface the specimen with names containing-V are the most interesting since these specimens were fully exposed to the climate in the vessel and not protected by a membrane as was the case for the other specimens. The largest occurrence of cracking on the circumferential surface was found on Asha specimens. The lower initial water content the faster occurrence of cracking was observed on Asha and Friedland. The first cracking was found on Asha_17-V and Asha_20-V after less than 3 weeks while the cracking on Friedland specimens was observed after longer time and mainly on specimens starting from lower water contents than the Asha material was tested for. Less cracking was observed on 30/70 specimens. On the specimen 30/70_15-V a small part was almost falling off the specimens, probably containing some larger stone present in the 30/70 mixture. In addition to the observed cracking it is of importance to notice that the Asha_17 specimens were brittle and fragile and fell apart when dismantling.

For each material and initial water content two specimens were studied as listed in Table 11-2. For some of the combinations the cracking observed was less on the specimens covered with a rubber membrane compared to the one without membrane, placed in a cage. This indicates that the membrane to some extent kept these specimens together.

Regarding the specimens placed at 10°C all specimens with the exception of Fr_20-T10 and 30/70_7-T10 had very small cracks at the end of the test. It is uncertain when these cracks initiated since they were only observed when all equipment had been removed.

11.4 Discussion

The following observations and conclusions can be made:

Absorption

- The absorption rate decreases with increasing initial water content for all material studied.
- Most water had been absorbed in the Asha material. The least absorption was seen in the 30/70 mixture.
- The 30/70 mixture with the initial water content 20% dried at room temperature.
- The absorption rate was higher at room temperature than at 10°C (except for 30/70_20).
- After 87 days the water content gradient in the specimens was less than 1% along all the initially 3 cm high specimens.

Swelling

- The swelling rate decreased with increasing initial water content for all material studied.
- The 30/70 mixture had the largest final density and the Asha material the lowest.
- There was almost no difference in final density between specimens placed at 10°C and at room temperature.

Cracking

- Considering the specimens with all surfaces exposed to the climate in the vessels the only specimens with no observed cracking due to the exposure were,
- the 30/70 samples and,
- the Friedland specimens with the highest initial water content, i.e. 24%.
- Cracking was first observed, within 3 weeks, on Asha_17-V and Asha_20-V, i.e. Asha material with the initial water contents 17% and 20%.

12 Summary and conclusions

12.1 General

The tests described in this report are intended to investigate several important properties of different backfill candidate materials, considered for use in backfilling of tunnels in the KBS-3V concept. The tests were focused on the processes occurring just after emplacement and the behavior of the materials when first exposed to water inflow from the rock.

This chapter summarizes the main conclusions from these tests.

12.2 Erosion properties of pre-compacted blocks

The erosion tests with pre-compacted blocks have only been done with one of the candidate materials, Friedland clay. Same type of tests were performed already earlier in the project, but with Friedland clay blocks that had a higher density compared to the blocks used in the new tests.

The results from the erosion tests on pre compacted blocks can be summarized as follows:

- There is an evident influence of the salt content in the water on the measured erosion rates. Independent of the flow rate the bentonite content in the eroding water was 0.1–0.4% when using tap-water (two tests at different water flow rates). In the tests performed with 1% and 3.5% salt content the bentonite content was between 0.6 and 2.7% in all tests (7 tests at different water flow rates).
- The influence of the water flow rate on the bentonite content in the discharged water was small.
- The density of the blocks seems to influence the erosion rate. The test with the highest erosion rate, 2.7% bentonite content in the discharge water, was performed with the new "low density" blocks, a water flow rate of 0.1 l/min and a salt content of 1% in the water.
- There is a small tendency for the erosion rate to decrease with time.

12.3 Piping and erosion properties of bentonite pellets and granules

Two test series have been performed in this Phase of the Baclo project in order to investigate piping and erosion properties of some backfill candidate materials. The following investigations were made:

1. **Influence of fine material.** The results from the erosion tests performed in Phase 2 of the Baclo project were not entirely conclusive and some were difficult to explain. One reason could be that the amount of fine material influences the results. Therefore it was decided to perform a new test series. The results from the new test series showed that the influence of fine material is very strong in the beginning of the tests (if fine material was present the erosion rate increased) but after 24 hours the erosion rate was very similar in all tests. Also the influence of the salt content in the water was investigated. Due to very fast swelling and sealing in the tests with 3.5% salt with the lower water flow rate (0.01 l/min) high counter water pressures were built up (up to 1 MPa) and it was not possible to measure erosion in these two tests. In the other two tests performed with 3.5% salt content and a water flow rate of 0.1 l/min, the erosion rate was very high during the first hours but after about 24 hours the erosion rate was the same as in the tests performed with 1% salt in the water. The results from this test series were very consistent and predictable, see Figure 4-4, 4-5 and 4-6. The bentonite content in the water was after 24 hours test duration between 0.1–0.2% for all performed tests in this series.

2. **Tests performed with other candidate "pellet" materials**. Complementing tests have been done with three other candidate materials. Two of them, Cebogel QSE and Minelco are also used in field tests performed at Äspö HRL. The third material tested was granules of Friedland clay. These three materials were all tested with two different applied constant flow rates, 0.1 and 0.01 l/min and with a salt content of 1%. The behavior of the materials was very different especially regarding the order of magnitude of the counter water pressure built up. The tests were performed by applying a constant water flow, which remained constant up to a counter pressure of 1 MPa. Depending on the behavior of the material (swelling and sealing) different counter pressures built up as shown in Figure 5-4. In three of the tests, both tests with Friedland material and one of the tests with Minelco (0.1 l/min), it was not possible to measure erosion due to the backpressure applied. In the other test with Minelco (0.01 l/min) was it possible to measure erosion for a period of 24 hours but then the backpressure increased. This test was also terminated in advance of its originally scheduled completion time. This difference in behavior is probably a very important factor for the choice of material.

One conclusion from the tests is that the erosion rate can vary a lot during the first 24 hours of water throughflow, depending on material and salt content in the water but will end up at almost the same level (0.1–0.3% bentonite in the out-flowing water). The erosion rate of the MX-80 material seems to be at the upper level and the Cebogel QSE material at the lower. This is probably as a result of the lower initial water content of the MX-80 pellets, which makes them more brittle. The amount of non-pellet fines in the pellet fill is also larger for the MX-80 material.

Another conclusion is that for some materials, Friedland granules and Minelco, high water counter pressure can be build up which may affect the ability of the pellet fill to "store" water and thereby delay the time before water will exit the backfilled volume into adjacent open areas. It is suggested that the dry pellets could be pushed forward and water filled cavities created as observed in some of the piping tests described in this report. This phenomenon could probably also occur with the other materials if hydraulically unfavorable conditions exist. This type of behavior is probably controlled by factors such as the grain size distribution, the size of the available voids and the geometry of the confinement. With a large pellet size the voids are rather large and the water can flow in a channel that remains open for long time (MX-80). When the pellets are smaller the voids are smaller and flow resistance can be built up and at an unfavorable geometry this clogging process may occur (Friedland, Minelco and Cebogel QSE). However, it has only been observed in tubes where the stiff walls prevent radial flow and valve formation may occur.

A conceptual model that may be used to predict the eroded clay mass as a function of the mass of throughflowing water has been suggested.

12.4 Large slot tests

Tests of this type have been performed earlier with MX-80 pellet in Phase 2 of the Baclo project and in this test series with Cebogel QSE pellet. Three types of measurements/observations have been done:

1. **The stability of the slope during water inflow**. There were no observations that the pellets filling could "float away". The slope swelled however in some of the tests and some material had rolled downwards the slope.
2. **Erosion measurements**. The erosion rate was measured also in these tests. The erosion rate was higher for the MX-80 pellets, 1–1.2%, compared to the results from the tube tests, 0.2–0.3%. The difference depends probably on that the amount of fine material was larger in the slot tests. The erosion rate of the Cebogel QSE material was of the same order of magnitude as in the tube tests.
3. **The wetting process**. The materials ability to "buffer" water inflow and subsequent throughflow was also studied. All tests with MX-80 pellets found that only a limited volume of the pellet fill was affected by water inflow and then water flowed along one channel and did not

affect the still dry parts of the assembly. The tests with Cebogel pellets exhibited different water uptake behavior. Almost all the pellet material was wetted before the breakthrough of water flow to the downstream face (0.011/min and 0.1 l/min). For the highest inflow rate (1 l/min) the wetting of the pellets continued after the breakthrough of flow through the system. This post-breakthrough wetting resulted in an almost completely saturated pellet fill after three hours of testing. The reason for this difference is probably the smaller size of the voids in Cebogel pellets, resulting in a higher flow resistance which makes the water flow in different directions, see section 6.3.

12.5 Modelling of erosion

An erosion model based on erosion tests has been suggested. It assumes a linear relation between accumulated eroded material and accumulated water flow in a double logarithmic diagram. It includes two parameters: α that corresponds to the inclination of the linear relation and β that determines the level of the accumulated erosion. Application of the model on an extreme case showed that the expected total mass of eroded material was reduced 7–70 times compared to what could be expected if a constant erosion rate of 1–10 g/l was assumed. Some observations and comments:

- α seems not very much affected by the test material or conditions and is according to the measurements a constant with the value 0.65.
- β must be measured and is dependant on the material type, the salt content, the water content, the pellet grain size distribution and the geometry etc.
- The model is preliminary but it may be possible to put limits to the consequences of erosion with this model.
- All tests have been made on bentonite with low water content (10–17%) but the erosion seems to decrease with increasing water content.
- Since only tests with short duration (less than a week) and with rather short flow paths have been performed so far, long term tests and tests in long tubes are needed in order to verify that the results can be extrapolated to actual field conditions.

12.6 Displacement of blocks during the installation Phase

These tests were done with three materials which could be used for manufacturing of backfill blocks, Asha 230B, Friedland and Mixture 30/70. The purpose of this test series was to investigate how different initial slot widths between the blocks after emplacement may affect the displacement and forces between blocks when water comes in contact with slots. The main conclusions from the test series are as follows:

5. **Influence of initial slot width**. The tests showed clearly that the initial slot width between the blocks influences the displacement very strongly under unconfined conditions. With a small initial slot width between the blocks (0–0.5 mm), the displacement started immediately when the bentonite got access to water. The total displacement with these small gaps was about 7 mm after one week, independent of the water type (1% salt and 3.5% salt). When the initial slot was increased to 5 mm it took almost 2 days before any displacement took place and after 1 week the total displacement was about 2 mm. The results from these tests with Friedland block were consistent with corresponding tests at confined conditions where instead of displacement, the force was measured. When the initial slot was small, the force that was build up due to the swelling of the bentonite was considerable higher, 5–6 times, than in the tests with specimens having an initial slot of 5 mm.

6. **Influence of salt content**. The results from the tests indicated that the influence of the initial slot width was stronger than the influence of the salt content in the water. The results were almost similar irrespective of the tests were performed with 1% salt or 3.5% salt in the water.
7. **Influence of material**. Asha 230 B has the highest montmorillonite content and is also more affected than the other materials. The tests with Friedland blocks show however that these blocks are almost as sensitive as the Asha blocks. The blocks made of the Mixture 30/70 were almost unaffected in these tests.

12.7 Plug tightness required to stop erosion of backfill materials

These tests were performed using an artificial slot with the width set to a pre-selected value by use of shims/steel parallels. Water entered via a pellet filled tube and out through the slot. Besides the slot widths the parameters of water inflow rate (0.01 and 0.1 l/min) and the salt content of the water (8 test were performed with 1% salt and 1 with 3.5% salt) were varied. The maximum allowed pressure was 5 MPa.

The test results for MX-pellets indicate that the maximum slot that can seal at these water flow rates is 0.15 mm (1% salt content in water). The total number of tests performed is limited and the results should be seen as an indication of the capability for bentonite to seal fractures rather than an absolute measure.

12.8 Self healing ability of some backfill materials

The self healing ability of the candidate backfill materials have been studied by drilling holes in saturated specimens and then letting them have access to water for a certain time in order to swell and seal the drilled hole. Before drilling the hole the hydraulic conductivity of each specimen was measured. After the healing time, a new measurement of the hydraulic conductivity was done. The tests were done with three materials that can be used for manufacturing blocks and with one pellet material. Each of the block materials were tested at two densities, one simulating the final average density in the tunnel and one lower simulating a lower density close to the pellet filling. All tests were done with both 1% and 3.5% salt in the water. The following conclusions and comments were generated:

- **Asha 230**. The specimens had healed essentially completely and it was not possible to measure any difference in hydraulic conductivity before drilling the hole and after three weeks of healing.
- **Friedland**. The specimens had extensively healed and no visual traces from the drilled hole could be seen. The specimens with the lower density and the highest salt content had however a distinct increase in hydraulic conductivity measured after the healing time when compared to the value determined before drilling.
- **Mixture 30/70**. It was not possible to detect any healing at all in any of the tests done with this material.
- **MX-80 pellets**. The drilled holes were filled with gel, but the density of this material was noticeably lower than the surroundings. The specimen saturated with water with 1% salt had visually healed even though a distinct increase in hydraulic conductivity could be determined. The specimens saturated with water with a salt content of 3.5% had however undergone very little healing at all. The explanation for this is the rather low density of a pellet filling in combination with the high salt content.

12.9 Relative humidity induced swelling and cracking of backfill blocks

The following observations and conclusions have been made so far:

Absorption

- The absorption rate decreases with increasing initial water content for all material studied.
- The greatest amount of water absorbed was observed in the Asha material. The least absorption was seen in the 30/70 mixture.
- The 30/70 mixture with the initial water content 20% showed water loss at room temperature.
- The absorption rate was higher at room temperature than at 10°C (except for 30/70_20).
- After 87 days the water content gradient in the samples was less than 1% along all of the initially 3 cm high specimens.

Swelling

- The swelling rate decreased with increasing initial water content for all materials studied.
- The 30/70 mixture had the largest final bulk density and the Asha material the lowest.
- There was almost no difference in final density between specimens placed at 10°C and at room temperature.

Cracking

- Considering the specimens with all surfaces exposed to the climate in the vessels the only specimens with no observed cracking due to the exposure were,
  - the 30/70 specimens and,
  - the Friedland specimens with the highest initial water content, i.e. 24%.
- Cracking was first observed, within 3 weeks, on Asha_17-V and Asha_20-V, Asha material with the initial water contents 17% and 20%.

13 Further work and recommendations

The reported tests have yielded a lot of information regarding the behavior of different backfill materials, but have also revealed some weaknesses and additional questions. Some suggestions of further work are listed below:

- **Manufacture pellets of same type but of different raw materials**. The possibility to manufacture the same type of pellets e.g. extruded pellets of Cebogel type should be investigated. This would facilitate the comparison of the different materials and exclude the influence of the different grain size distribution on the behavior (erosion rate, counter pressure build up and wetting process).
- **Erosion of bentonite with high degree of saturation**. The influence of the degree of saturation of the bentonite on the erosion properties should be investigated. Some preliminary results from another project (KBS-3H) have indicated that the erosion seems to be much lower when the material has a high degree of saturation. However, the effect of high initial water content might affect also some other properties, e.g. the swelling capacity in volume, which would then require studies as well.
- **Self healing ability of unsaturated material**. The tests performed regarding this issue were done at saturated conditions. In the field piping usually occurs before saturation. The self healing ability at these conditions should also be considered. Also the time dependence regarding the self healing ability should be investigated.
- **Relative humidity induced swelling and cracking of backfill blocks**. The occurrence of cracking has been investigated in this report in a small scale. However, the disposition of blocks to cracking is according to /Sandén et al. 2007/ affected by the size of the block. Since cracking might be a critical issue e.g. for installation of the blocks, tests in a medium scale should be done.
- **Erosion tests in long tubes and with long duration**. Since tests have so far only been made short durations (less than a week) and with rather short flow paths, long term tests and tests in long tubes are needed in order to verify that the results can be extrapolated to actual field conditions.

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