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**Deep repository-engineered
barrier system. Piping and
erosion in tunnel backfill**

**Laboratory tests to understand
processes during early water uptake**

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July 2008

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

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Abstract

SKB in Sweden and Posiva in Finland are developing and implementing similar disposal concepts for the final disposal of spent nuclear fuel. A 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 aims to acquire more knowledge regarding the behavior of the backfilling material (bentonite/ballast 30/70 mixture, MX-80 pellets and compacted blocks of bentonite), when they are exposed to water inflow from the rock during the emplacement. Mainly two important properties are investigated: erosion and piping. In addition also a minor investigation has been done regarding the healing ability of the material after a piping scenario. The parameters varied in the investigation are except the flow also the salinity of the water and the test length.

The results from the erosion rate on the pre-compacted bentonite blocks shows, as expected, that the influence of the flow rate on the erosion is very strong. The salinity of the water is also affecting the erosion rate very strongly while the length of the samples does not seem to influence the erosion. The reason for this is probably that the solution gets “saturated” with particles and cannot transport more. The erosion rate also seems to be reduced with time. This should be further investigated by a number of long term tests.

The piping/erosion tests with MX-80 pellets showed that it is difficult for the pellets to swell and seal off all the existing channels when there is a constant flow applied. Only in two of the performed tests (low flow and high salinity) a water pressure was built up. It was also observed in all the tests performed with MX-80 pellets that the water was mainly flowing in one channel. The results from the erosion tests with pellets showed, like the one with the blocks, that the magnitude of the erosion is very dependent on the flow rate and the salinity of the water.

The same test equipment was used for the bentonite/ballast mixture which gave completely different results. The results showed that it was very difficult to get piping. Instead high water pressures were built up and the material was pressed out through the perforated ends of the sample holder. The equipment used turned out to be too weak for the high water pressures (1,000–1,400 kPa) that was built up. One conclusion which could explain the behaviour is that due to the impenetrability of the material, it behaved like a tight filter. This meant that a water pressure could be built up, working on the full cross-section, compacting the material ahead which increases the density and by that getting tighter and tighter. This theory could also be verified with photos and other observations. Modifications of the equipment were done, moving the water inlet from the tube end to the middle and changing the material from Plexiglas to steel. The modifications made it possible to perform the tests with higher pressures but did not solve the problem with getting piping.

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 backfill materialen (bentonit/ballast 30/70 blandning, MX-80 pellets och kompakterade block av bentonit) reagerar när de utsätts för olika vattenflöden från berget under själva inplaceringsfasen. Huvudsakligen har två viktiga egenskaper undersökts: piping och erosion. En mindre undersökning av den självläkande förmågan efter ett piping scenario har också undersökts. Parametrar som har varierats är förutom flödet också salthalt och testlängd.

Resultaten från erosionsförsöken på de förkompakterade bentonitblocken visar som väntat att flödes hastighetens inverkan på erosionen är mycket stor. Inverkan av salthalten är också markant, medan provlängden inte verkar ha någon betydelse. Anledningen till detta kan vara att lösningen blir ”mättad” på partiklar och bara kan transportera en viss mängd. Erosions hastigheten verkar också reduceras med tiden. Detta bör dock undersökas vidare med att antal långtidsförsök.

Piping/erosions-försöken med MX-80 pellets visar att det är svårt för pelletsen att svälla och täta alla existerande kanaler när man har applicerat ett konstant flöde. Bara i två av de genomförda testerna (lågt flöde och hög salthalt) byggdes ett vattentryck upp. En annan observation som gjordes i alla försök med pellets var att vattnet huvudsakligen rann i en kanal. Resultaten från erosionsmätningarna visar, precis som med blocken, att erosionen är starkt beroende av flödes hastighet och salthalt i vattnet.

När samma testutrustning användes för bentonit/ballast blandningen erhöles helt andra resultat. Försöken visade att det var mycket svårt att provocera fram piping hos det inpackade materialet. Istället byggdes höga vattentryck upp och materialet pressades ut ur de perforerade gavlarna på provhållaren. Utrustningen som användes visade sig också vara för liten för de höga tryck (1 000–1 400 kPa) som byggdes upp. En slutsats som skulle kunna förklara utfallet kan vara att beroende på att materialet är så tätt, uppförde det sig som ett tätt filter. Detta gjorde att höga vattentryck kunde byggas upp, som verkade på hela tvärsnittsarean och därmed kunde pressa materialet framför sig och som därför blev tätare och tätare. Denna teori kunde också verifieras med foto och andra observationer. Utrustningen modifierades, bl a flyttades vatteninläppet från gaveln på röret till en mittpunkt och materialet byttes till stål. Förändringarna gjorde det möjligt att utföra testerna med högre tryck men löste inte problemet med att provocera fram piping.

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1 Introduction

SKB in Sweden and Posiva in Finland are developing and implementing similar disposal concepts for the final disposal of spent nuclear fuel. A 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. In order to design and optimize backfilling concepts for the repository sites in Finland and Sweden there is a need to understand processes related to the early stages of water uptake from the rock. These processes influences the backfill design and the necessary backfilling rate. The studies in this report are performed in laboratory scale and the aim of the tests is to isolate and study individual processes. The combined effect of the processes and the scale effects will be studied in larger test setups.

This report concerns work done during 2005–2006.

2 Performed tests

2.1 General

Four types of tests have been performed within this project:

1. **Erosion of pre-compacted blocks.** Pre-compacted blocks were placed in a special groove and exposed to different water flows. The length of the groove and the salinity of the water were also varied. The rate of erosion was measured during the tests.
2. **Piping and erosion tests of pellets and in situ compacted backfill material.** The measurements were done, using tubes made of Plexiglas that were filled with pellets. After filling a tube, constant water flow was applied in one end. The inflow rate and the water type were varied. The rate of erosion was measured during the tests.
3. **Test of pellets stability in a large slot.** A special slot with walls made of PMMA was manufactured. The slot has a length of 2 m, a height of 1 m and a width of 0.1 m. The aim with this test was to investigate the stability of a large pellet volume when exposed to different water inflows and different water types.
4. **The healing ability of the materials.** After a piping/erosion scenario, the specimens will have some time for healing and then be exposed to an increasing water pressure in order to detect if the material have healed or if there are remaining defects. Only one test of this type has been performed.

2.2 Materials and water used in the tests

The tests include the following material:

- **Bentonite pellets, Mx80.** Tests of type 2 and 3, see above.
- **Bentonite/Ballast 30/70** (IBECO Deponit-C-A-N/Crushed rock, BallastB). Test of type 2 and 4, see above.
- **Friedland blocks** (German bentonite). Tests of type 1, see above.

The tests have been made with the following water:

- **Water1**, tap water
- **Water2**, water with salinity of 1% (50/50 NaCl/CaCl₂)
- **Water3**, water with salinity of 3.5% (50/50 NaCl/CaCl₂)

The most probable water type in a real installation is type 2. The main part of the tests have been done with this water, but complementary tests have been done with the other water types in order to get information regarding the influence of the water type's on the piping and erosion properties.

3 Erosion of pre-compacted blocks

3.1 General

This test type simulates a tunnel, which have been filled with pre-compacted blocks, during the installation phase. One problem is how the blocks can handle different water inflows from the rock. The water will come in contact with the block surfaces and depending on the flow rate and the individual distance between the blocks, a number of scenarios can occur. The most obvious scenario is that material will erode along the surface and that separation of the blocks may occur due to the swelling when water comes into the slot between the blocks. Blocks made of Friedland bentonite were available from another project. These blocks have the approximately dimensions $300 \times 300 \times 170$ mm. They have been sawed in parts and used in this test series.

3.2 Test description

The available blocks were cut in slices ($100 \times 100 \times 30$ mm) with use of a band saw. The bulk density of the blocks varied between $2,233$ – $2,320$ ton/m³ having a water content of 10.8–12.1%. The slices were placed in a groove made of a steel profile (Figure 3-1). In order to determine the blocks sensitivity to erosion, different water flow rates were applied on the blocks surface. The steel profile was inclined 1% during the tests.

The blocks were locked in the ends by a number of angle-irons; see Figure 3-2. A pre-test was done without these angels, which resulted in a very strong separation of the blocks. The steel profile was quite slippery and the conditions were not representative for the real case, so it was decided to lock the blocks in the ends.

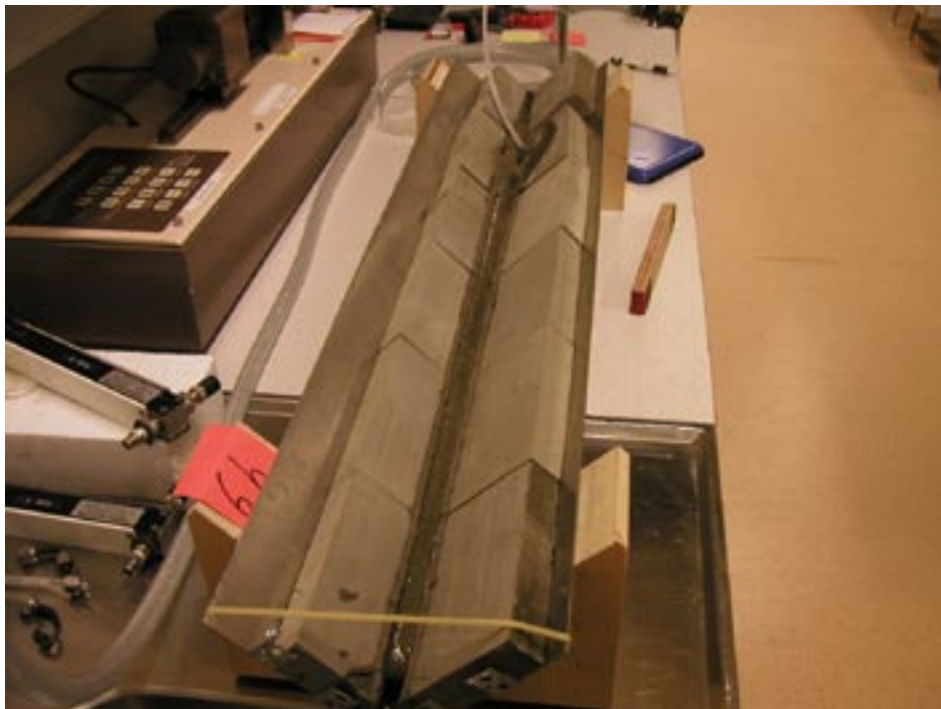


Figure 3-1. Picture showing the test equipment. A one meter long steel profile was filled with blocks of compacted bentonite. A constant water flow was applied in one end and the amount of eroded material in the out flowing water was measured.



Figure 3-2. Picture showing a part of the used test equipment. In the front the steel angle-irons, locking the bentonite blocks, can be seen.

The following have been measured during the tests:

1. **Water flow into the system.** Different equipments were used for the different flow rates. For the lowest flow rate a GDS (a microprocessor controlled hydraulic actuator for the precise measurement of liquid pressure and liquid volume change) was used. For the highest flow rate a microprocessor controlled pump was used. For the other flows, flow meters with needle valves were used. The water was supplied from a vessel placed about 2 meter above the test equipment. The vessel was placed on a scale, which means that the flow rate could be checked.
2. **The water flow out from the system.** The water volume coming out from the test equipment was collected continuously except for the tests with the highest flow rate, where samples were taken at intervals.
3. **The amount of eroded material in the water.** From the collected water, the amount of clay was determined by evaporating the water in an oven at 105°C.
4. **Observing of the test development.** A digital camera was used and photos taken regularly.
5. **The amount of clay eroded.** The installed blocks were weighed before installation and the water ratio was determined on some samples. After the test, all material left was dried at 105°C, and the solid mass eroded could be calculated. This method was especially useful for the tests with the highest flows where only a small part of the flowing water was collected and dried.

3.2.1 Parameters

The bentonite blocks were exposed to the water types described in Chapter 2. The water flow rates were varied between 0.001–1 l/min. The sample length was varied, 0.2 m and 1.0 m.

3.2.2 Test matrix

The complete test matrix is shown in Table 3-1. The planned tests are marked with bold text and the performed are marked with green squares. Tests D:221–D:224 were chosen in order to determine the influence of the flow rate. Test D:122 and D:322 were chosen to detect the influence of the water type. Test D:212 was chosen to detect the influence of the test length. Test D:124 was an extra test.

Table 3-1. Test matrix for the erosion tests on Friedland bentonite blocks. The planned tests are marked with bold text and the performed are marked with grey squares.

Friedland blocks						
Flow	Tap water		1% salt		3.5% salt	
l/min	0.2 m	1 m	0.2 m	1 m	0.2 m	1 m
0.001	D:111	D:121	D:211	D:221	D:311	D:321
0.01	D:112	D:122	D:212	D:222	D:312	D:322
0.1	D:113	D:123	D:213	D:223	D:313	D:323
1	D:114	D:124	D:214	D:224	D:314	D:324

3.3 Results

3.3.1 General

The test results are compiled in Table 3-2. A more detailed description of the results from each test is given in Appendices 1–8.

The total amount of eroded material was determined in two ways:

1. The total amount of water coming out from the system was collected at decided intervals and the solid mass in the water was determined by evaporating the water.
2. The blocks were weighed before installation and the water ratio determined. After the test, all material left was weighed and dried in 105°C and the solid mass eroded was calculated.

Table 3-2. Compilation of the performed tests and the results.

Sample	Water type	Flow	Test length	Test duration	Total amount solid mass eroded		Erosion velocity in average	Difference inflow and outflow after 7 hours	Comments
					Dried clay	Water samples			
		l/min	m	h	g	g	g/h	litres	
D122	Tap water	0.01	1	7	39	17	2.4	0.3	Low erosion velocity. The main part of the block areas are not influenced.
D124	Tap water	1	1	7	347	395 **	49.5	*	The main part of the block areas are not influenced. Sharp ditch in the middle.
D212	1% salt	0.01	0.2	7	40	45	6.4	0.6	Low erosion velocity.
D221	1% salt	0.001	1	8	0	0	0	0.5	All water from inflow was left in the clay.
D222	1% salt	0.01	1	7	65	58	8.3	1.4	Low erosion velocity.
D223	1% salt	0.1	1	7	*	260	37	1.5	The water affect the surrounding bentonite blocks. A lot of material erodes.
D224	1% salt	1	1	3	1159	1169**	390	*	The water affect the surrounding bentonite blocks. Very high erosion velocity.
D322	3.5% salt	0.01	1	8	84	92	11.5	2.2	Low erosion velocity. Most of the water stays in the clay which swells on the surface.

* not measured

**calculated from 16 water samples out of 420 litres (19 samples out of 180 litres for test D224)

3.3.2 Influence of flow

The influence of the flow rate on the erosion is very strong. The diagram in Figure 3-3 shows the accumulated amount of eroded material plotted vs. time. Comparing the four tests with the same water type (1% salt) and same test length, i.e. black dots with large size, the influence of flow rate is shown very evidently. The result is the same when comparing the two tests performed with tap water (transparent dots).

The erosion rate at different times for the 8 tests is presented in Figures 3-4 to 3-6. In Figure 3-5 the tests with different flow rates but with the same water types are plotted. The influence of the flow rate is obvious. It seems that if the flow rate is low, the bentonite will get more time for swelling which prevents the flow and a greater part of the bentonite surface will be influenced by the water, see Figure 3-7.

The results are also plotted as the accumulated eroded mass vs. the accumulated flow, see Figure 3-8. The tests with same water types but different flow rates are all collected together, showing that the amount of eroded material per litre solution is almost the same, independent of the water flow rate. In Figure 3-9 the average amount of eroded material is plotted vs. the water flow rate. The diagram shows the average bentonite content in the water and does not consider the fact that the erosion rate seems to decrease by time.

3.3.3 Influence of water type

In order to test the influence of the water salinity, three tests were performed with the same flow and the same test length, but with different water types. Comparing the three tests plotted with triangles of large size, in Figure 3-4, the influence on the erosion velocity is obvious. Pictures from the three tests are shown in Figure 3-10, which also shows that the influence of the salinity of the water on the surrounding bentonite is very strong.

3.3.4 Influence of test length

Only one test has been done with a different test length. The length does not seem to influence the erosion very much. Comparing the two tests performed with the same water type and the same water flow but with different test lengths, the difference seems to be very small (Figure 3-4, black triangles with different sizes).

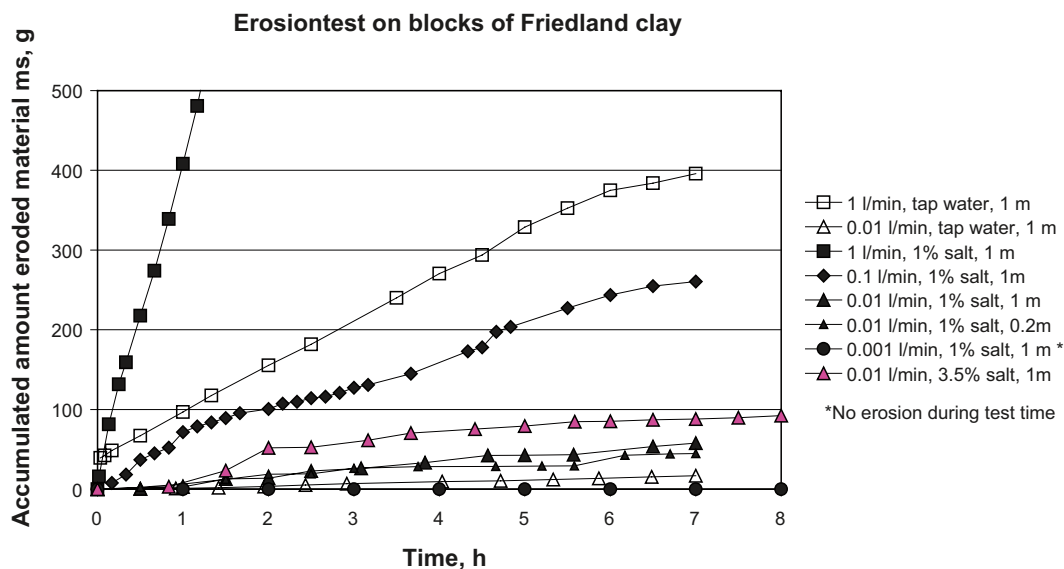


Figure 3-3. The accumulated amount of eroded material plotted vs. time.

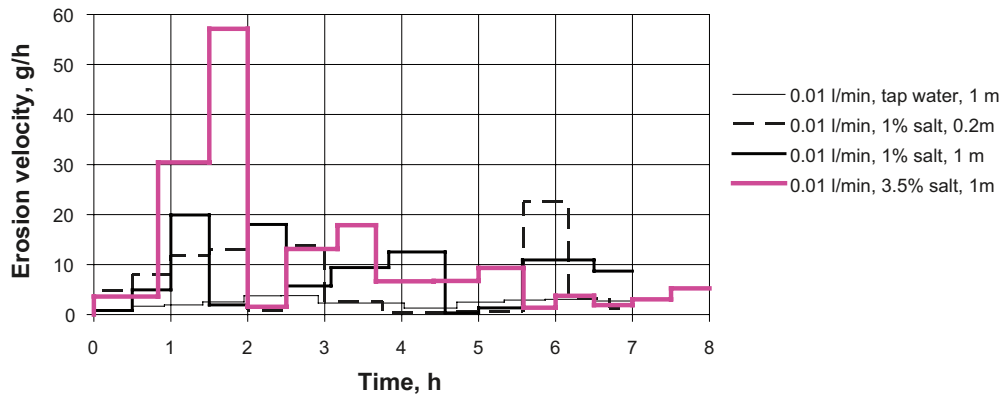


Figure 3-4. The erosion velocity plotted vs. time. The diagram shows the result for the 4 tests with the same flow rate, 0.01 l/min, but with different water types. Also the test with shorter length is plotted here.

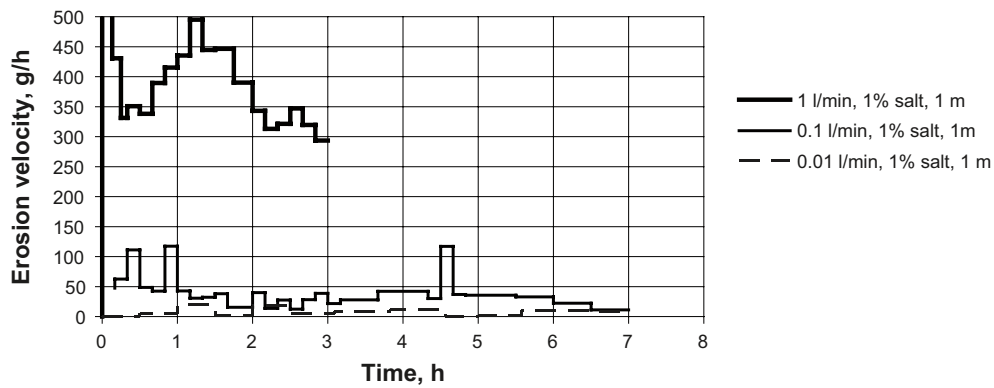


Figure 3-5. The erosion velocity plotted vs. time. The diagram shows the result for the three tests with the same water type, 1% salt, but with different water flow rates. The test with the lowest flow rate, 0.001 l/min, is not plotted since it was not possible to measure any erosion during the test time.

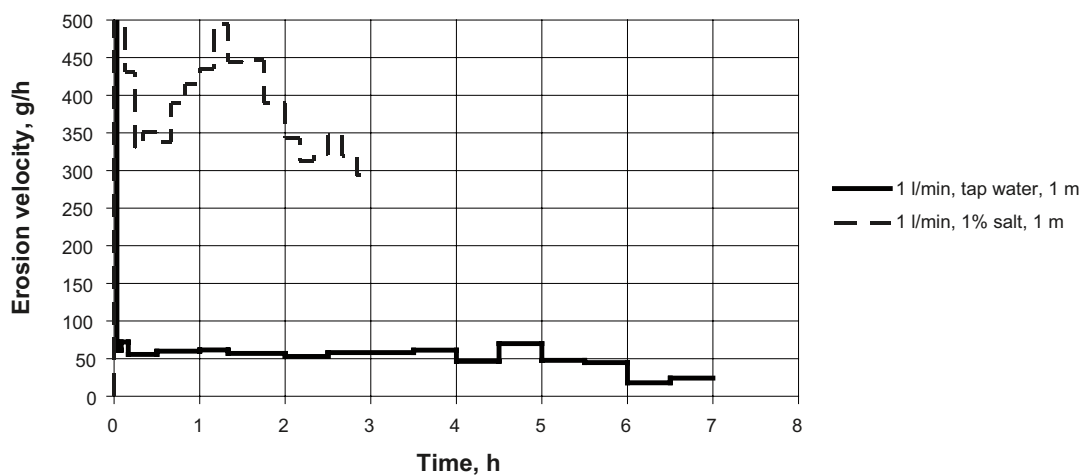
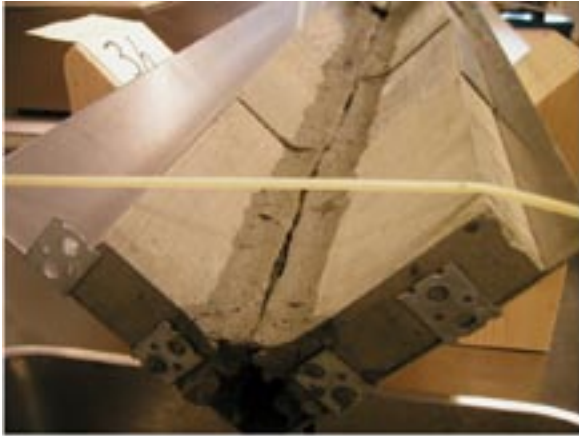


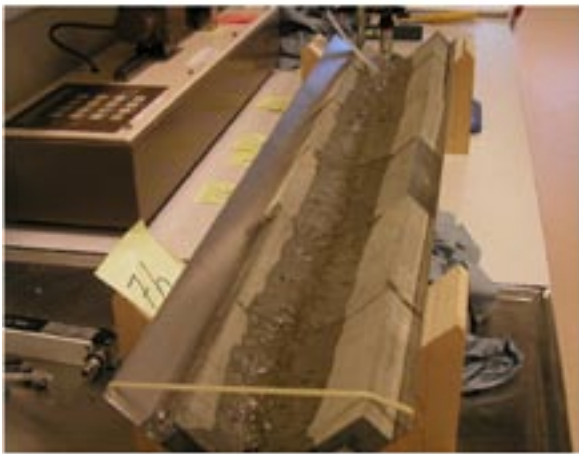
Figure 3-6. The erosion velocity plotted vs. time. The diagram shows the result for the 2 tests with the same flow, 1 l/min, but with different water types.



Test D224, 1% salt in water, flow 1 l/min.



Test D223, 1% salt in water, flow 0.1 l/min.



Test D222, 1% salt in water, flow 0.01 l/min.



Test D221, 1% salt in water, flow 0.001 l/min.

Figure 3-7. Pictures from the four tests with 1% salt in the water and with different flows. The pictures are taken just before interruption of the tests. The test with the highest flow rate, 1 l/min, D224, has only been running for 3 hours compared to the other tests that have been running for 7 and 8 hours respectively.

Erosion on blocks, Friedland

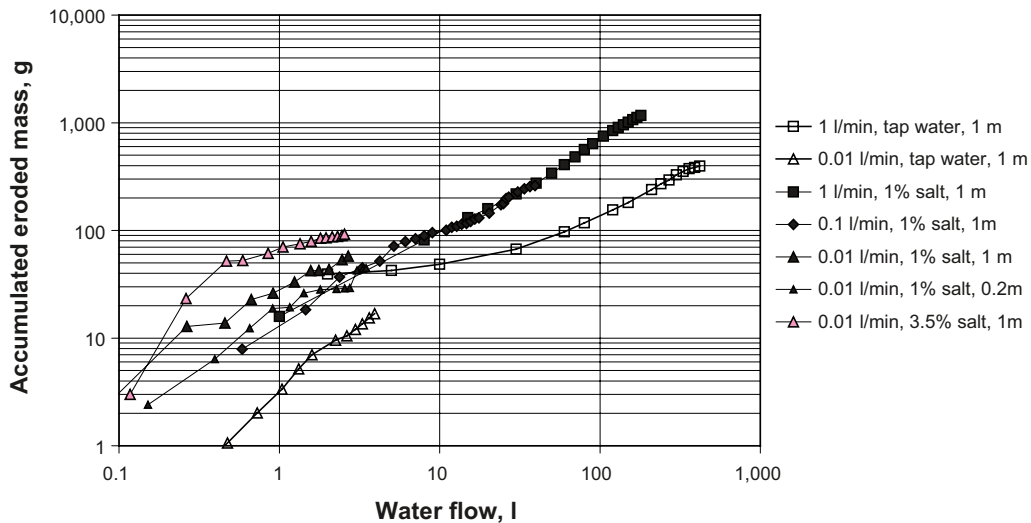


Figure 3-8. The accumulated eroded material plotted vs. the accumulated water flow.

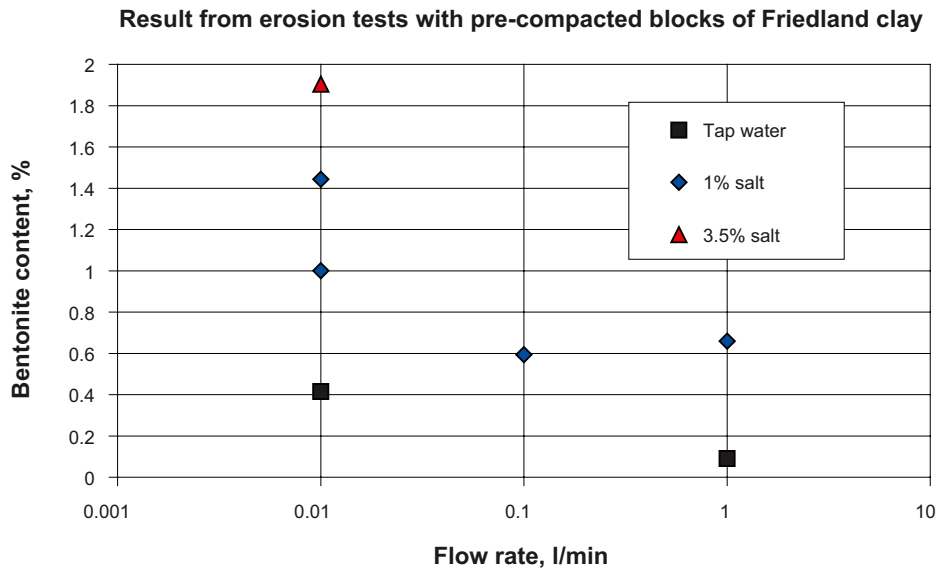
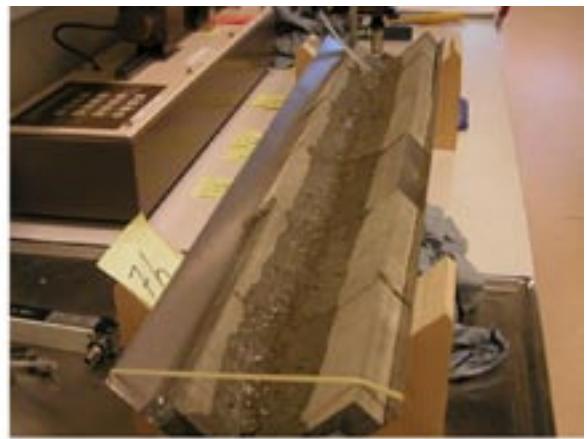


Figure 3-9. The average bentonite content in the discharged water plotted vs. different water flow rate for the erosion tests on Friedland blocks.



Test D122, tap water, flow 0.01 l/min.



Test D222, 1% salt in water, flow 0.01 l/min.



Test D322, 3.5% salt in water, flow 0.01 l/min.

Figure 3-10. Pictures from the three tests with the same flow, 0.01 l/min and with different salt content in the water. The pictures are taken just before interruption of the tests.

4 Piping and erosion tests of bentonite pellets and in situ compacted backfill material

4.1 General

The aim with the tests was to investigate the maximal inflow from a fracture that the installation procedure can handle. In order to test this a number of one dimensional tests simulating either a pellet filled slot or 30/70 backfill, close to the rock have been done. The test equipment consists of tubes made of Plexiglas, Figure 4-1. With this equipment the course of events could be observed and photographed from the outside.

4.2 Test description

4.2.1 General

The tubes have an inner diameter of 100 mm. Six of the tubes have a length of 0.5 m and one is 0.2 m long. The tubes can be connected in order to get different test lengths. Every half meter, a 5 mm thick ring with an inner diameter of 90 mm has been placed in order to simulate the unevenness of the rock surface. The material was poured into the tubes (pellet) or in situ compacted in layers (bentonite/backfill, 30/70).

At the front of the Plexiglas-tube a perforated plate was placed in order to keep the pellet or backfill material in position. At the other side of the Plexiglas tube a point inflow or a zone inflow was applied. Different water types have been used, see Section 2.2. The aim was to apply a constant flow rate which remains constant independent of the water pressure that builds up during the test. In order to simulate the inclined tunnel the test tubes were positioned with an inclination of 1%.

The intention was that the tests should be interrupted when the rate of erosion was constant or the change of erosion rate was constant. The amount of eroded material was determined by evaporating the water and weighing the solid mass left. This procedure takes time which means that it was not possible to determine the rate of erosion “online”. For the tests with the highest flow rate, it was also practical reasons that determined how long the tests could run.

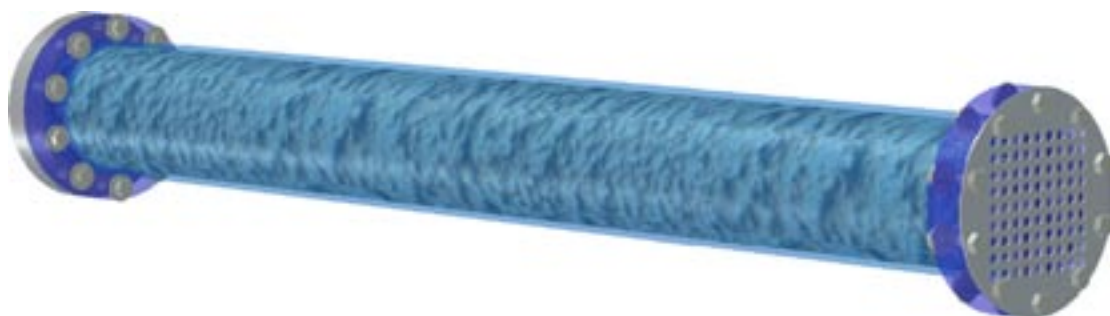


Figure 4-1. Picture showing the test equipment consisting of a 1 m long Plexiglas tube filled with backfill material or pellets. A constant water flow was applied in one end and the piping and erosion scenario was studied. The strength of the Plexiglas tube has been calculated and with the chosen wall thickness of 5 mm the tube should withstand an inner pressure of 1 MPa with a safety factor of 6.

The following measurements and observations have been done during the tests:

1. **Water flow into the system** (was set to a decided value on the GDS or the microprocessor controlled pump).
2. **Water pressure on the inflow side.** A separate transducer registered the water pressure built up.
3. **Water flow out from the system.** The volume coming out was measured at decided intervals.
4. **The amount of eroded material in the water.** Samples were taken from the out coming water were the amount of clay was determined by evaporating the water in an oven at 105°C.
5. **Observation of the material in order to detect any signs of collapse.** A digital camera was used in order to register the test development.

After interrupting the tests, the water ratio was determined in a number of positions.

4.2.2 Parameters

Besides the different materials and the different water types, described in Section 2.2, a number of parameters have been varied.

1. The length of the tubes:
 - **Length1**, 0.2 m
 - **Length2**, 1.0 m
 - **Length3**, 3.0 m
2. The applied flow rates:
 - **Flow1**, 0.001 l/min. For this flow rate a GDS (a microprocessor controlled hydraulic actuator for the precise measurement of liquid pressure and liquid volume change) has been used.
 - **Flow2**, 0.01 l/min. For this flow rate a special microprocessor controlled pump has been used.
 - **Flow3**, 0.1 l/min. As above.
 - **Flow4**, 1 l/min. As above.
3. Pellet composition.
 - **Pellet material.** The tests were run with MX-80 pellets, see Section 2.2.
4. Point inflow or zone inflow.
 - **Inflow type.** All tests in the matrix have been performed simulating a point inflow.

4.3 Test performed with MX-80 bentonite pellets

4.3.1 General

The complete test matrix for the test series is shown in Table 4-1. The planned tests are marked with bold text and the performed with green squares.

The main part of the performed tests were made with the water salinity 1%. This water type is the most probable during the installation phase. For the pellet material, tests A:221–A:224 were chosen in order to determine the influence of the flow rate. Tests A:212 and A:232 were chosen to detect the influence of the test length. These tests were supplemented with A:112 and A:312 in order to see the influence of the water type. These tests were later exchanged to testA:122 and A:322.

Table 4-1. Test matrix for the piping and erosion tests with MX-80 pellets. The planned tests are marked with bold text and the performed tests with grey squares.

PELLET MX-80									
Flow	Tap water			1% salt			3.5% salt		
l/min	0.2 m	1 m	3 m	0.2 m	1 m	3 m	0.2 m	1 m	3 m
0.001	A:111	A:121	A:131	A:211	A:221	A:231	A:311	A:321	A:331
0.01	A:112	A:122	A:132	A:212	A:222	A:232	A:312	A:322	A:332
0.1	A:113	A:123	A:133	A:213	A:223	A:233	A:313	A:323	A:333
1	A:114	A:124	A:134	A:214	A:224	A:234	A:314	A:324	A:334

4.3.2 Results

Eight different tests have been made with the MX-80 pellets. A compilation of the results is shown in Table 4-2. The results from the tests are presented in Figure 4-5 to 4-10. A detailed description of every test is presented in Appendices 8 to 16.

Due to the applied constant flow and the swelling capability of the bentonite pellets, a water pressure build up was expected in some of the tests. This occurred only in two of the tests: Test A:221 (0.001 l/min, L=1 m, 1% salt) where a water pressure of about 600 kPa was built up (see Figure 4-2) and in test A:322 (0.01 l/min, L=1 m, 3.5% salt) where a water pressure of about 100 kPa was built up (see Appendix 16).

In all the tests with MX-80 pellets, the water was after a while mainly flowing in one channel, which in all tests was located on the upper part of the Plexiglas tubes.

Table 4-2. Compilation of the results from the tests with MX-80 pellets in plexi-glas tubes.

Sample	Water type	Flow	Test length	Test duration	Total amount solid mass eroded		Erosion velocity in average	Difference between inflow and outflow after test	Comments
					Dried clay	Water samples			
		l/min	m	h	g	g	g/h	litres	
A122	Tap water	0.01	1	48	*	108.5	2.5	4.0	
A212	1% salt	0.01	0.2	31	*	133	4.3	0.9	
A221	1% salt	0.001	0.5	47	*	49.6	1.1	3.5	The sample was divided in two parts depending on leakage and the erosion test was done on a 0.5m long sample.
A222	1% salt	0.01	1	31	*	266	10.2	4.0	
A223	1% salt	0.1	1	6.3	*	376	65	3.1	
A224	1% salt	1	1	3	2133	1955**	651	*	
A232	1% salt	0.01	2.5	175	*	79	0.45	14.2	
A322	3.5% salt	0.01	1	48	*	283	5.9	4.7	

* not measured

**calculated from 19 water samples out of 182 litres

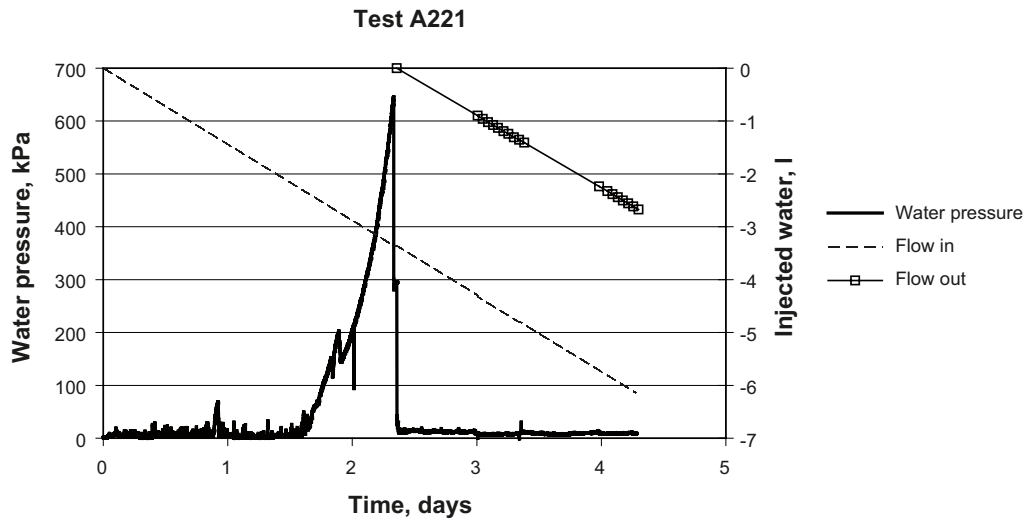


Figure 4-2. The inflow, the water pressure and the measured outflow in test A:221 plotted vs. time.

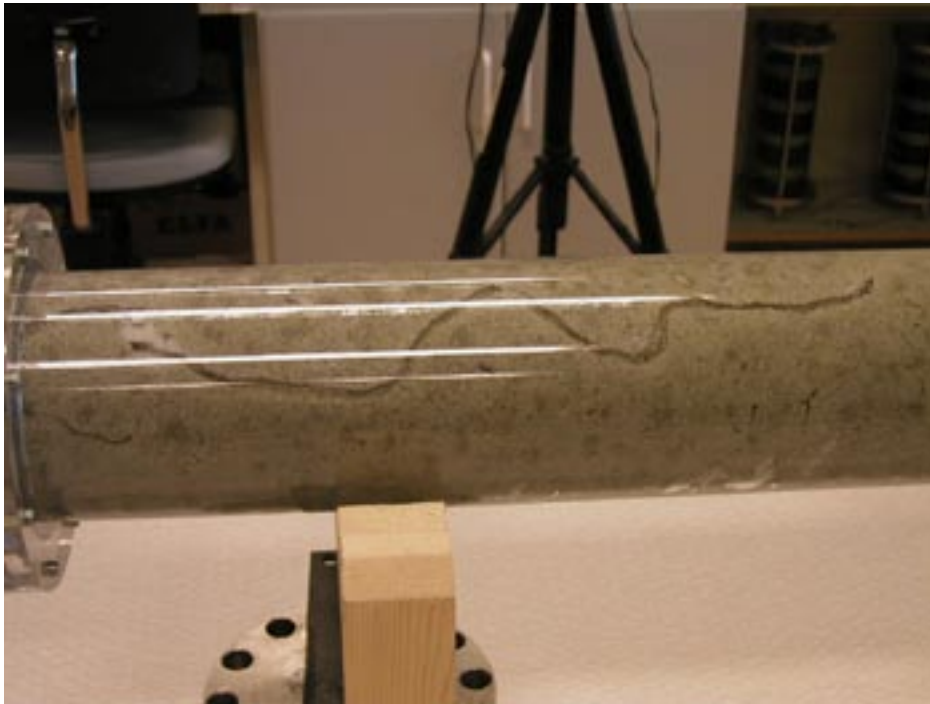


Figure 4-3. Photo taken of test A:223. The photo shows clearly the channel where most of the water is flowing.

When interrupting the tests, samples were taken in different positions in order to determine the water ratio. The samples were taken in the central parts and in the zone around the flow channel. An example of results is shown in Figure 4-4. The results are very similar for all tests, showing higher water ratios around the water channel.

The accumulated amount of eroded material is plotted vs. time for all performed tests in Figure 4-5. It is obvious that the influence of flow rate is very strong, comparing the black dots with same size. Also the salinity of the water (triangular dots with different colour) has a strong influence on the erosion rate even if the results are not completely clear. Two of the tests, the two with different lengths (0.2 m and 2.5 m, triangular black dots) show however results which are difficult to interpret. When comparing the 0.2 m test with the 1 m test (same salinity and

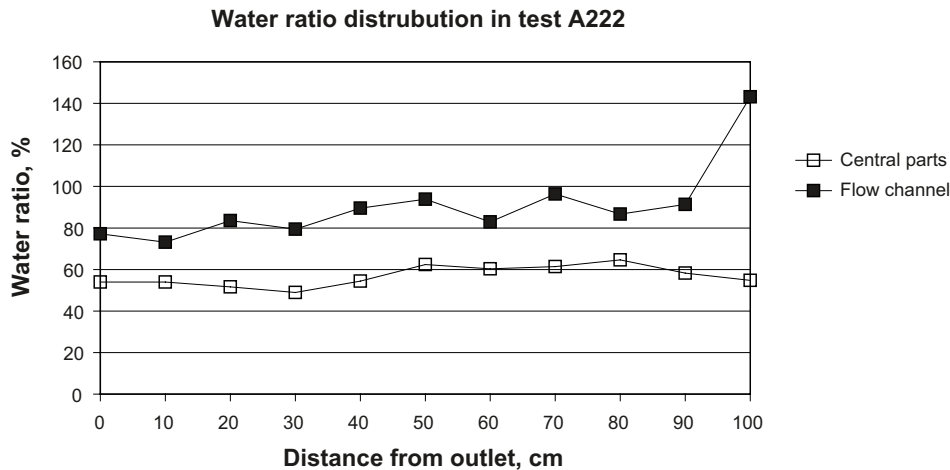


Figure 4-4. The water ratio distribution in test A:222. The samples were taken just after the termination of the test. The water ratios are considerable higher around the flow channel.

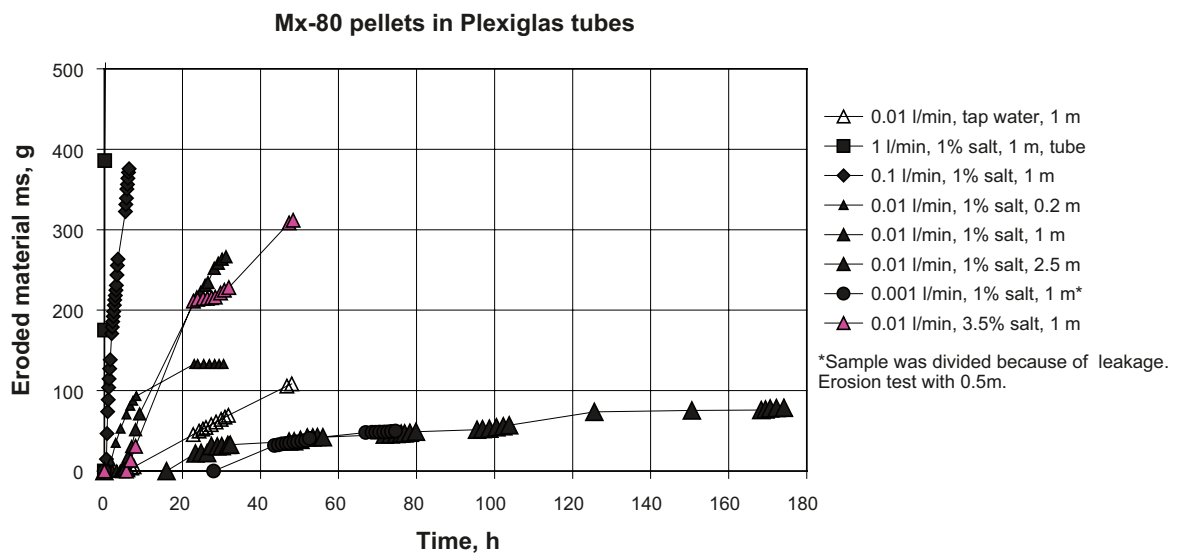


Figure 4-5. The accumulated amount of eroded material plotted vs. time.

flow), the erosion velocity is almost the same for about 20 hours and then the erosion decreases to almost zero for the 0.2 m test. This could mean that the length of the sample has no influence for the erosion velocity in the beginning, but when the flow channel is established (which has been the case in all pellets tests) and all loose particles are transported away, the erosion velocity goes down very fast. The erosion velocity from the 2.5 m sample was however very low from the beginning and was then slowly decreasing to almost zero. This could be explained by the fact that the time for transporting a particle out from the system increased, which means that the time for swelling also increases and by that also the possibility for an individual particle to grow/swell and then get stuck somewhere in the pellets volume. The 2.5 m test was also a long term test to study the influence of the time on the erosion. The test showed that the erosion velocity seems to decrease with time.

In Figure 4-6 is the average amount of eroded material during test time plotted vs. the different water flow rates. The diagram only shows the average bentonite content in the water and does not consider the fact that the erosion rate seems to decrease by time.

The results are also plotted as the accumulated eroded mass vs. the accumulated water flow in logarithmic scales, see Figure 4-10.

Result from erosion tests with Mx-80 pellets

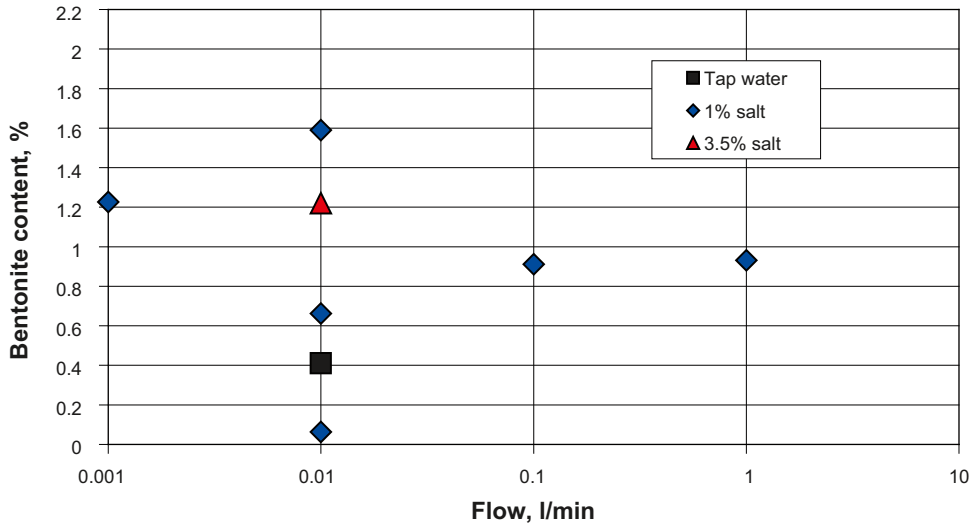


Figure 4-6. The average bentonite content in the water during test time, plotted vs. the different water flow rates.

Tube tests, 1m, 1% salt water

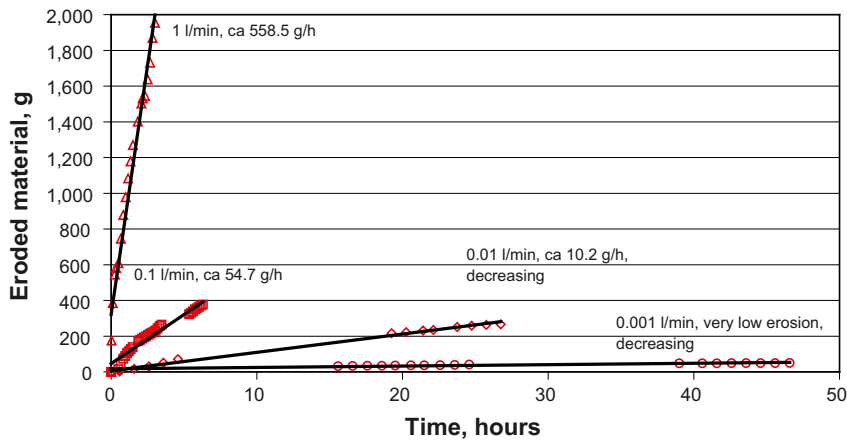


Figure 4-7. The influence of the flow rate. The time for the first water drip out from each test is set to zero.

Tube tests 1m, 0.01 l/min

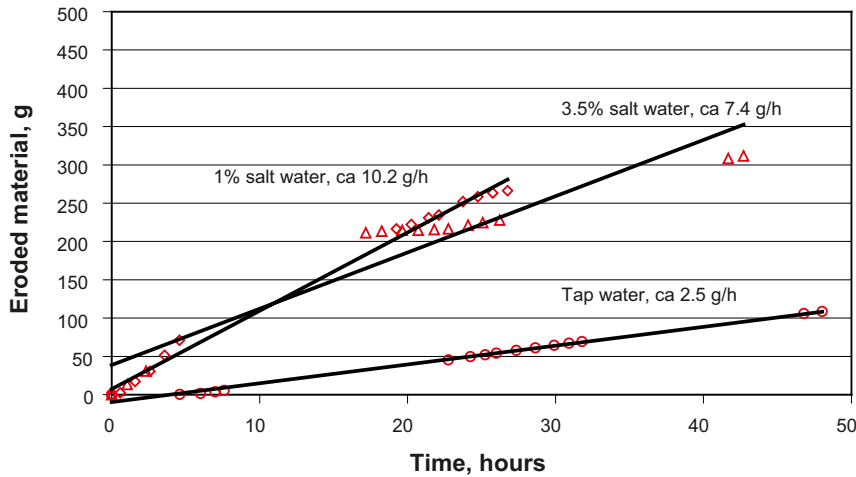


Figure 4-8. The influence of salt in the water:

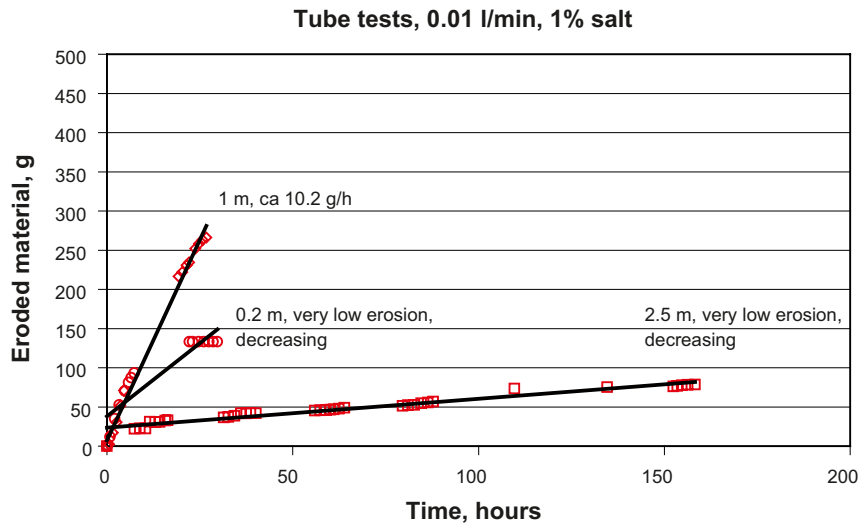


Figure 4-9. The influence of the test length.

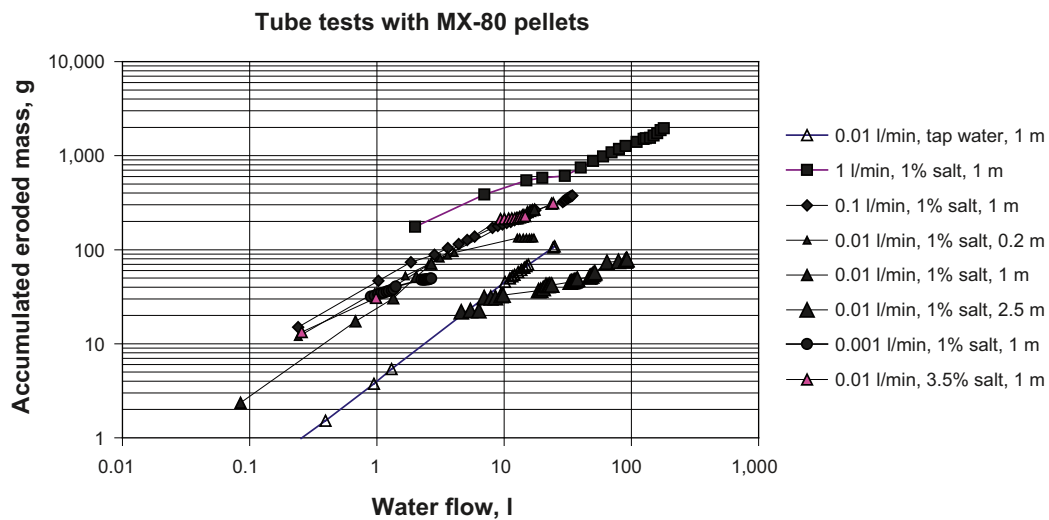


Figure 4-10. The accumulated eroded mass plotted vs. the accumulated flow.

4.4 Test performed with in situ compacted bentonite/ballast mixture

4.4.1 General

The complete test matrix of the test series with 30/70 backfill is shown in Table 4-3. The planned tests are marked with bold text and the performed with grey squares. In addition a number of tests have been done, where changes have been done with the equipment i.e. material and the position of the water inlet point.

The selection of tests for the in situ compacted backfill material, 30/70, with a dry density of 1.6 g/cm^3 was done according to the same principles as for the pellets tests in order to detect the influence of flow, salinity in the water and the test length. According to the plan, a number of tests then should be chosen from the next density, 1.8 g/cm^3 , in order to understand the influence of the dry density. This was never done since piping didn't occur even of the low density.

Table 4-3. Test matrix for the piping and erosion tests with the bentonite/backfill material

BENTONITE/BACKFILL 30/70, DRY DENSITY 1.6 g/cm ³									
Flow	Tap water			1% salt			3.5% salt		
l/min	0.2 m	1 m	3 m	0.2 m	1 m	3 m	0.2 m	1 m	3 m
0.001	B:111	B:121	B:131	B:211	B:221	B:231	B:311	B:321	B:331
0.01	B:112	B:122	B:132	B:212	B:222	B:232	B:312	B:322	B:332
0.1	B:113	B:123	B:133	B:213	B:223	B:233	B:313	B:323	B:333
1	B:114	B:124	B:134	B:214	B:224	B:234	B:314	B:324	B:334
BENTONITE/BACKFILL 30/70, DRY DENSITY 1.8 g/cm ³									
Flow	Tap water			1% salt			3.5% salt		
l/min	0.2 m	1 m	3 m	0.2 m	1 m	3 m	0.2 m	1 m	3 m
0.001	C:111	C:121	C:131	C:211	C:221	C:231	C:311	C:321	C:331
0.01	C:112	C:122	C:132	C:212	C:222	C:232	C:312	C:322	C:332
0.1	C:113	C:123	C:133	C:213	C:223	C:233	C:313	C:323	C:333
1	C:114	C:124	C:134	C:214	C:224	C:234	C:314	C:324	C:334

4.4.2 Results

Eight different tests have been made with the 30/70 mixture. A compilation of the results is made in Table 4-4. The results from the tests are also presented in Figure 4-2 to 4-6. For every test, data is also presented in Appendices 17 to 19.

Due to the applied constant flow rate, it was expected that a water pressure in the same order of magnitude as the swelling pressure for the saturated material, would be build up. When the maximal water pressure was reached it was expected that piping should occur. After having performed 3–4 tests, the results from these indicated that it was very difficult to get piping in the material. In these first tests very high water pressures were built up (1,000–1,400 kPa) which meant that the limits of the equipment was reached. The pump could give a maximal pressure of about 1,200–1,400 kPa and the Plexiglas tubes were designed to withstand an internal pressure of 1,000 kPa. This resulted in that some of the tests were interrupted depending on the high water pressure (see Figure 4-11) and for some tests that leakage occurred on the sample holders, which meant that the tests could not be finished. In test B:212 and later also test B:222-2, the Plexiglas tubes cracked.

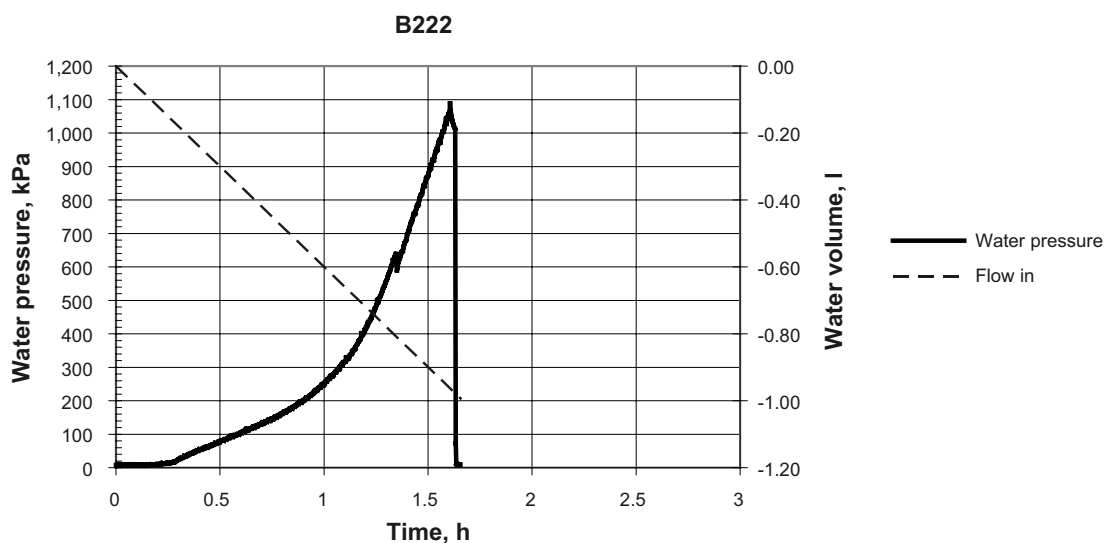


Figure 4-11. Measured inflow and water pressure. At 1,100 kPa the pump had to be switched off reaching its maximum, before any piping had occurred.

Table 4-4. Compilation of the results from the tests with 30/70 mixture in Plexiglas/steel tubes.

Sample	Water type	Flow	Sample length	Test duration	Total amount dried clay	Comments
					Water samples	
		l/min	m	h	g	
B212	1% salt	0.01	0.2	8	-	The test was interrupted when the plexi-glas tube cracked after about 8 hours.
B221	1% salt	0.001	0.5	33	-	After 7 hours the water pressure was set to 800 kPa instead of the constant flow. After 33 hours a strong leakage occurred and the test was interrupted.
B222	1% salt	0.010	1	1.5	-	The test was interrupted after about 1.5 hour depending on a very fast increasing water pressure. Neither the pump nor the plexi-glas tube could stand higher pressure.
B223	1% salt	0.10	0.5	0.25	-	The test was interrupted after about 15 minutes when the water pressure had reached to the maximum pump pressure. No erosion during the test time.
B221-2	1% salt	0.001	0.5	96 (168)	18	Steel tube with inlet on the middle. The test was interrupted after 4 days. After 2 days rest it was started again. Before the final interruption a higher flow was applied resulting in that the material was pressed through the ends.
B222-2	1% salt	0.01	0.5	3	-	Plexi glas tube with inlet on the middle. The test was interrupted when the plexi glas tube cracked after about 3 hours.
B222-3	1% salt	0.01	0.5	3.5	-	Steel tube with inlet on the middle. The test was interrupted after 3.5 hours when the material was pressed through the ends of the test equipment.
B222-4	1% salt	0.01	0.5	2	-	Steel tube with inlet on the middle. The test was performed without any bars in one of the sample holders end. This resulted in that the material was pressed through the ends of the test equipment in almost one piece.

The behaviour may be explained by impenetrability of the material. This meant that a water pressure could be built up, acting on the full cross-section, and compacting the material on both sides of the fracture, see photo in Appendix 20. When the tests were terminated, the water ratio was determined in a number of positions (see example in Figure 4-12). These investigations confirm that the saturation seems to be very homogenous radial direction and that there is no “flow channel” which was the case for the pellets tests. The water inlet was then moved from the end to the middle of the tube. A pre-test with this solution was done with one of the Plexiglas tubes which was modified, see test B:222-2. The result of this test was that the tube (sample holder) was cracked, see Appendix 22. The measured values before cracking indicated that the same problem was still present. After discussions it was decided to manufacture new equipment made of steel. Two tests have been performed with this equipment, B:221-2 and B:222-3. The first test performed was B:222-3. The test resulted in that a rather high water pressure was built up, 900 kPa, and then the material started to be squeezed out through the perforated end lids, see picture in Appendix 23.

Test B:221-2 i.e. the test with the lowest flow was the only test performed in which it was possible to measure any erosion (see figure in Appendix 21). The amount of eroded material was very low, about 18 g in three days. After 4 days the test was temporary interrupted (see figure in Appendix 21). After about 2 days resting, the same constant flow was applied again. The water pressure increased to almost the same level as before the rest. An attempt was then made to increase the flow to 0.01 l/min, but this resulted immediately in a raised water pressure and by that also that the material was pressed out from the ends of the sample holder. A later calculation showed that the flow out from the test was in the same order as if the sample had been percolated i.e. it was the hydraulic conductivity of the sample that was measured (about 5×10^{-8}) and not a piping scenario.

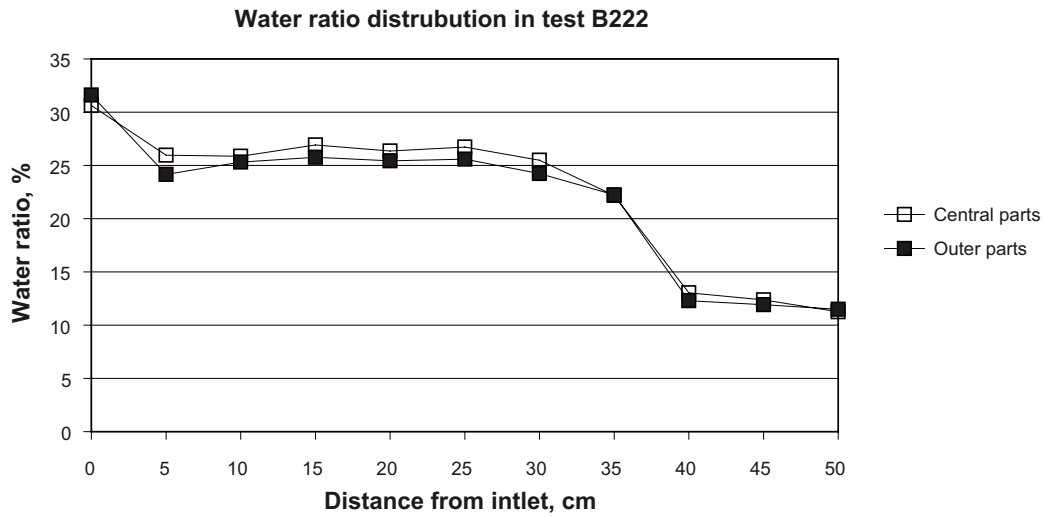


Figure 4-12. The water ratio distribution. The samples are taken just after the termination of the test. There is no clear difference in water ratio between the central parts and the outer parts. The initial water ratio of the material was about 12%.

5 Test of pellet stability in large slot

5.1 General

The aim with these tests was to check the stability of a large inclined pellet volume when exposed to a water inflow. A worst case is that a water inflow with a certain water type (salinity), leads to a collapse of the whole pellet slope which then could flow away.

The equipment consists of an artificial slot, $2 \times 1 \times 0.1$ m, made of Plexiglas, Figure 5-1. The slot was filled with pellets and a water inflow was applied on the side of the slot. The water inflow is positioned 0.5 m up from the bottom and 0.3 m from the end i.e. almost in the middle between the two rear black beams.

The measurements and observations done during the tests are the same as described in Section 4.2.

5.2 Test description

5.2.1 Parameters

Three water flow rates were applied in the tests: 1.01 and 0.01 l/min. In all tests water with a salinity of 1% was used.

5.2.2 Test matrix

The complete test matrix for the slot tests is shown in Table 5-1. The original plan was to perform six tests, but since the tests were very time consuming it was decided to reduce the number to three tests. The planned tests are marked with bold text and the performed with grey squares.

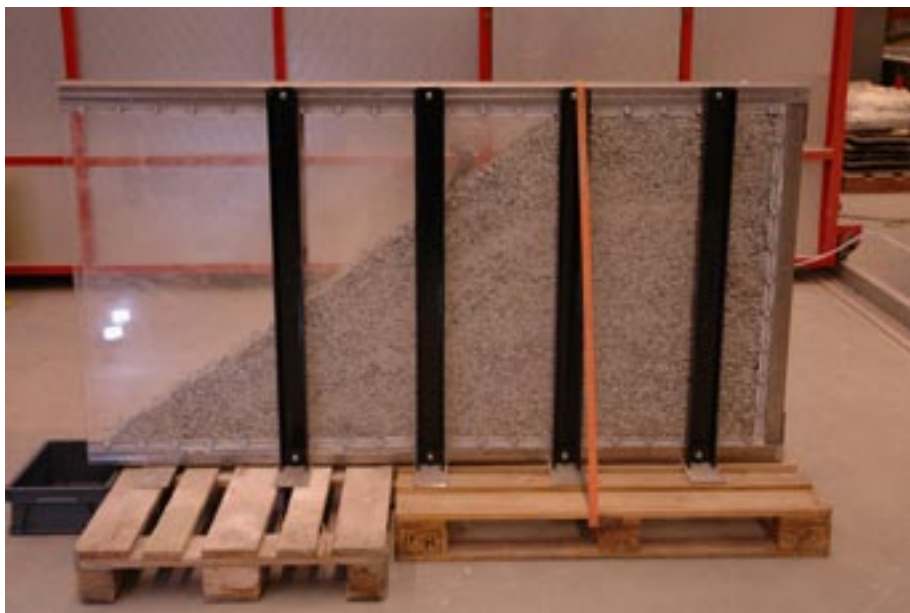


Figure 5-1. Picture showing the test equipment. The slot is 2 m long and 1 m high. The width of the slot is 0.1 m. Three tests of this type have been made in order to determine the influence of different water flow rates and different water types on the stability of a slope of pellets

Table 5-1. Test matrix for the tests of pellets in large slot.

PELLET MX-80 IN SLOT			
l/min	Tap water	1% salt	3.5% salt
0.001	E:11	E:21	E:31
0.01	E:12	E:22	E:32
0.1	E:13	E:23	E:33
1	E:14	E:24	E:34

5.3 Results

Three tests with pellets in a large slot have been performed. All three tests were performed with salt water (1%) and the water inflow rates were 0.01 l/min, 0.1 l/min and 1 l/min. The results from the tests are presented in Figures 5-2 to 5-4. Additional data from the tests are presented in Appendices 25 to 27. One obvious difference between the tests was that different parts of the pellets volume were affected. At the two higher inflow rates, only the lower part of the pellets volume was wetted but in the test with the lowest water inflow rate the upper part above the inflow point and the slope surface wetted (see pictures in Appendices 25 to 27).

The results from the erosion measurements are also plotted as the accumulated eroded mass vs. the accumulated water flow, see Figure 5-4. All tests in this series are performed with same water type but different flow rates.

A compilation of all results from the pellets tests is done in Figure 5-5. The results show that the amount of eroded material per litre solution is almost the same for identical water, independent of the flow rate.

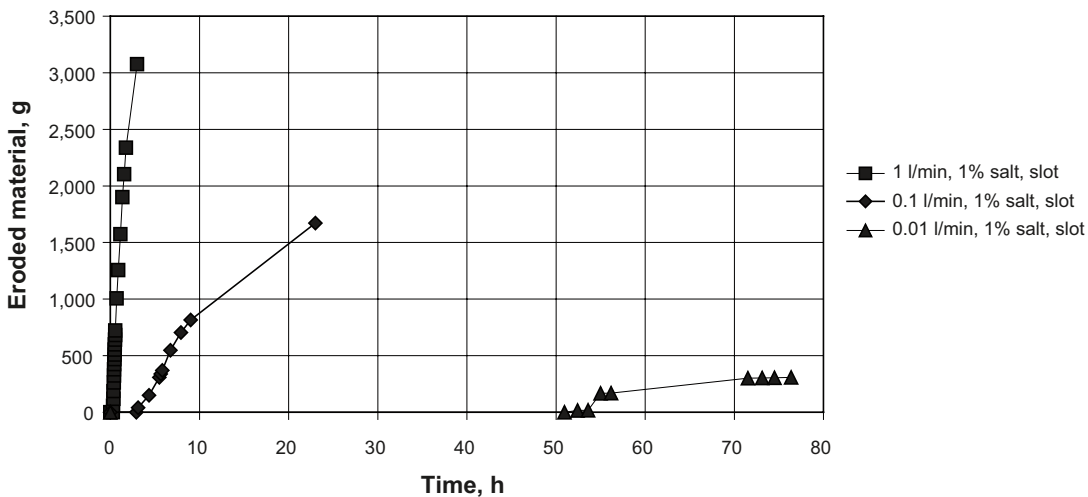


Figure 5-2. The results from the slot tests. The amount of eroded material is plotted vs. time.

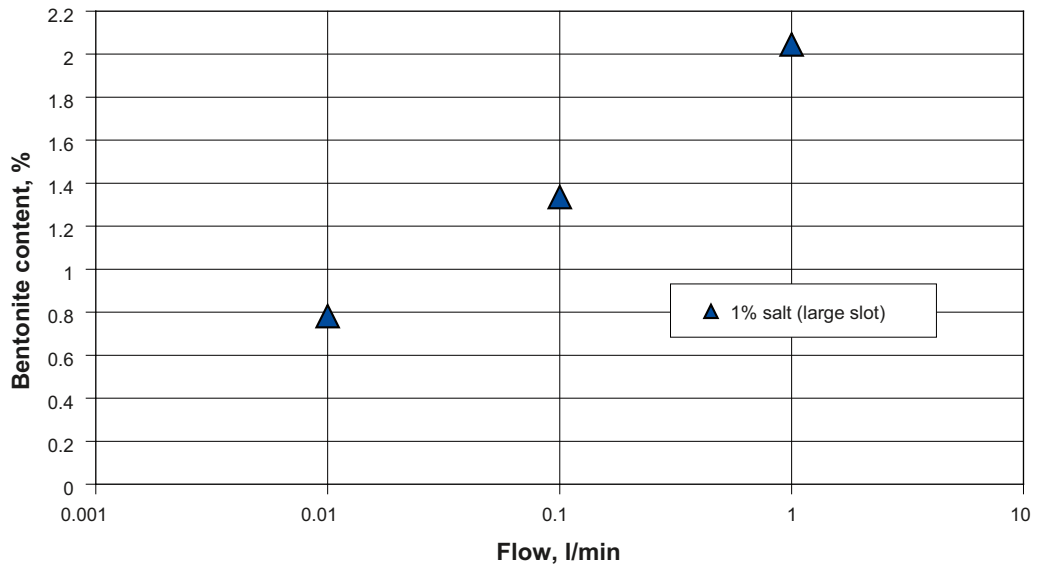


Figure 5-3. The results from the slot tests. The amount of solid mass in the solution is plotted vs. the water flow rates.

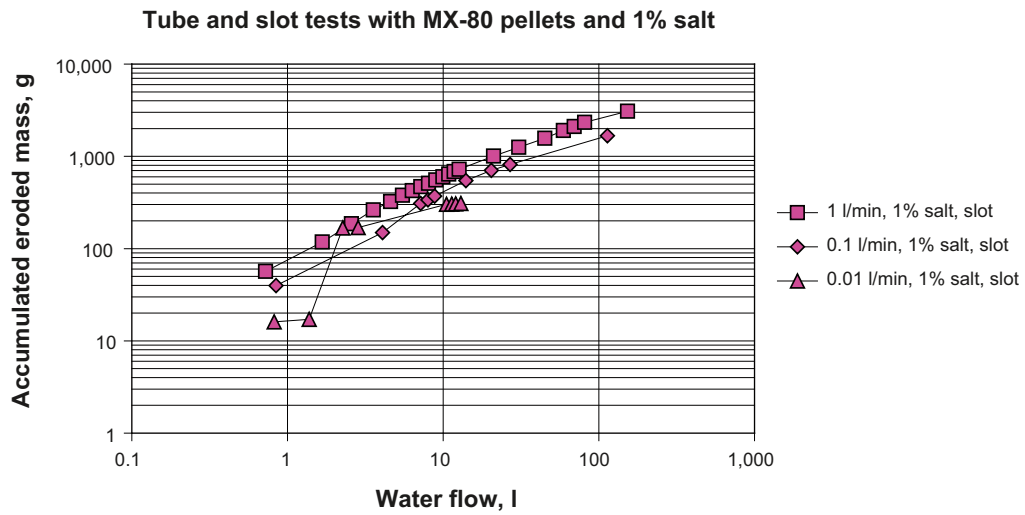


Figure 5-4. The results from the slot tests. The accumulated eroded mass is plotted vs. the accumulated water flow.

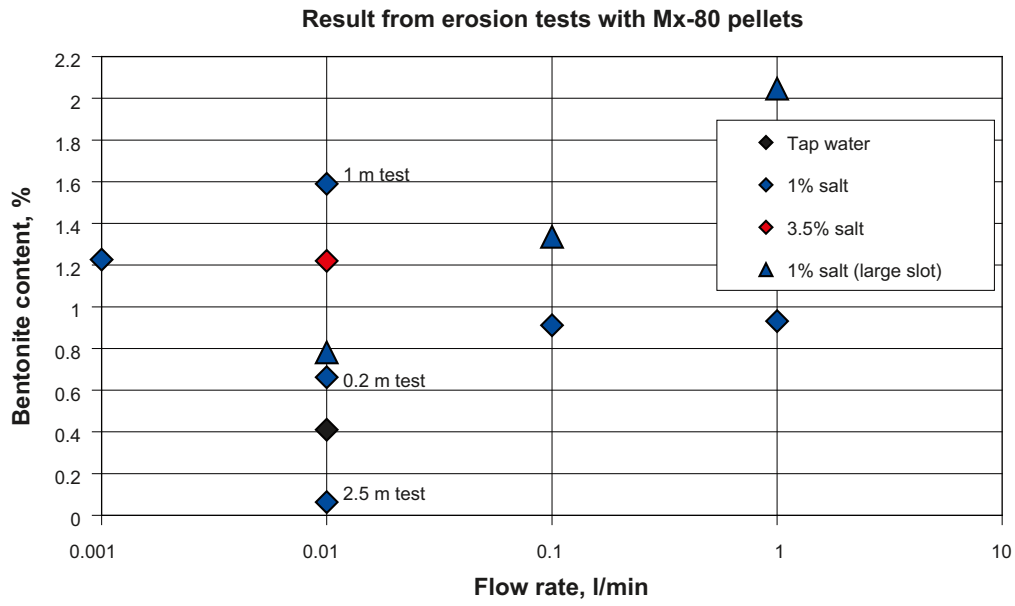


Figure 5-5. Compilation of all results from the pellets tests. The average bentonite content in the water during test time is plotted vs. the different water flow rates. The diagram only shows the average bentonite content in the water and does not consider the fact that the erosion rate seems to decrease by time.

6 Sealing ability of backfill materials

6.1 General

The sealing ability of backfill materials after a piping scenario is an important property. A pre-test have been done, testing the mixture of bentonite/ballast 30/70.

6.2 Test description

The aim with the test was to get information and understanding regarding the healing ability of the in situ compacted backfill material after piping. Two steel tubes ($d=100$ mm $L_1=5$ cm $L_2=20$ cm) with flanges, were bolted together. The backfill material, bentonite/ballast 30/70 (the same type as in the other tests in this project) was compacted into the tubes to a dry density of $1,600$ kg/m³. Since earlier tests had shown that it was very difficult to get piping with this material, a hole was drilled ($d=3$ mm) through in the middle of the sample. A constant flow rate of 0.01 l/min was applied at one side of the sample. The water used was of type 2, which means that it contains 1% salt. Water was percolated through the hole for about 7 hours. The discharging water was collected and the amount of solid mass eroded determined, see Appendix 28. Finally the sample was divided in two parts, $L=5$ cm and $L=20$ cm. Each part was connected to a burette. The 20 cm sample was given access to water from the pre-drilled central hole while the shorter sample was given access to water from filters covering both ends.

After a homogenization time of about 1 month the two samples were tested. A water pressure of 1 m water column was applied in one end of each of the samples and the amount of water coming out on the other side was measured.

6.3 Results

Both samples were leaking very strongly and it was obvious that no healing had taken place. In order to ensure that there had been no problems with the access to water, the 5 cm sample was connected to a backpressure of 1 MPa for about 1 week. A new measurement was then performed with the same result. The tests were then terminated and the water ratios were determined in a number of positions, see Appendix 28.

It seems that the healing ability of this material is very low. The pre-drilled holes were still open when terminating the tests. The water ratios measured after the test showed that the samples were completely saturated. The probable explanation to the low healing ability is the low clay density in the mixture. In combination with salt water the swelling ability is very low at this clay density.

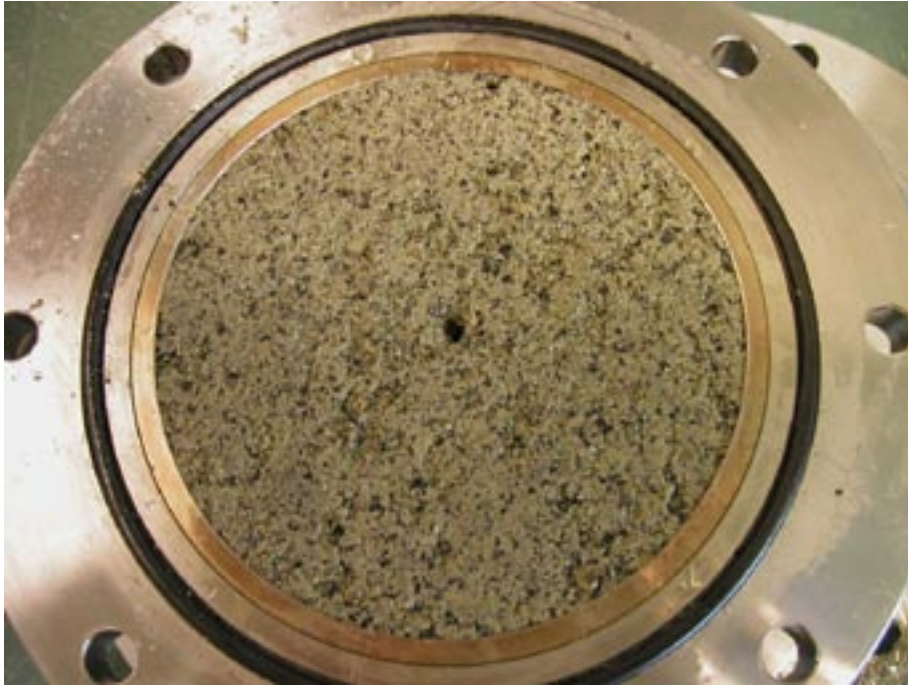


Figure 6-1. Picture showing the 5 cm sample after termination of the test. The pre-drilled hole is still open in spite of the long homogenization time (1 month plus 1 week with 1 MPa backpressure).

7 Summary of results and comments

7.1 General

The performed tests aimed to investigate different materials, which are considered to be used for backfilling tunnels in the KBS3-V concept. The tests were focused on the time just after emplacement and aimed to study the behavior of the backfill materials when they were exposed to different water flow rates and different water salinity. The main problem areas studied were erosion, piping and the stability of a large pellets volume. An additional test type was to study the healing ability of the materials, but only one such test has been done so far.

The following sections summarize the most interesting results from the work.

7.2 Pre-compacted blocks

The tests with pre-compacted blocks have been focused on the erosion properties of the blocks. The influence of the flow rate on the erosion is very strong (Figure 3-3). The erosion rate seems to be almost proportional to the water flow rate. One observation is that if the water flow rate is low, the bentonite will have more time for swelling which seems to prevent the flow and a larger part of the bentonite surface is influenced by the water when water flows freely on the block surface. Another observation is that the erosion rate seems to decrease with time. No long term test has been performed but should be considered.

The influence of the salinity in the water on the erosion rate was also very strong. An increase of the salinity from 0 to 1% increased the erosion rate about 5 times in these tests. The influence from salt water on the surrounding bentonite surface is also very strong (Figure 3-10). When tap water comes in contact with the block surface, the bentonite swells and seals the flow very efficiently. The salty water can however penetrate the bentonite surface faster and also capillary be led to drier parts of the surface. Salt in the groundwater leads to that a large part of the bentonite surface will be affected i.e. get wet and very sticky.

No evidence of that the test length influences the erosion rate has been seen so far. This depends probably on the fact that the solutions possibility to carry particles is limited.

Figure 3-9 shows the erosion rate from the block tests presented as the amount of solid mass per litre solution plotted vs. different flow rates. The bentonite content is determined as an average of the erosion rate during test time.

7.3 MX-80 pellets

Tests have been done with pellets in order to study three different processes:

- **Piping.** After applying constant water flow into a pellet filled volume the pellets swell rather fast and seal off all flow paths. This would result in an increased water pressure. However, this only happened in two of the eight performed tests, Test A:221 with the lowest flow (0.001 l/min) where a water pressure of about 600 kPa was build up and in Test A:322 with low flow (0.01 l/min) and salty water (3.5%) where a water pressure of about 100 kPa was build up. In the other tests the water after a while was mainly flowing in one channel, which was located in the upper part of the Plexiglas tube without any significant water pressure increase. A long term test was also performed, lasting for about 1 week, with the same result. It is obvious that the pellets in most cases cannot seal all existing channels when a constant flow is applied.

- Erosion.** The results from the erosion tests with pellets were very similar to those from the erosion tests with blocks. The influence of water flow rate and salinity was very strong even if the results are not completely distinct. The influence of the test length was not evident in these tests either. Comparing the 0.2 m test with the 1 m test (same salinity and flow), shows that the erosion rate was almost the same for about 20 hours and then the erosion decreased to almost zero for the 0.2 m test. This could be interpreted so that the length of the sample has no influence on the erosion rate in the beginning, but when the flow channel is established (which has been the case in all pellets tests) and all loose particles are transported away, the erosion rate decreases very fast. The erosion rate from the 2.5 m sample was however very low from the beginning and then slowly decreased to almost zero. The 2.5 m test was also a long term test to study the influence of time on erosion rate. The erosion rate seems to decrease with time. All erosion tests with MX-80 pellets, both the tube tests (all lengths) and the slot tests, are compiled in Figure 5-5. In the diagram the average amount of eroded material during test time was plotted vs. the different water flow rates. The diagram only shows the average bentonite content in the water and does not consider the fact that the erosion rate seems to decrease by time. In Figure 4-10 the amount of eroded material was plotted vs. the accumulated flow. The results are not as distinct as for the block tests but the influence of flow rate and salinity is obvious. The variation of the results, mainly the erosion rate in the beginning of the tests, depends probably on the influence of bentonite powder mixed with the pellets. The amount of powder in a test setup can vary a lot. A more detailed study should be done.
- Stability of a large volume.** Three tests of this type have been performed. All three tests were performed with 1% salt water and the water flow rate was varied (0.01, 0.1 and 1 l/min). The aim of these tests was to check the stability of a large pellet volume when exposed to water inflow. A worst case is that water inflow with a certain water type (salinity) and flow rate, leads to collapse of the whole pellet slope, which then could flow away. There was no such tendency in any of the tests. An obvious difference between the three performed tests was that different parts of the pellets volume were affected (Figure 7-1). For the two higher flow rates, 0.1 and 1 l/min only the lower part of the pellets volume was wetted but for the lowest inflow rate the part above the inflow point and the slope surface were affected. In Figure 5-4 the total amount of eroded material was plotted vs. the accumulated flow. The results show very clearly that the total volume of flowing water controls the amount of eroded clay, not the flow rate. The diagram in Figure 5-5 shows the amount of solid mass per liter solution for the different flow rates and water types.



Figure 7-1. Pictures from the slot tests. The picture to the left shows the test where a water flow rate of 0.01 l/min was applied and the picture to the right the test with a water flow rate of 1 l/min.

7.4 Bentonite/Ballast 30/70

Piping and erosion. This backfill mixture was planned to be tested in the same way as the pellets according to piping and erosion, but after a few preliminary tests it was obvious that the behavior was quite different from the expected. It turned out to be very difficult to achieve piping. Due to the applied constant flow rate and the fact that no piping occurred, high water pressures were built up. The test equipment allowed water pressures up to 1,200–1,400 kPa but this was not enough to get piping. Some of the equipment was exchanged (Plexiglas tubes were exchanged to steel tubes) but the problem was still present. It was only possible to measure erosion in one test, Test B:221-2 (0.001 l/min and 1% salt), out of eight performed. The behavior may be explained by the impenetrability of the material at high flow rates. This meant that a water pressure could be built up, acting on the full cross-section, consolidating the material.

Healing ability. Only one pre-test was done. The result from this test showed that the healing ability of this material is very low. The probable explanation is the low clay density in the mixture. In combination with salt water the swelling ability is very low at these clay densities.

Test D:122 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:122	Tap water	0.01 l/min	1 m

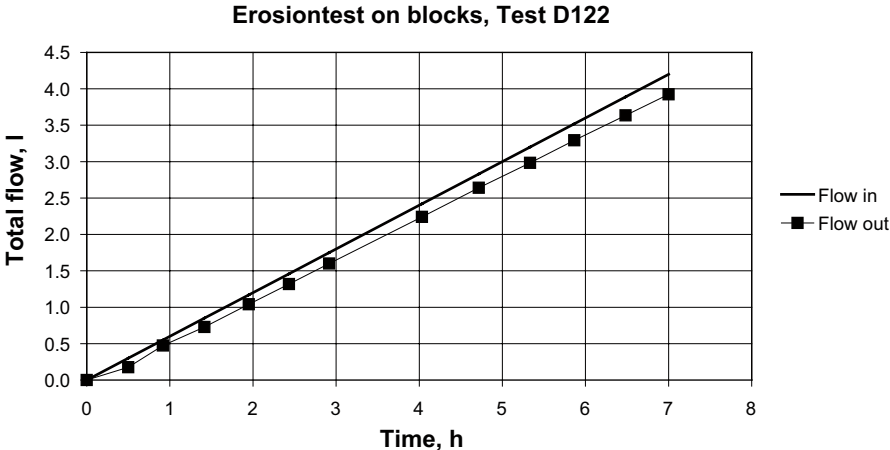


Figure A1-1. The measured inflow and outflow plotted vs. time.

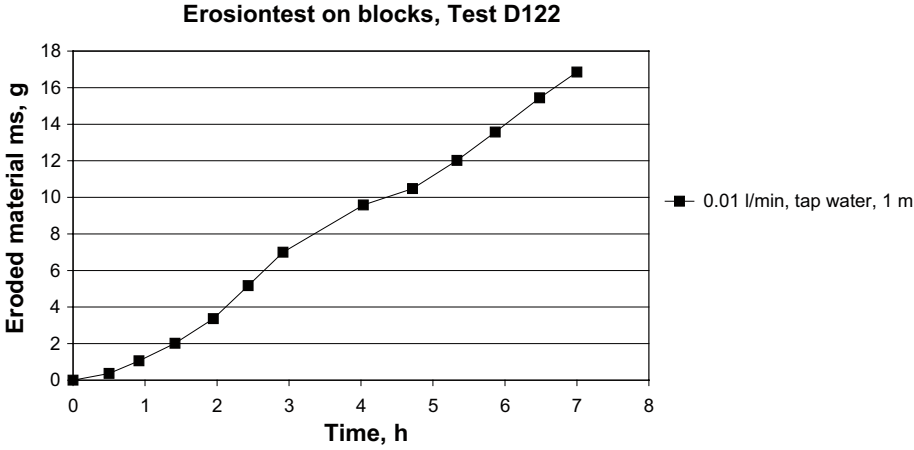


Figure A1-2. The total amount of material eroded during the test plotted vs. time.



Figure A1-3. Pictures from the test. The picture to the left shows the situation after one hour. The right picture shows the situation just before the interruption. There is a small sharp ditch in the middle. The surrounding block surfaces are not affected.

Test D:124 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:124	Tap water	1 l/min	1 m

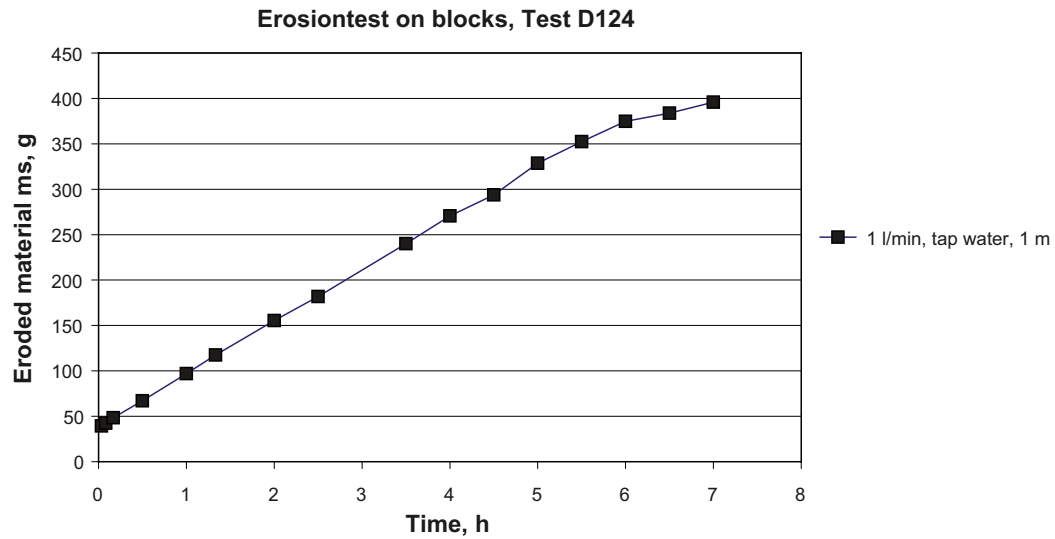


Figure A2-1. The total amount of material eroded during the test plotted vs. time.

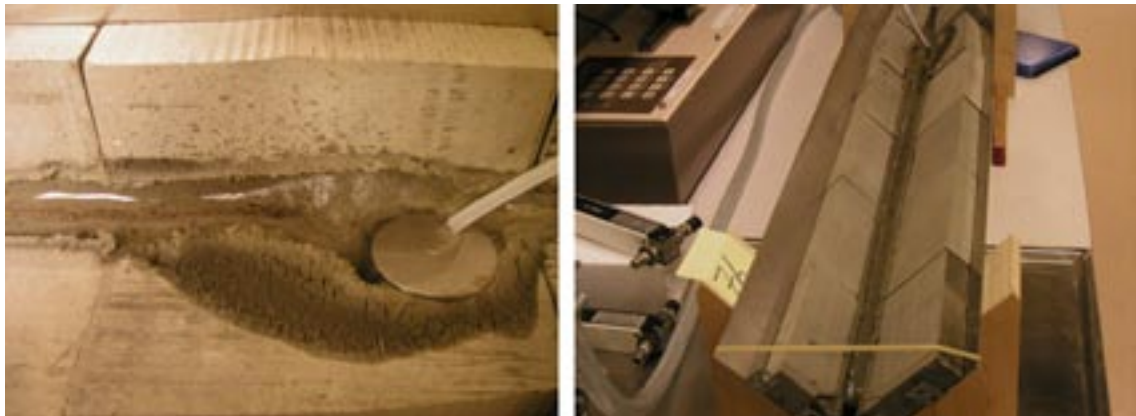


Figure A2-2. Pictures from the test. The right picture shows the situation just before the interruption. There is a small sharp ditch in the middle. The surrounding block surfaces are not affected flow except for the area around the inflow point, shown to the left. A filter plate was placed here in order to distribute the flow more evenly.

Test D:212 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:212	1% salt	0.01 l/min	0.2 m

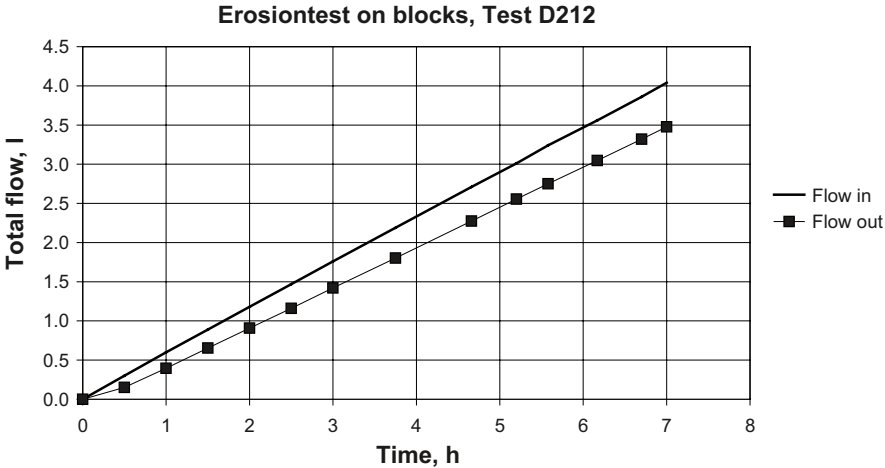


Figure A3-1. The measured inflow and outflow plotted vs. time.

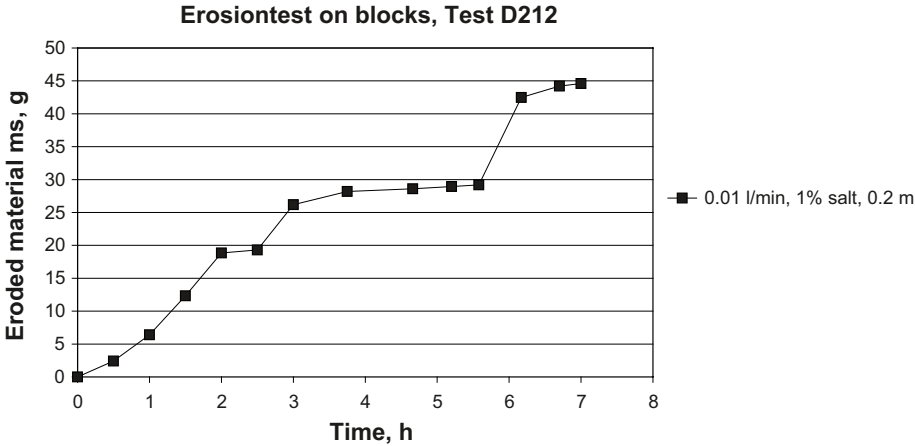


Figure A3-2. The total amount of material eroded during the test plotted vs. time.

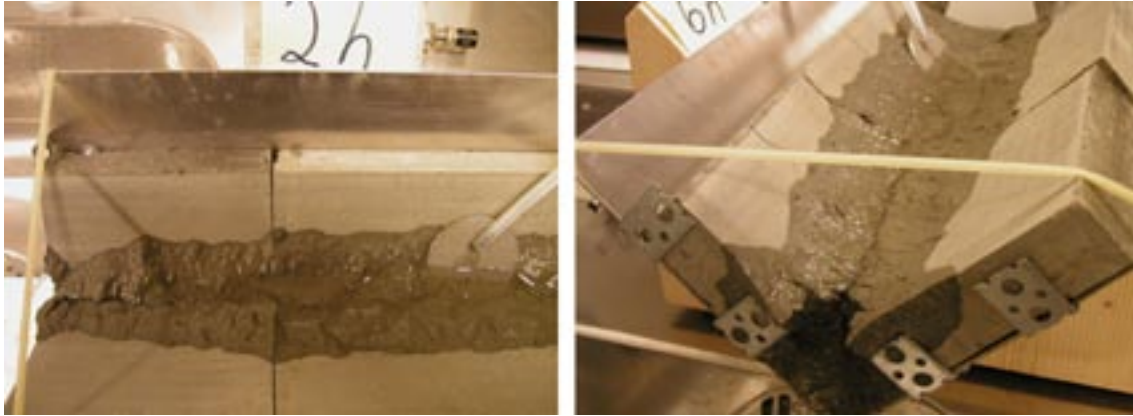


Figure A3-3. Pictures from the test. The left picture shows the inflow point after 2 hours. The right picture shows the situation just before the interruption. The surrounding block surfaces are strongly affected.

Test D:221 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:221	1% salt	0.001 l/min	1 m

No material eroded during the test.



Figure A4-1. Pictures from the test. The left picture shows a section during excavation. The right picture shows the situation just before the interruption. Due to the low flow rate, no erosion took place.

Test D:222 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:222	1% salt	0.01 l/min	1 m

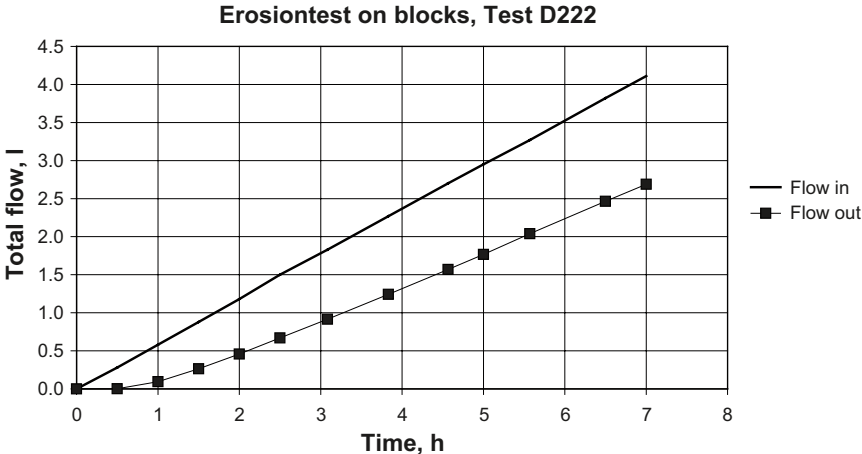


Figure A5-1. The measured inflow and outflow plotted vs. time.

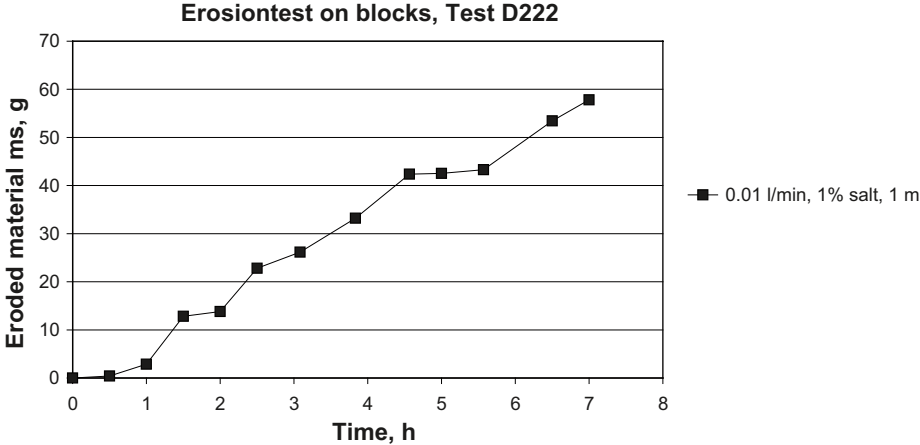


Figure A5-2. The total amount of material eroded during the test plotted vs. time.

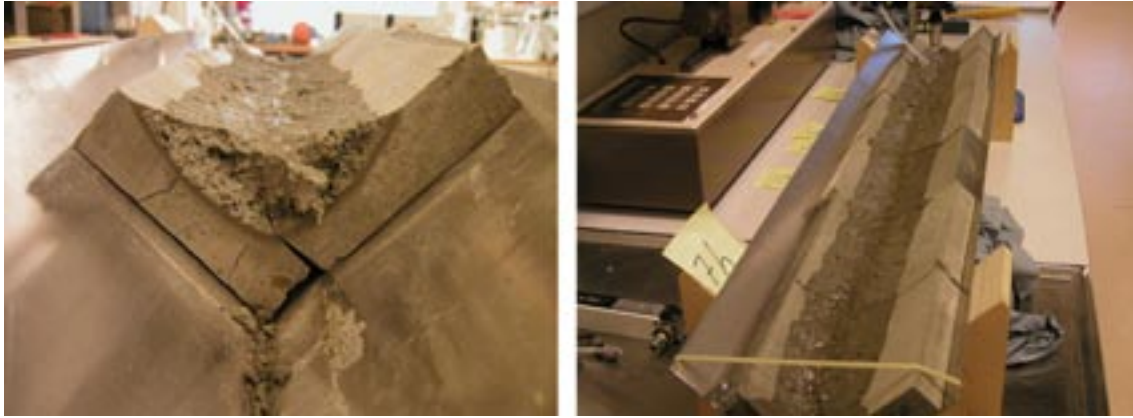


Figure A5-3. Pictures from the test. The left picture shows a section during the excavation. The right picture shows the situation just before the interruption. The surrounding block surfaces are strongly influenced of the water.

Test D:223 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:223	1% salt	0.1 l/min	1 m

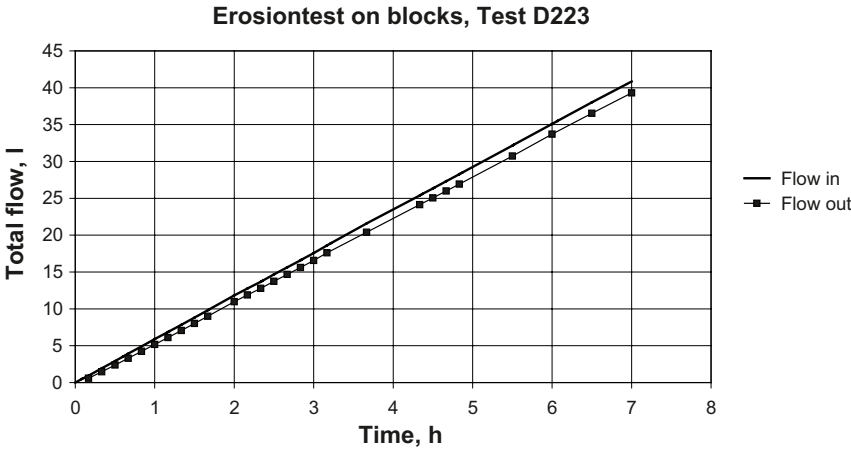


Figure A6-1. The measured inflow and outflow plotted vs. time.

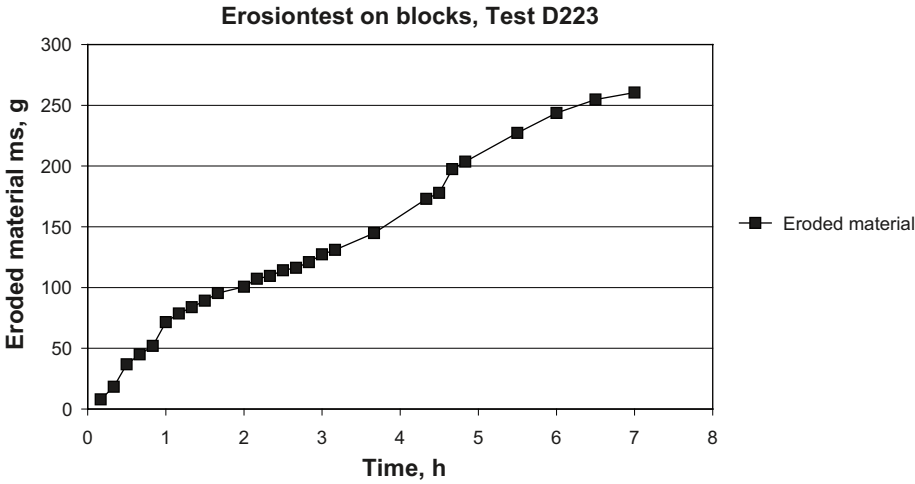


Figure A6-2. The total amount of material eroded during the test plotted vs. time.



Figure A6-3. Pictures from the test. The left picture shows a section during the excavation. The right picture shows the situation just before the interruption. The surrounding block surfaces are strongly influenced of the water.

Test D:224 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:224	1% salt	1 l/min	1 m

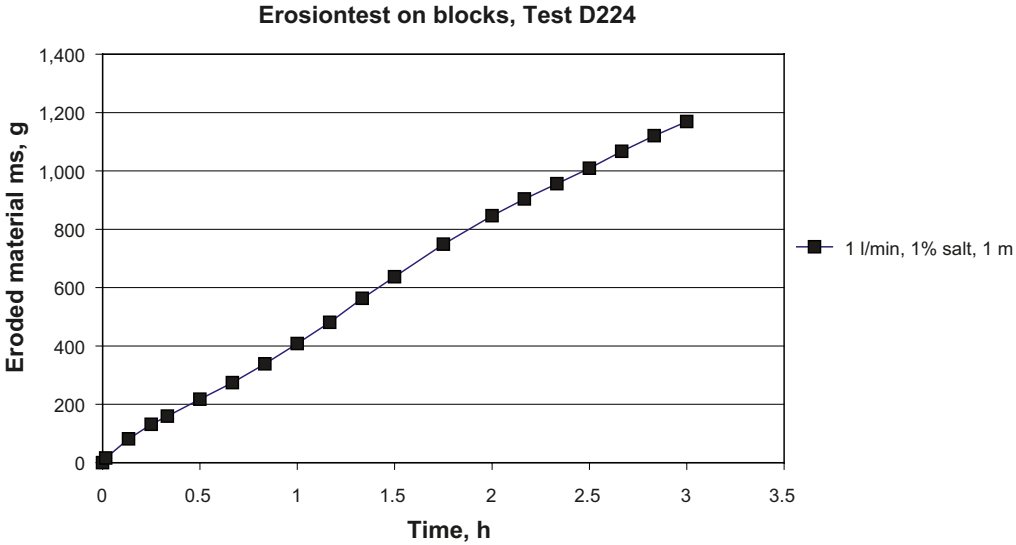


Figure A7-1. The total amount of material eroded during the test plotted vs. time.



Figure A7-2. Pictures from the test. The left picture shows a section during the excavation. The right picture shows the situation just before the interruption. There was a sharp ditch in the middle.

Test D:322 Erosion of pre-compacted blocks

Sample	Water type	Flow	Test length
D:322	3.5% salt	0.01 l/min	1 m

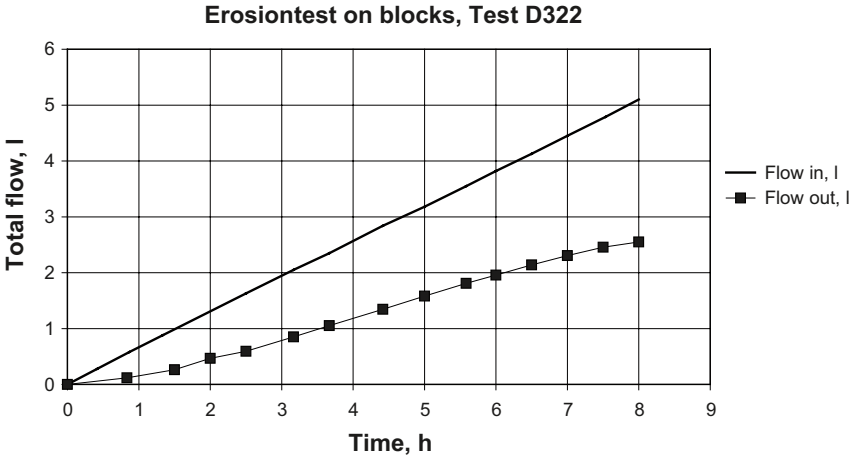


Figure A8-1. The measured inflow and outflow plotted vs. time.

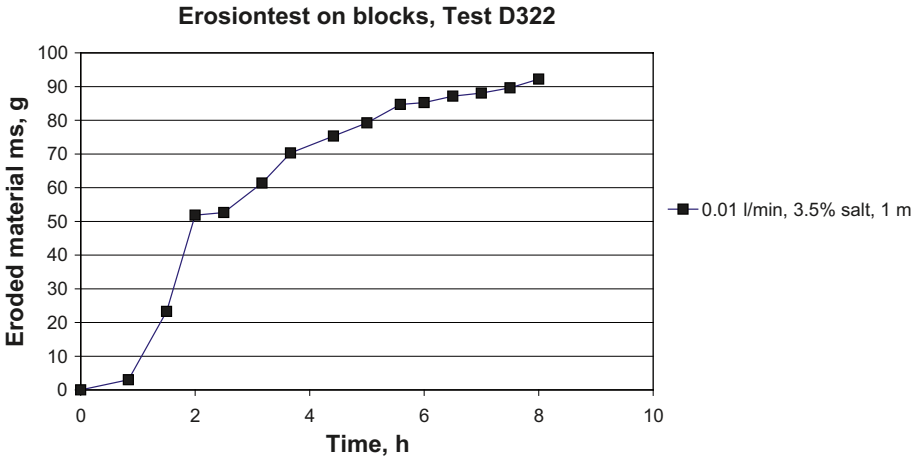


Figure A8-2. The total amount of material eroded during the test plotted vs. time.

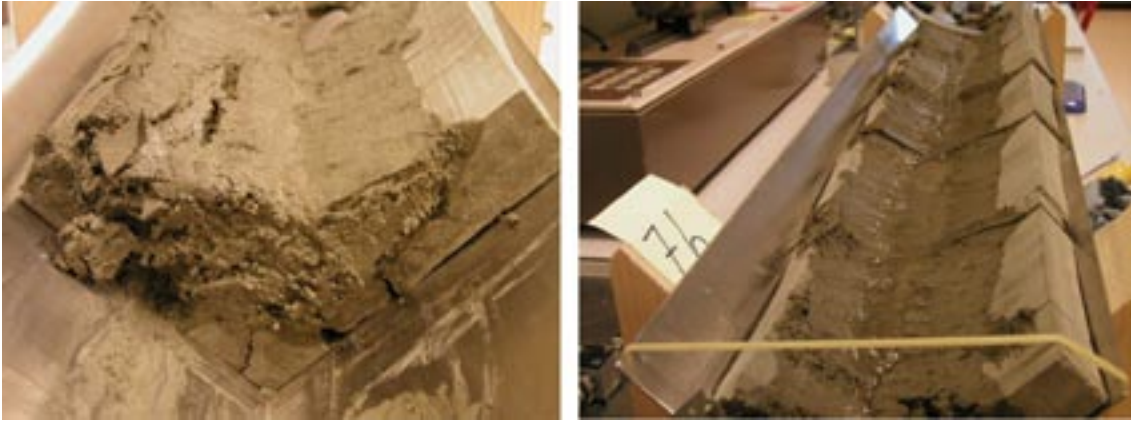


Figure A8-3. Pictures from the test. The left picture shows a section during the excavation. The right picture shows the situation just before the interruption. The surrounding block surfaces are strongly influenced of the water.

Test A:122 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:122	Pellets MX-80	Tap water	0.01 l/min	1 m

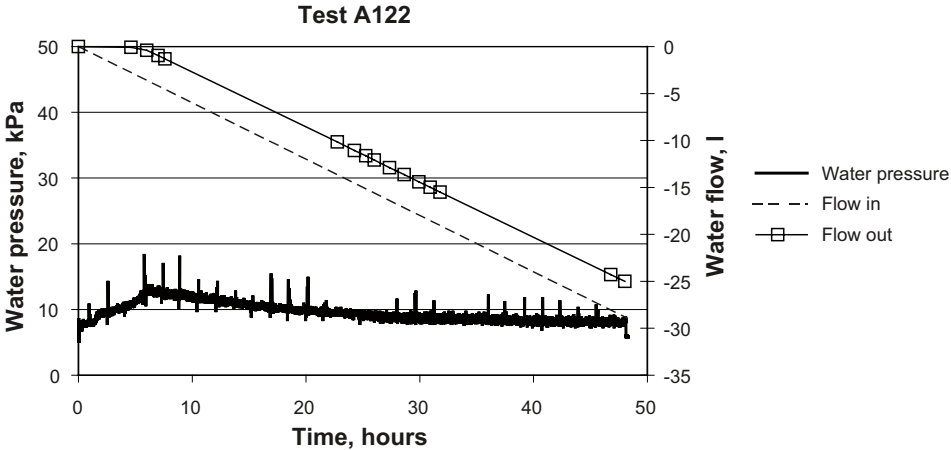


Figure A9-1. The measured inflow, the outflow and the water pressure plotted vs. time.

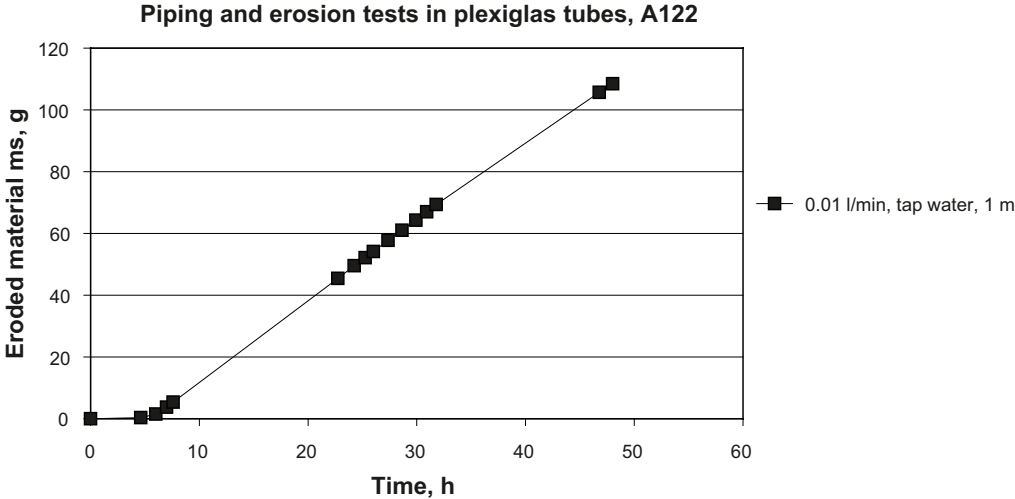


Figure A9-2. The total amount of material eroded during the test plotted vs. time.

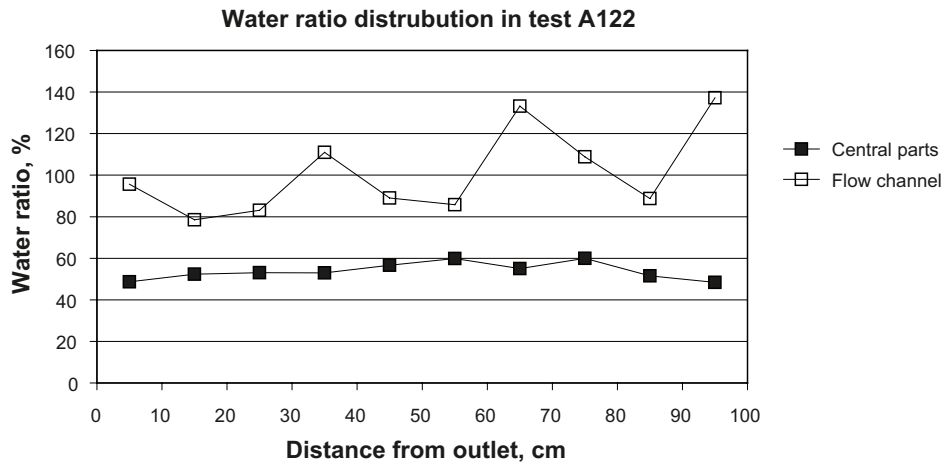


Figure A9-3. The water ratio distribution. The samples are taken just after the termination of the test.



Figure A9-4. Pictures from the test. The left picture shows the situation after 3 hours during the water filling. The right picture shows the channel where all water seems to flow. The channel is located on the top of the sample.

Test A:212 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:212	Pellets MX-80	1% salt	0.01 l/min	0.2 m

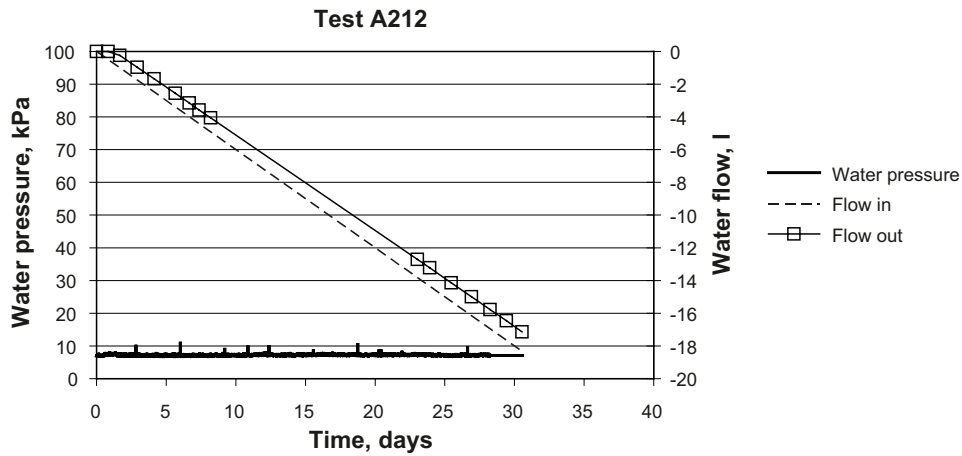


Figure A10-1. The measured inflow, the outflow and the water pressure plotted vs. time.

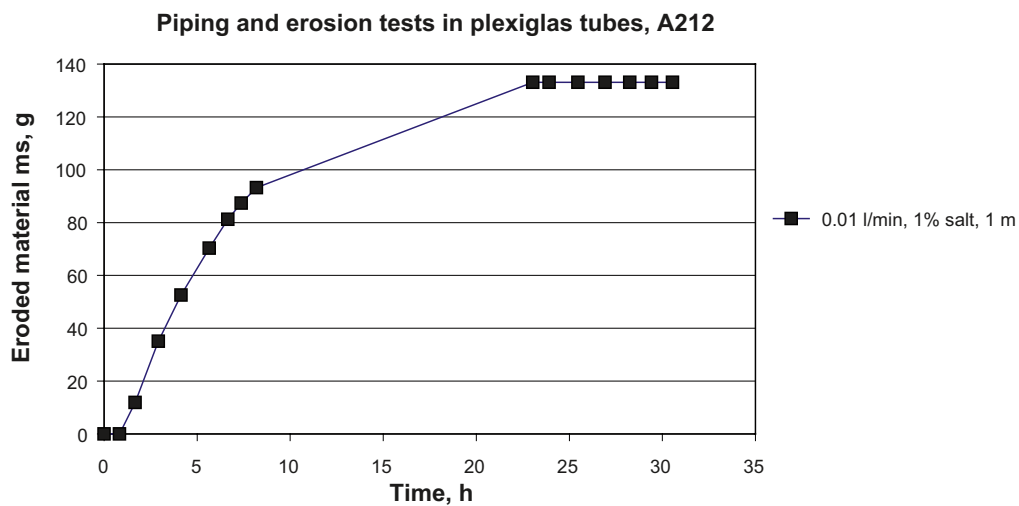


Figure A10-2. The total amount of material eroded during the test plotted vs. time.

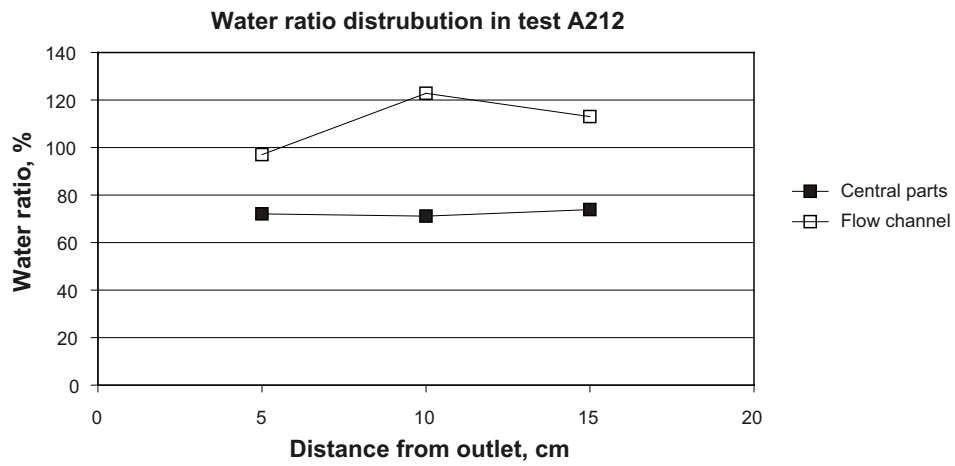


Figure A10-3. The water ratio distribution. The samples are taken just after termination of the test.



Figure A10-4. Pictures from the test. The left picture shows the situation after 2 hours during the water filling. The right picture shows the situation just before termination.

Test A:221 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:221	Pellets MX-80	1% salt	0.001 l/min	1 m

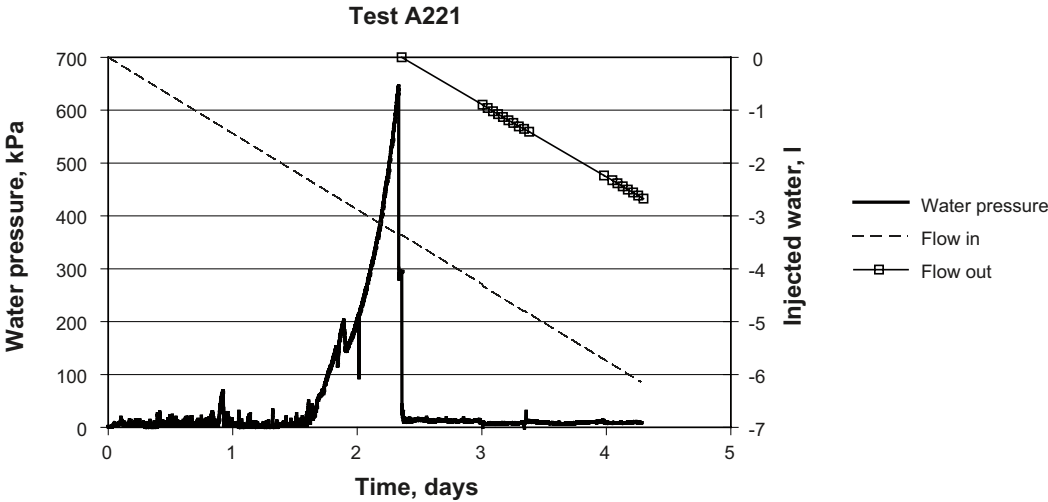


Figure A11-1. The measured inflow, the outflow and the water pressure plotted vs. time.

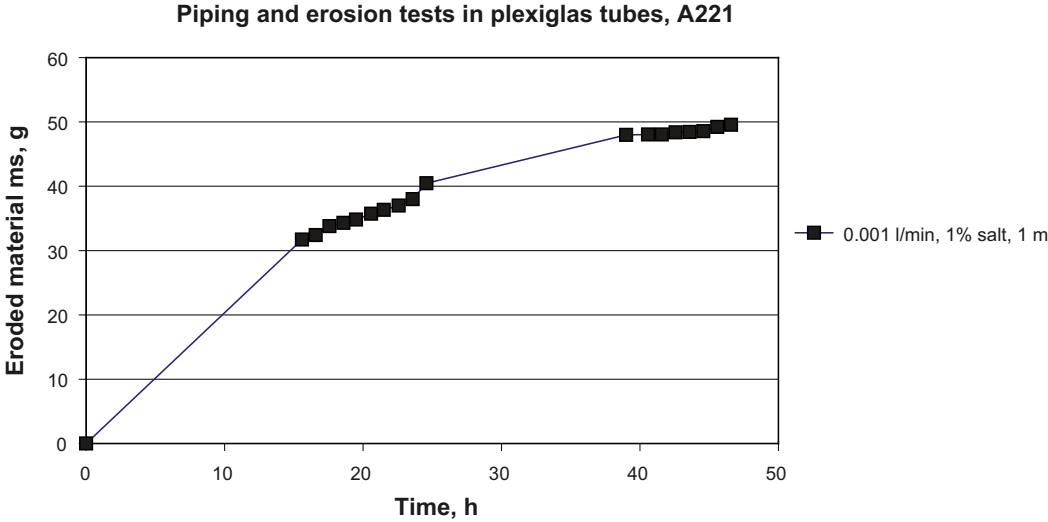


Figure A11-2. The total amount of material eroded during the test plotted vs. time.

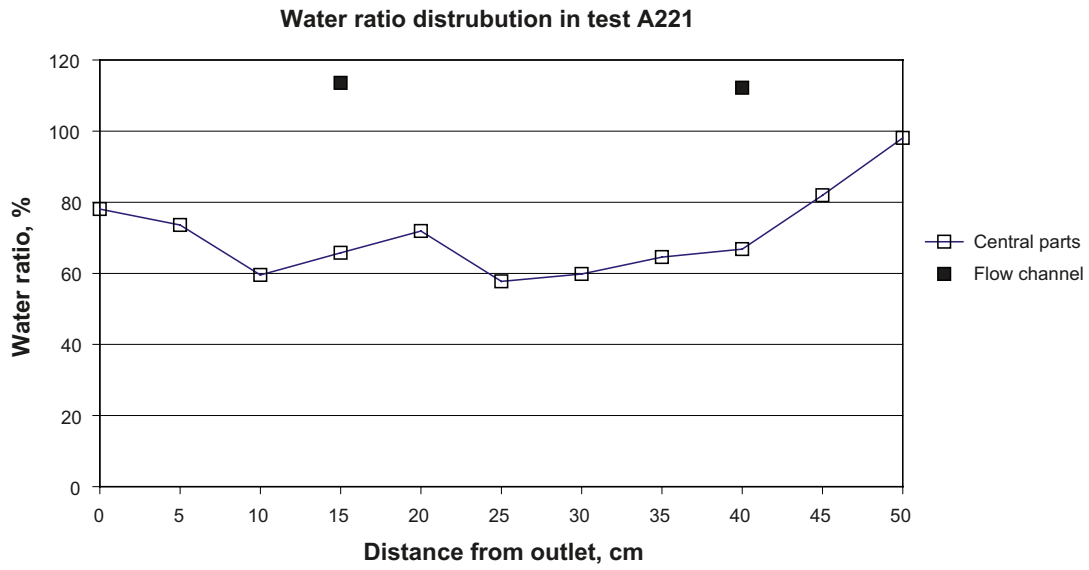


Figure A11-3. The water ratio distribution. The samples are taken just after termination of the test.

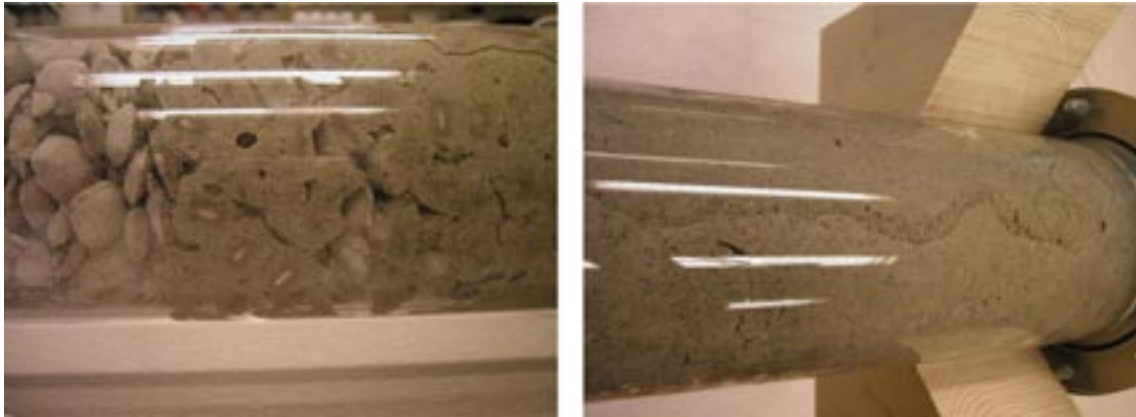


Figure A11-4. Pictures from the test. The left picture shows the situation after 3 hours during the water filling. The right picture shows the channel where all water seems to flow. The channel is situated on the top of the sample.

Test A:222 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:222	Pellets MX-80	1% salt	0.01 l/min	1 m

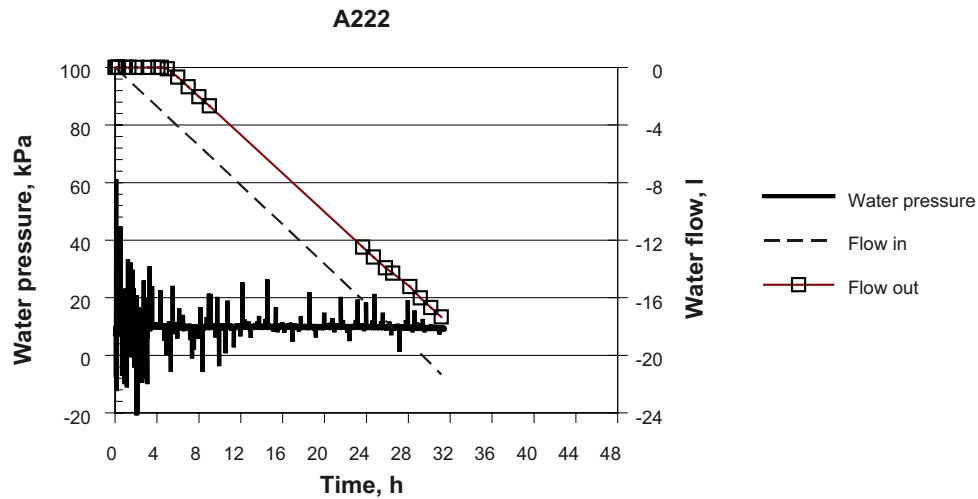


Figure A12-1. The measured inflow, the outflow and the water pressure plotted vs. time.

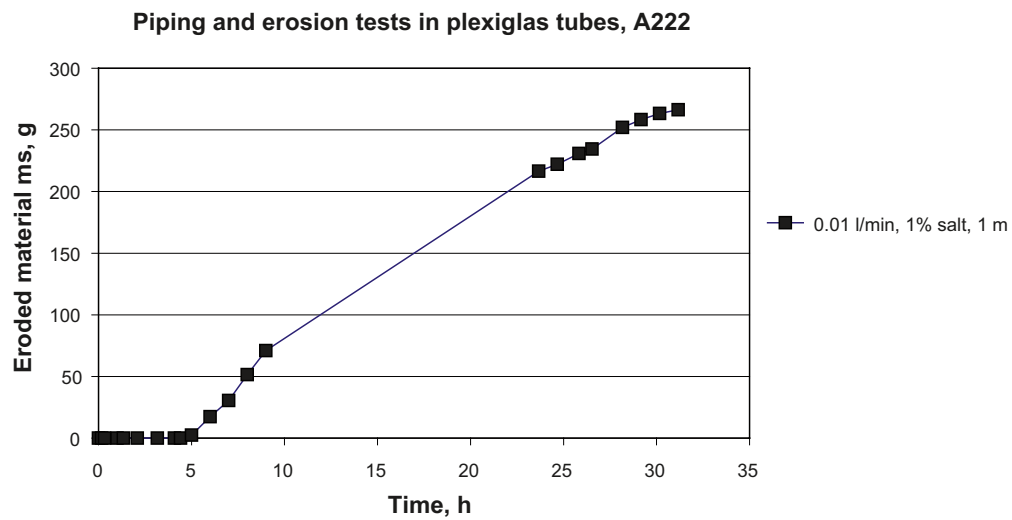


Figure A12-2. The total amount of material eroded during the test plotted vs. time.

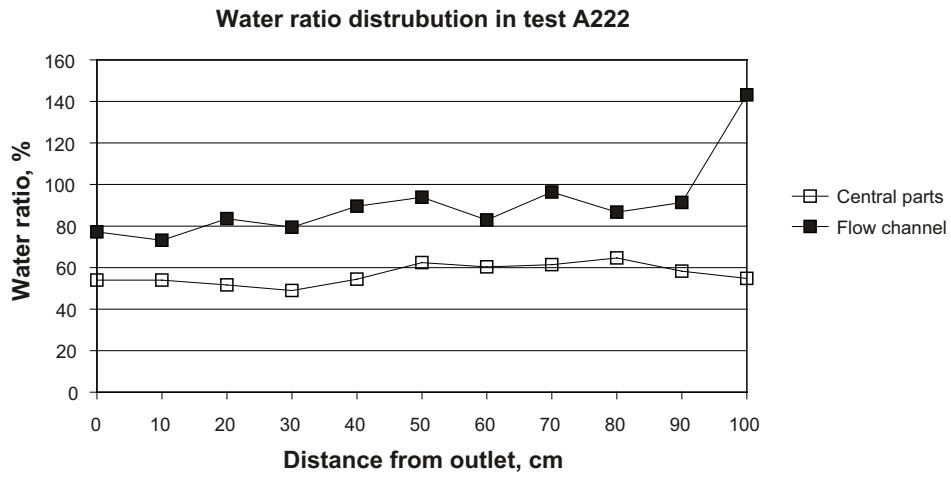


Figure A12-3. The water ratio distribution. The samples are taken just after termination of the test.

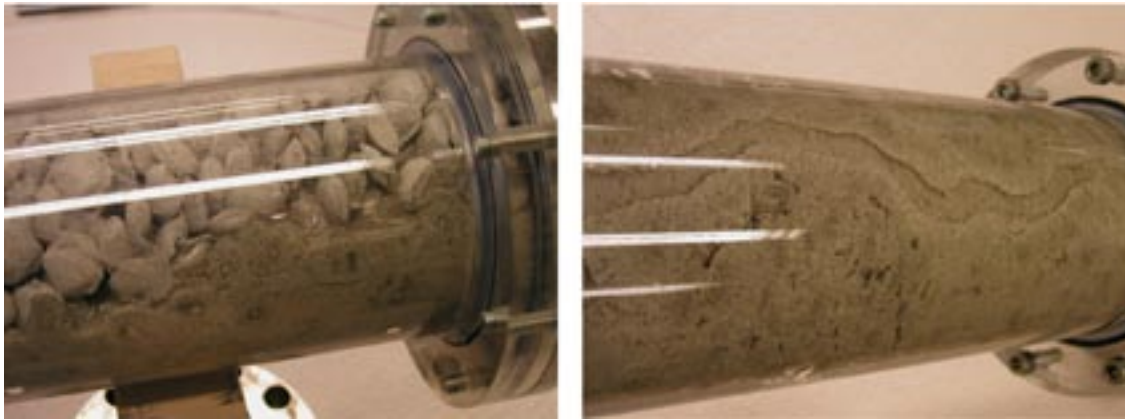


Figure A12-4. Pictures from the test. The left picture shows the situation after 3 hours during the water filling. The right picture shows the channel where all water seems to flow. The channel is situated on the top of the sample.

Test A:223 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:223	Pellets MX-80	1% salt	0.1 l/min	1 m

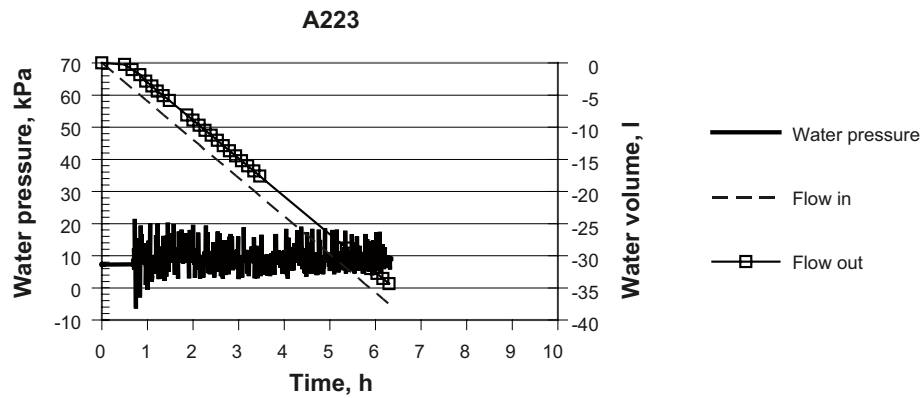


Figure A13-1. The measured inflow, the outflow and the water pressure plotted vs. time.

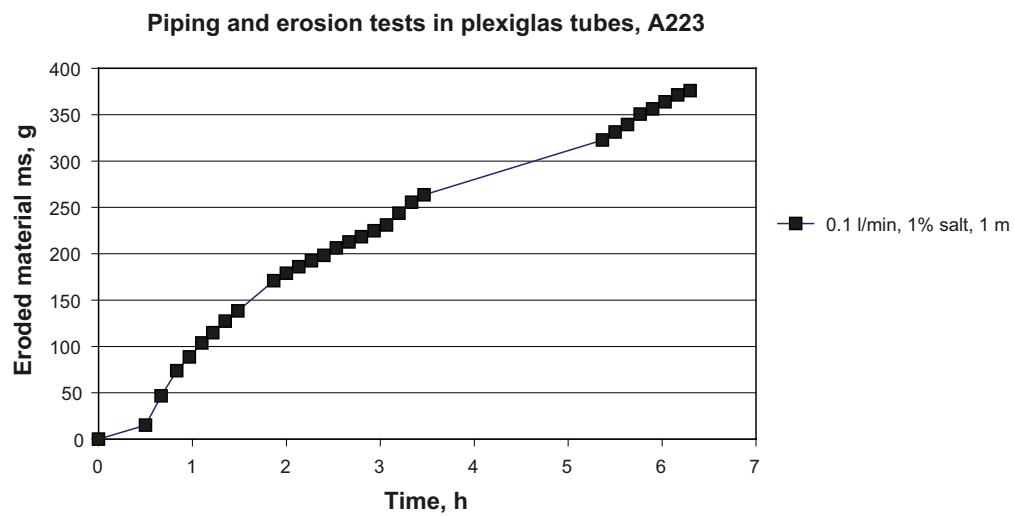


Figure A13-2. The total amount of material eroded during the test plotted vs. time.

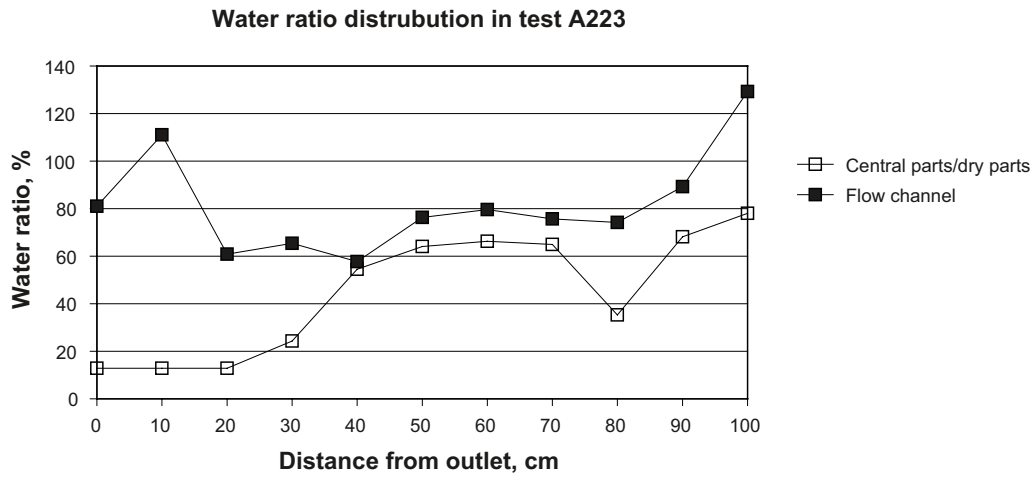


Figure A13-3. The water ratio distribution. The samples are taken just after termination of the test.

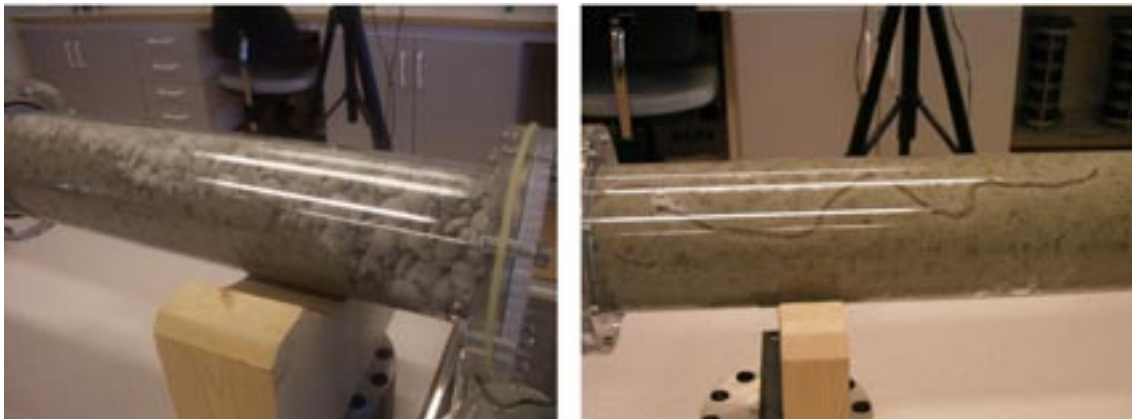


Figure A13-4. Pictures from the test. The left picture shows the situation after 3 hours during the water filling. The right picture shows the channel where all water seems to flow. The channel is situated on the top of the sample.

Test A:224 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:224	Pellets MX-80	1% salt	1 l/min	1 m

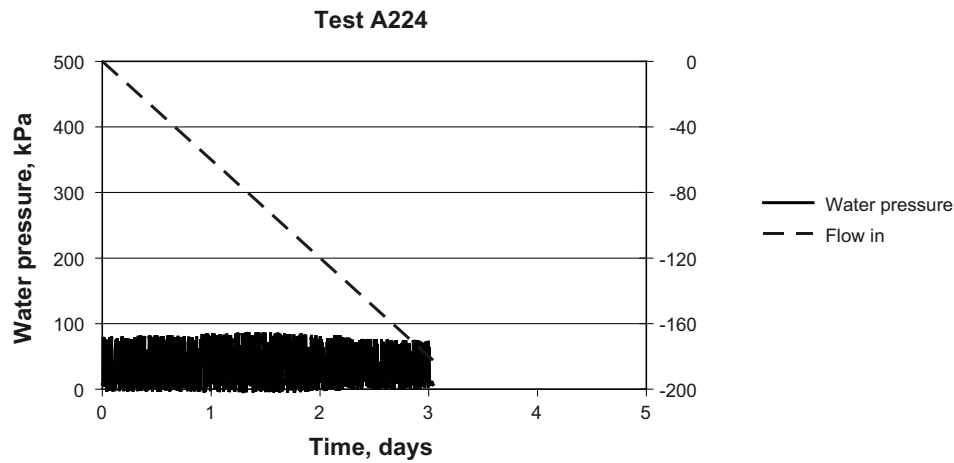


Figure A14-1. The measured inflow and the water pressure plotted vs. time. The erosion was measured by taking out samples every ten minutes, which means that the total outflow was not measured.

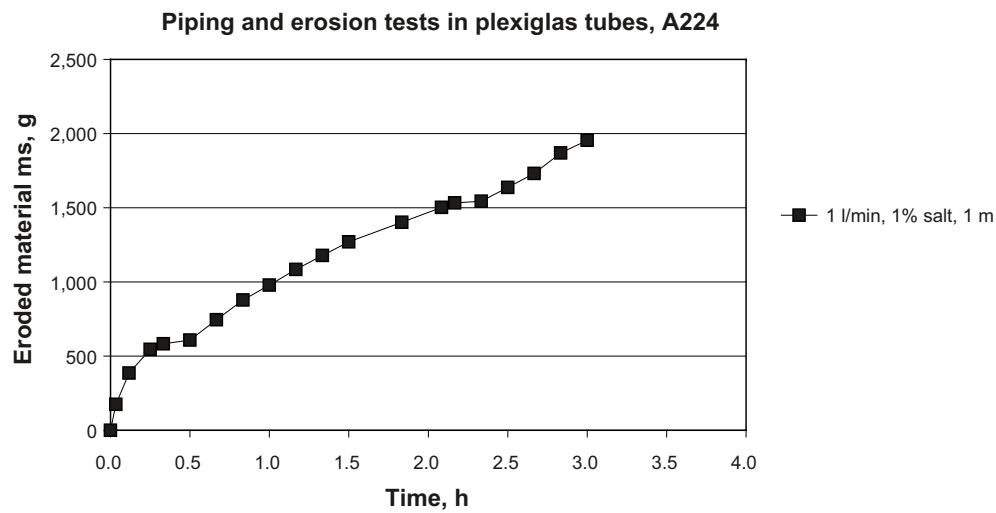


Figure A14-2. The total amount of material eroded during the test.

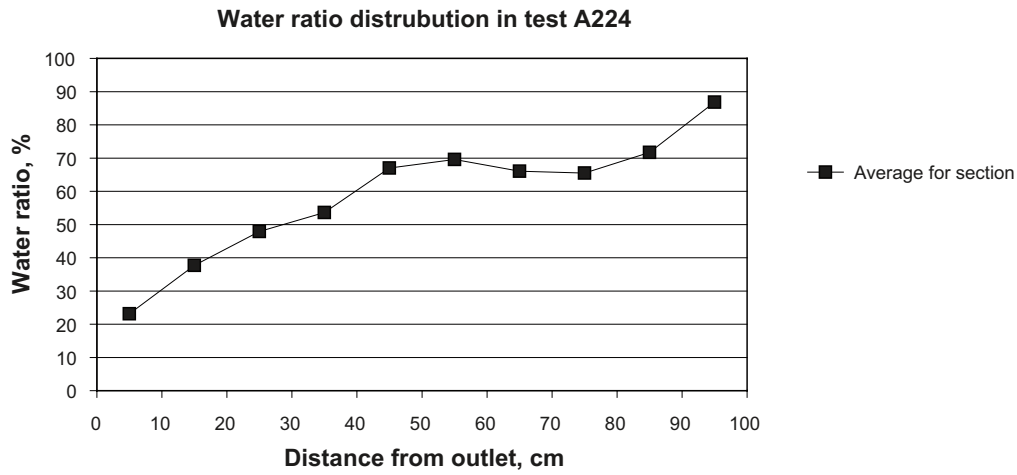


Figure A14-3. The water ratio distribution. The samples are taken just after termination of the test.



Figure A14-4. Pictures from the test. The left picture shows the situation after 3 hours during the water filling. The right picture shows the channel where all water seems to flow. The channel is situated on the top of the sample.

Test A:232 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:232	Pellets MX-80	1% salt	0.01 l/min	3 m

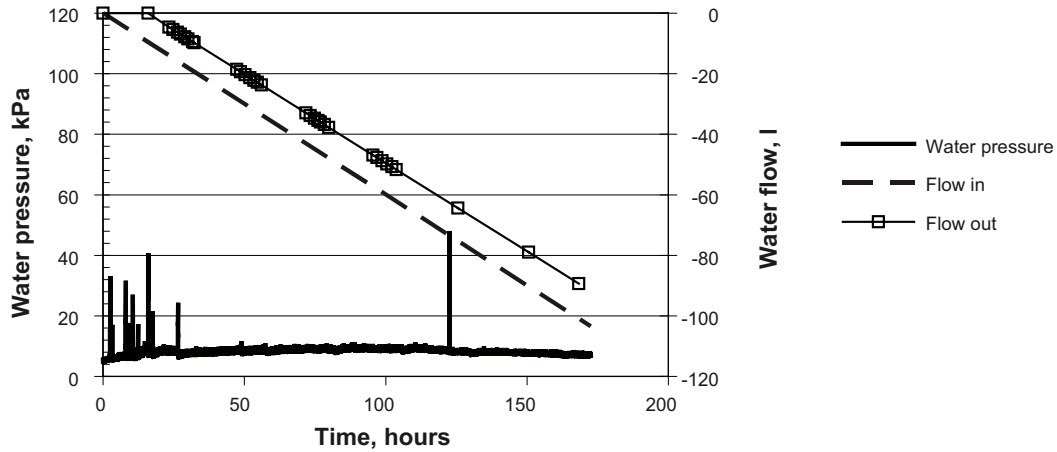


Figure A15-1. The measured inflow, the outflow and the water pressure plotted vs. time.

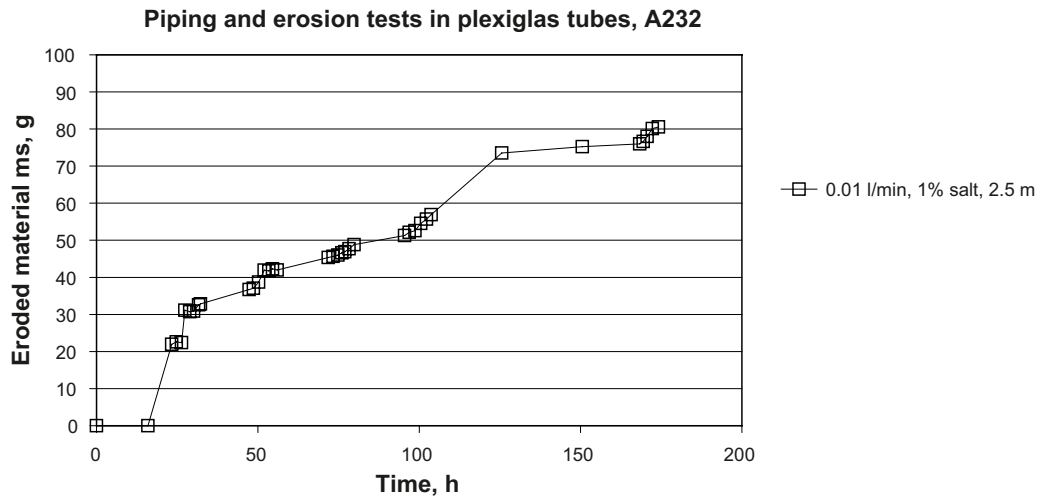


Figure A15-2. The total amount of material eroded during the test plotted vs. time.

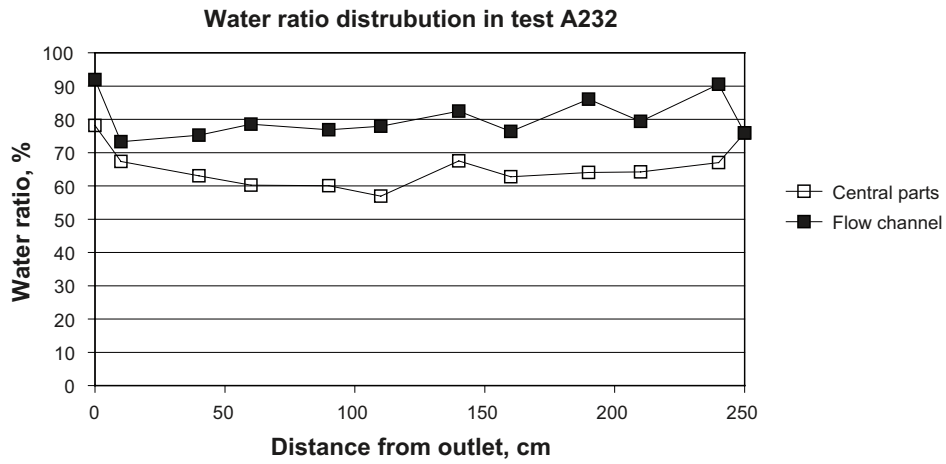


Figure A15-3. The water ratio distribution. The samples are taken just after termination of the test.



Figure A15-4. Pictures from the test. The left picture shows the situation after 7 hours during the water filling. The right picture shows the channel where all water seems to flow. The channel is situated on the top of the sample.

Test A:322 Piping/erosion of MX-80 pellets

Sample	Material	Water type	Flow	Test length
A:322	Pellets MX-80	3.5% salt	0.01 l/min	1 m

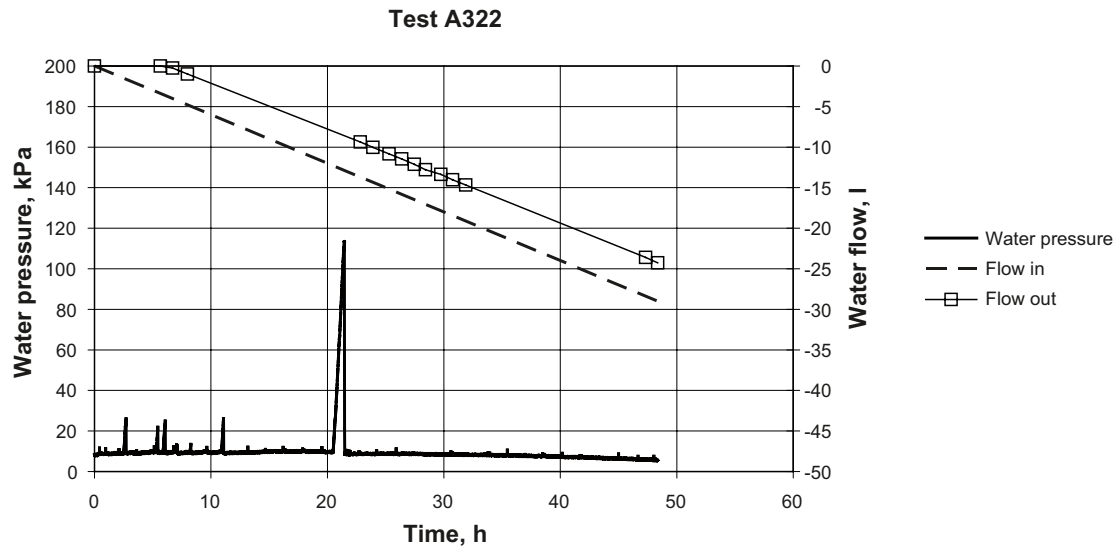


Figure A16-1. The measured inflow, the outflow and the water pressure plotted vs. time.

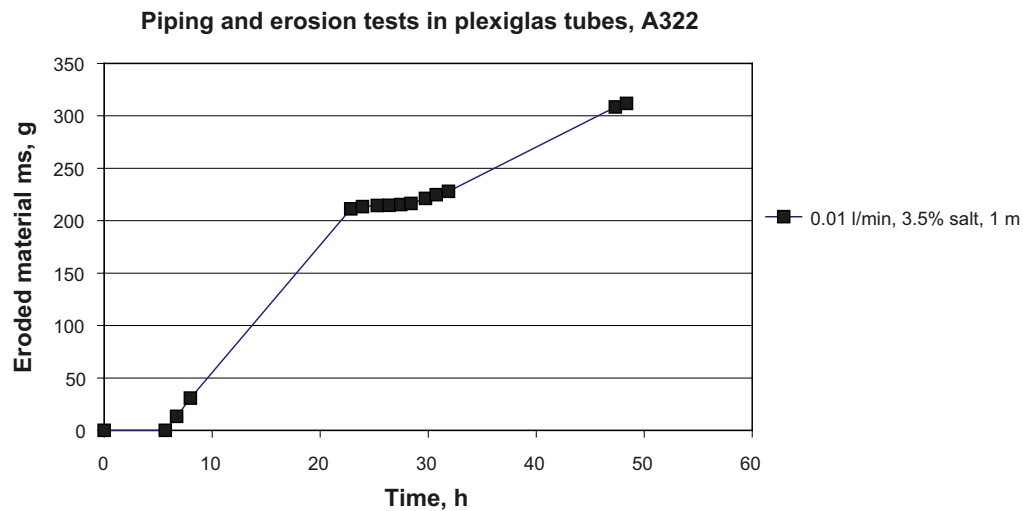


Figure A16-2. The total amount of material eroded during the test plotted vs. time.

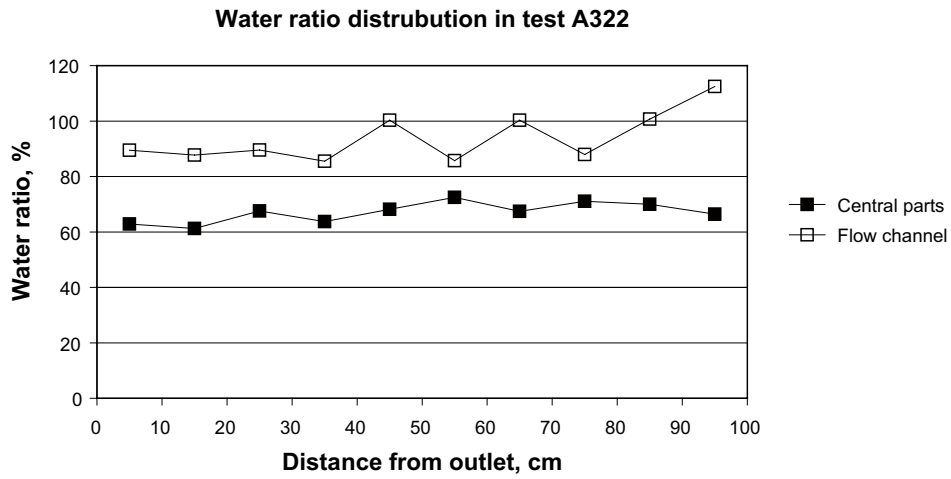


Figure A16-3. The water ratio distribution. The samples are taken just after termination of the test.



Figure A16-4. Pictures from the test. The left picture shows the situation after 2.5 hours during the water filling. The right picture shows the channel were all water seems to flow. The channel is situated on the top of the sample.

Test B:212 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:212	Bentonite/Backfill 30/70	1% salt	0.0 l/min	0.2 m

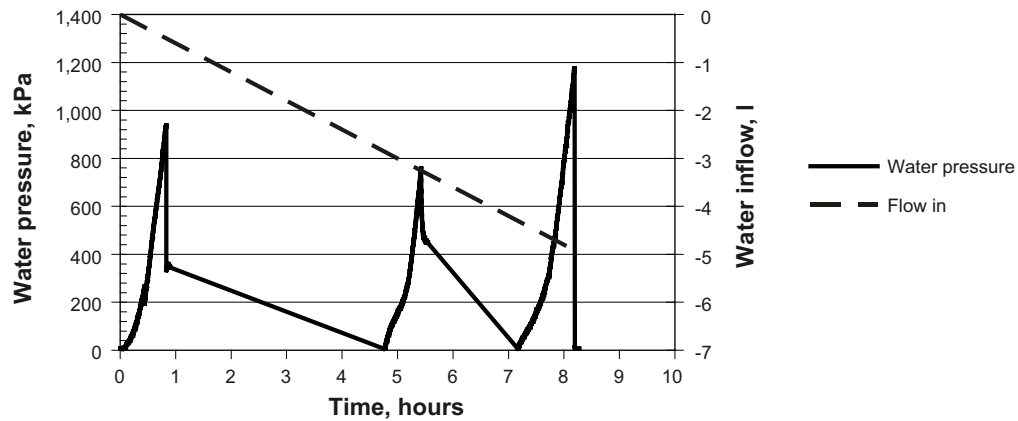


Figure A17-1. The measured inflow, the outflow and the water pressure plotted vs. time. The test was interrupted when the Plexiglas tube cracked.



Figure A17-2. Picture from the test showing the situation after 0.5 hour. There is a very clear front of water saturation.

Test B:221 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:221	Bentonite/Backfill 30/70	1% salt	0.001 l/min	0.5 m

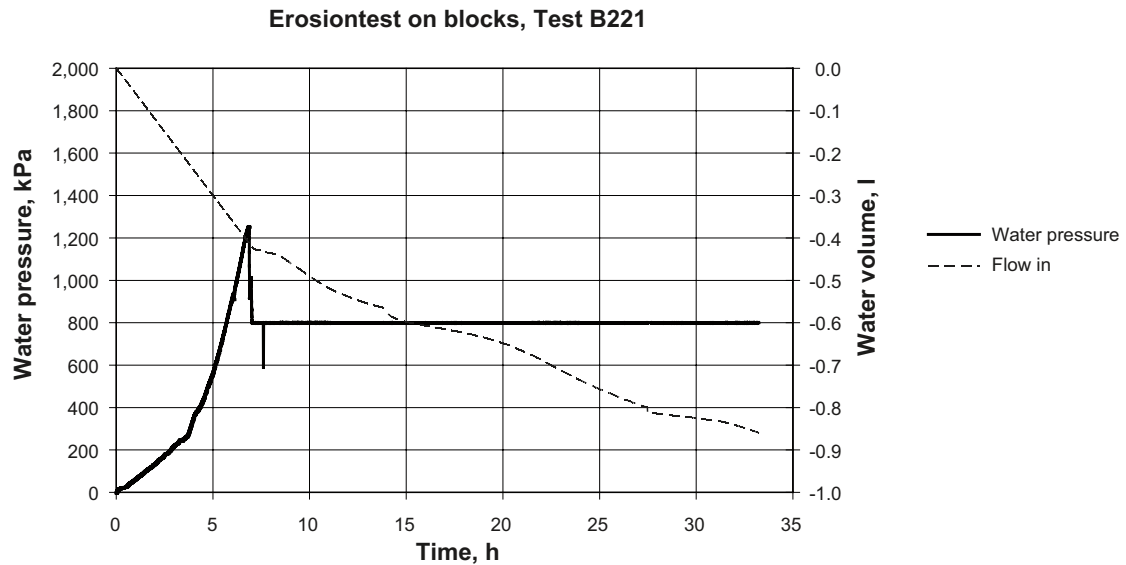


Figure A18-1. Diagram showing the measured inflow and the water pressure plotted vs. time. The water pressure was set to 800 kPa after about 7 hours. After about 33 hours the equipment started to leak and the test was interrupted. No erosion could be measured.

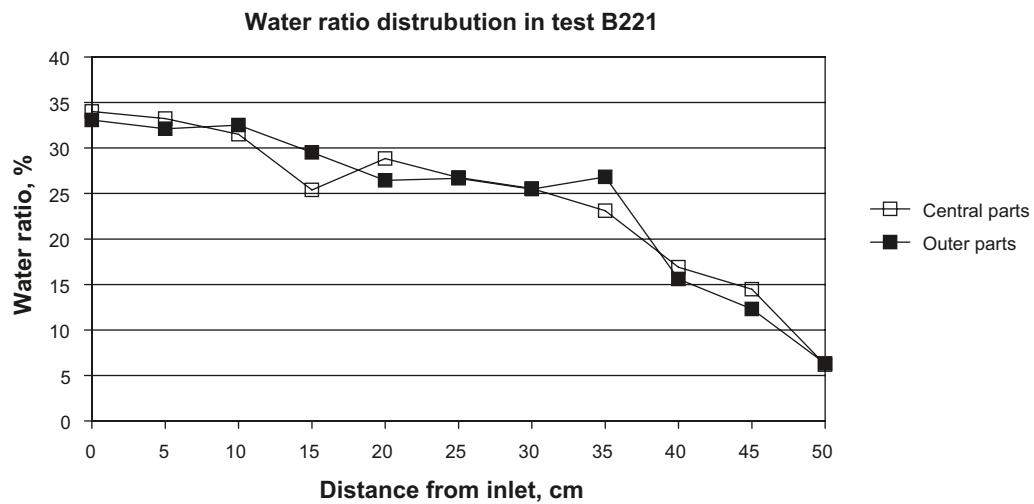


Figure A18-2. The water ratio distribution. The samples are taken just after termination of the test.

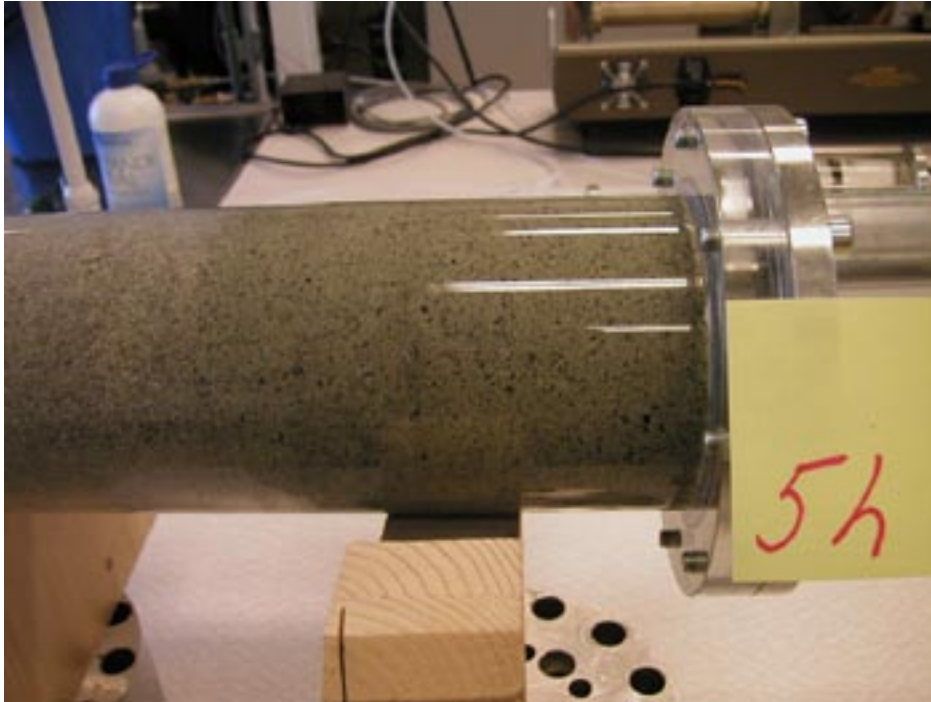


Figure A18-3. Picture from the test. The picture shows the situation after 5 hours during the water filling. There is a very significant front of the wetting.



Figure A18-4. Picture from the test showing the situation just before interruption of the test.

Test B:222 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:222	Bentonite/Backfill 30/70	1% salt	0.01 l/min	1 m

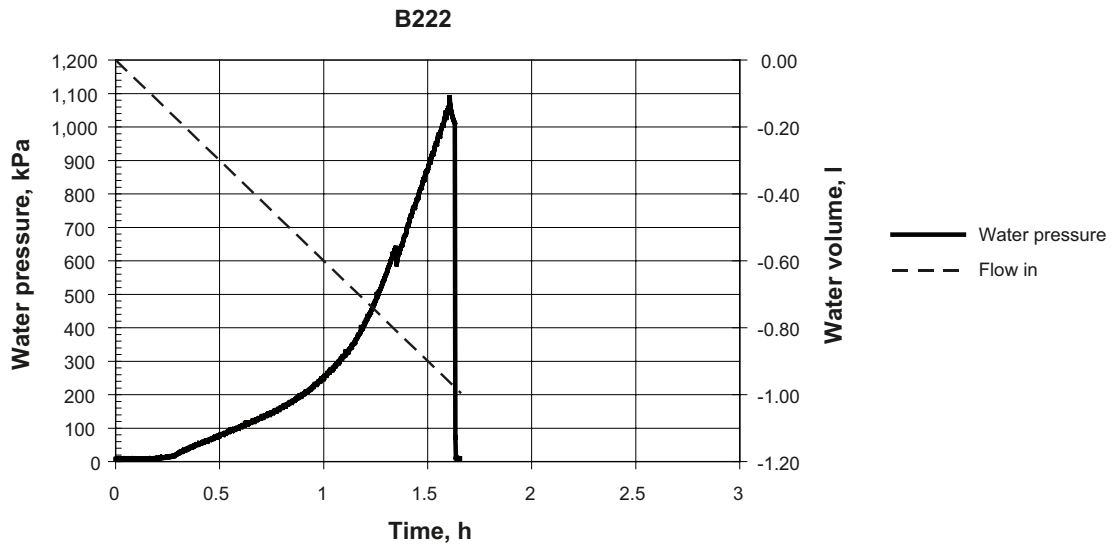


Figure A19-1. The measured inflow, the outflow and the water pressure plotted vs. time. At 1,100 kPa the pump was switched of reaching its maximum, which meant that no erosion could be measured.

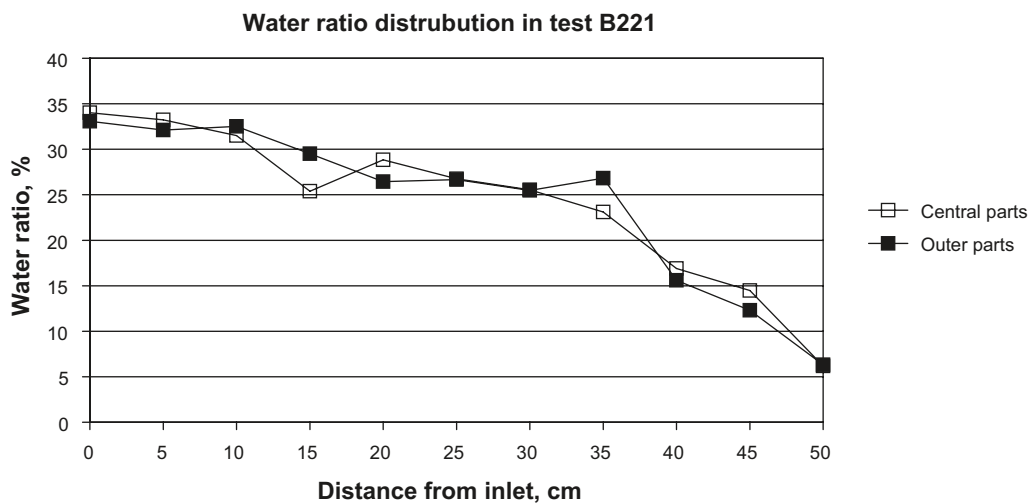


Figure A19-2. The water ratio distribution. The samples are taken just after termination of the test. There is no clear difference in the water ratios between the central parts and the outer parts. The initial water ratio of the material is about 12%.



Figure A19-3. Pictures from the test. The upper picture shows the situation after 40 minutes during the water filling. There is a very clear front of the water. The right picture shows the inlet side at dismantling. The material is quite loose here. No special channel can be detected. The material seems to be very evenly wetted.

Test B:223 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:223	Bentonite/Backfill 30/70	1% salt	0.1 l/min	0.5 m

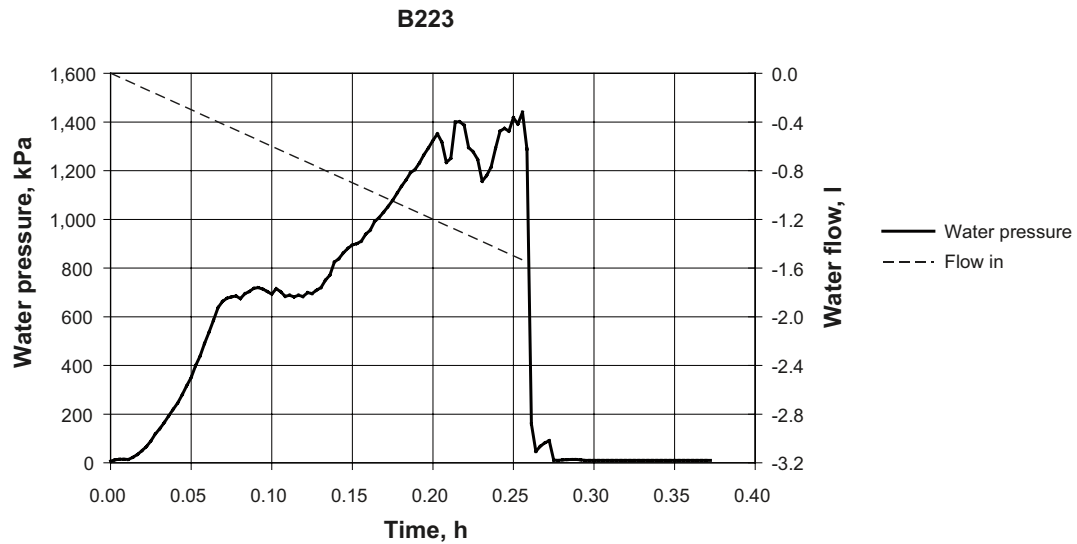


Figure A20-1. The measured inflow and the water pressure. The test was running until the maximal pressure of the pump was reached.

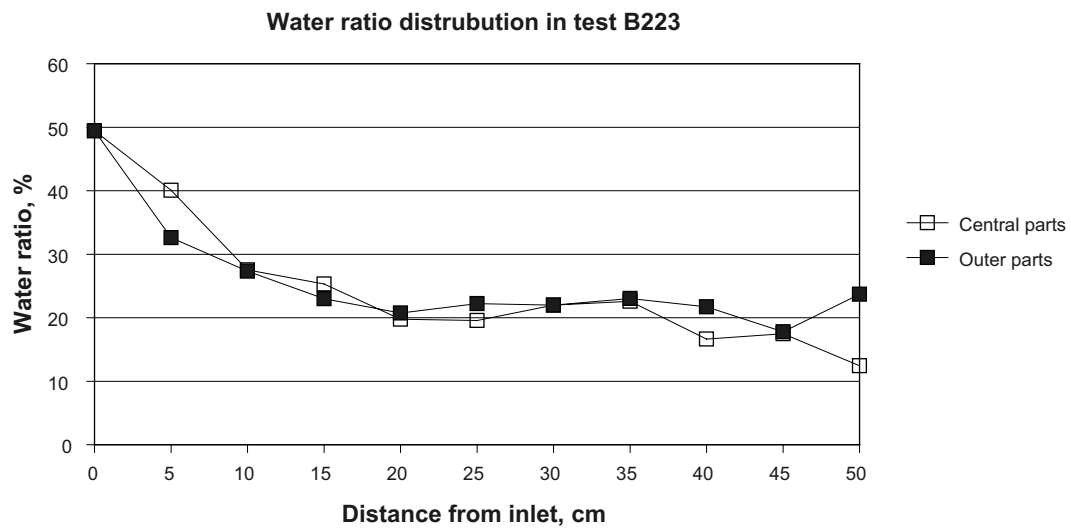


Figure A20-2. The water ratio distribution. The samples are taken just after termination of the test.



Figure A20-3. Picture showing the outer surface of the sample. At first the wetting was done as a front, but the water was after a few minutes located to channels. In the channels the bentonite was washed out leaving the crushed rock left. In spite of the channels, the pressure was raised to about 1,400 kPa and the test had to be interrupted.

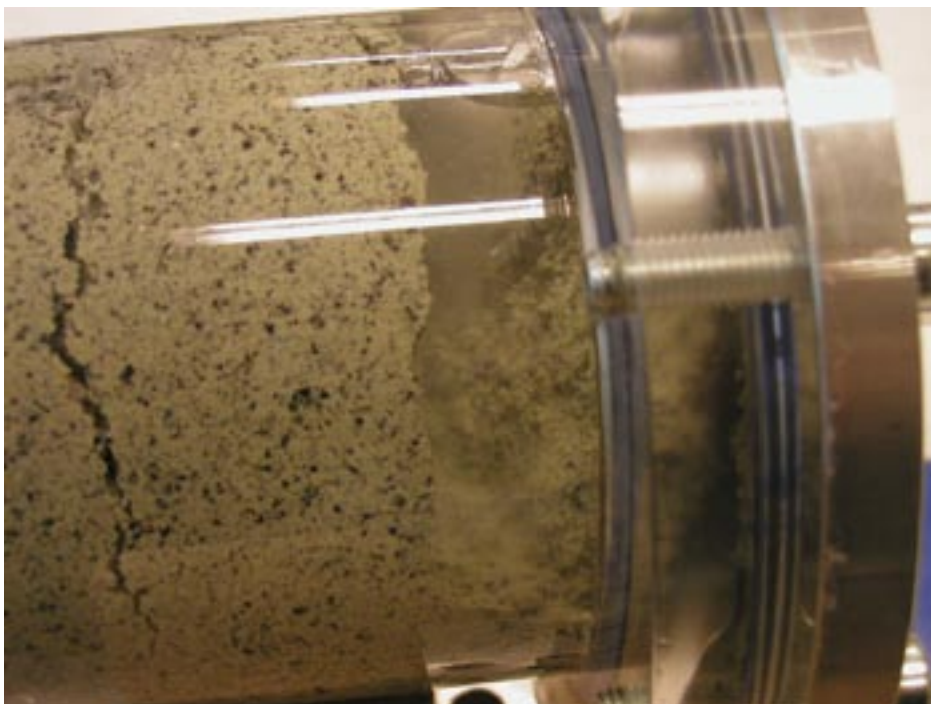


Figure A20-4. Picture from the test showing the water inlet side. The material was compacted by the water pressure, creating a slot with a thickness of about 4 cm.

Test B:221-2 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:221-2	Bentonite/Backfill 30/70	1% salt	0.00 l/min	0.5 m

Steeltube with water inlet on the middle.

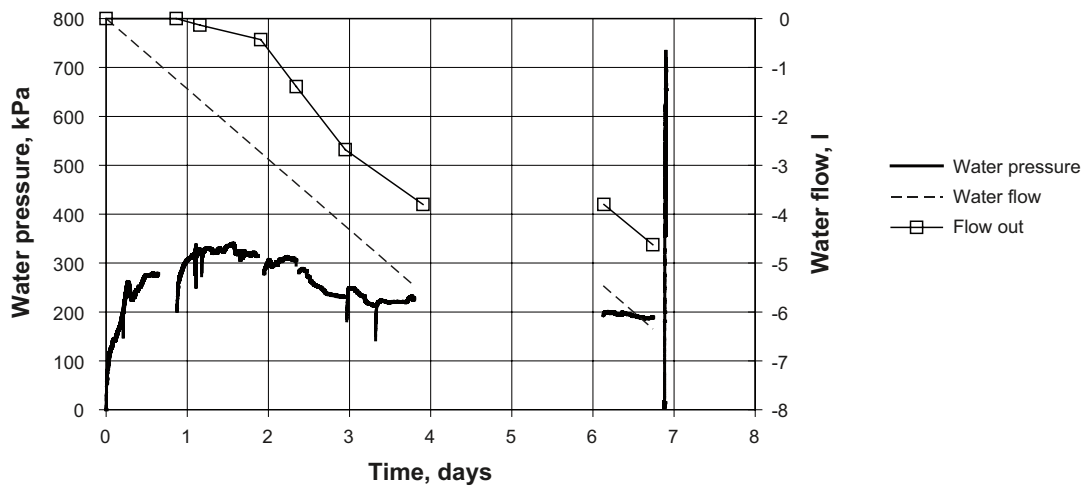


Figure A21-1. The measured inflow, the outflow and the water pressure plotted vs. time. After 4 days the test was temporary interrupted. After about 2 days resting, the same constant flow was applied again. The water pressure increased to almost the same level as before the resting. An attempt was then made to increase the flow to 0.01 l/min, but this resulted immediately in a raised water pressure and by that also that the material was pressed out from the ends of the sample holder.

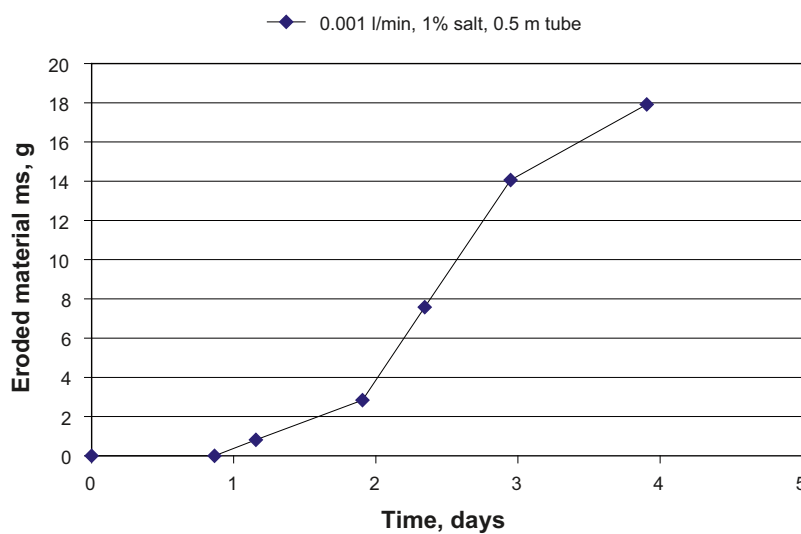


Figure A21-2. The total amount of material eroded during the test plotted vs. time.

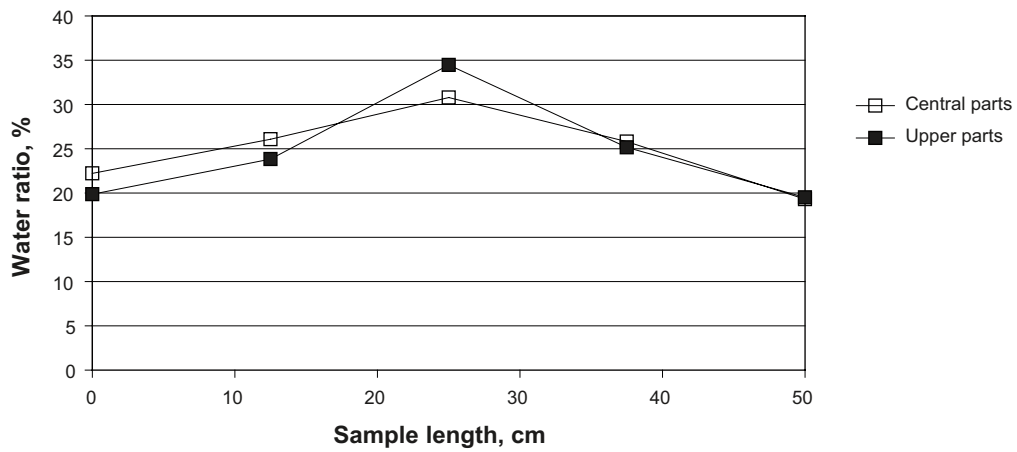


Figure A21-3. The water ratio distribution. The samples are taken just after termination of the test.



Figure A21-4. Picture from the test showing the situation when the higher flow has been applied and the pressure is rising. The material is pushed out in both ends of the sample holder.

Test B:222-2 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:222-2	Bentonite/Backfill 30/70	1% salt	0.01 l/min	0.5 m

New test layout: Plexiglas tube with water inlet on the middle.

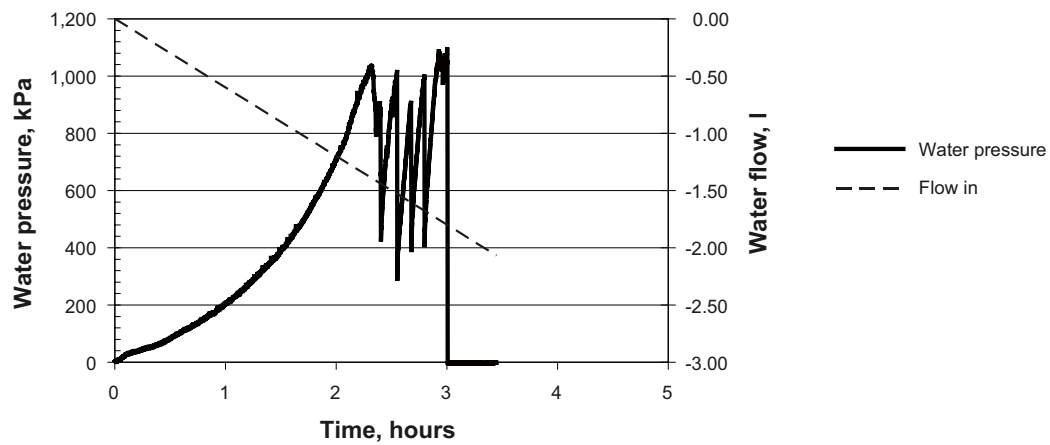


Figure A22-1. The measured inflow, the outflow and the water pressure plotted vs. time. After about 3 hours the sample holder cracked completely, see picture.



Figure A22-2. Picture showing the water inlet positioned on the middle of the tube.



Figure A22-3. Picture showing the equipment after the crash.

Test B:222-3 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:222-3	Bentonite/Backfill 30/70	1% salt	0.01 l/min	0.5 m

New test layout: Steel tube with water inlet on the middle.

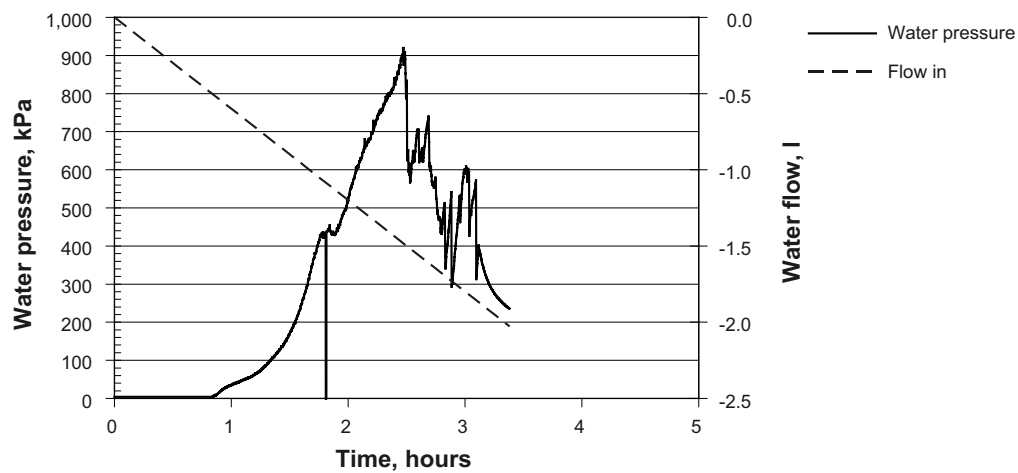


Figure A23-1. The measured inflow and the water pressure plotted vs. time.

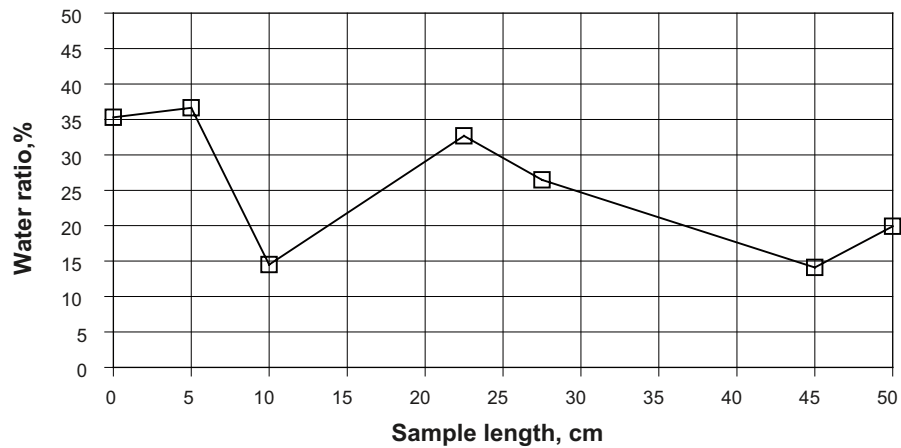


Figure A23-2. The water ratio distribution. The samples are taken just after termination of the test. The water inlet is positioned on the middle of the sample holder i.e. at 25 cm.

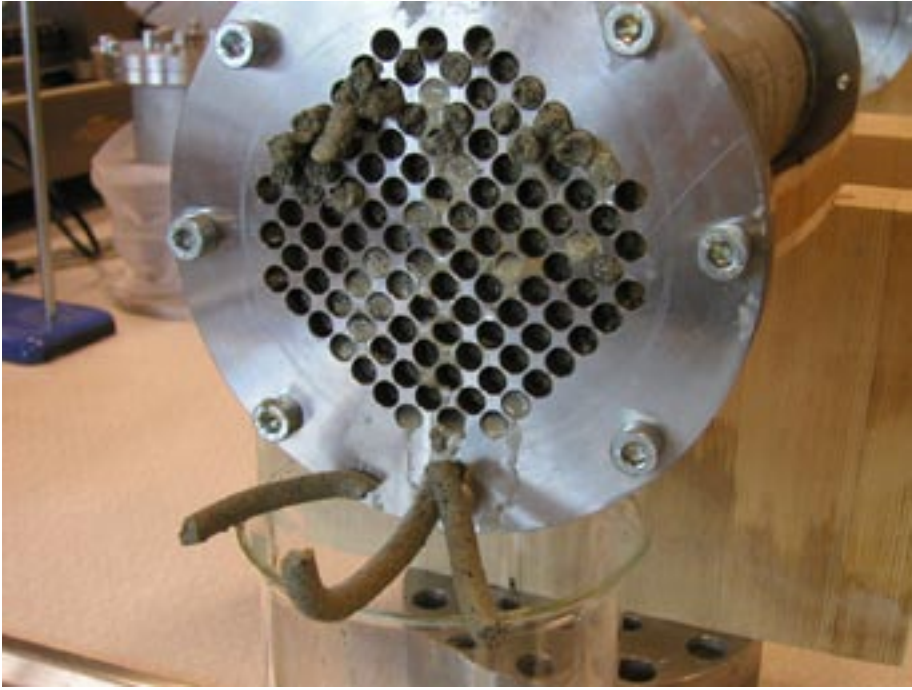


Figure A23-3. Picture from the test. The picture shows how the material is pressed out from the sample holder. It was not possible to measure any erosion.

Test B:222-4 Piping/erosion of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test length
B:222-4	Bentonite/Backfill 30/70	1% salt	0.0 l/min	0.5 m

Steel tube with water inlet positioned on the middle. One end open.

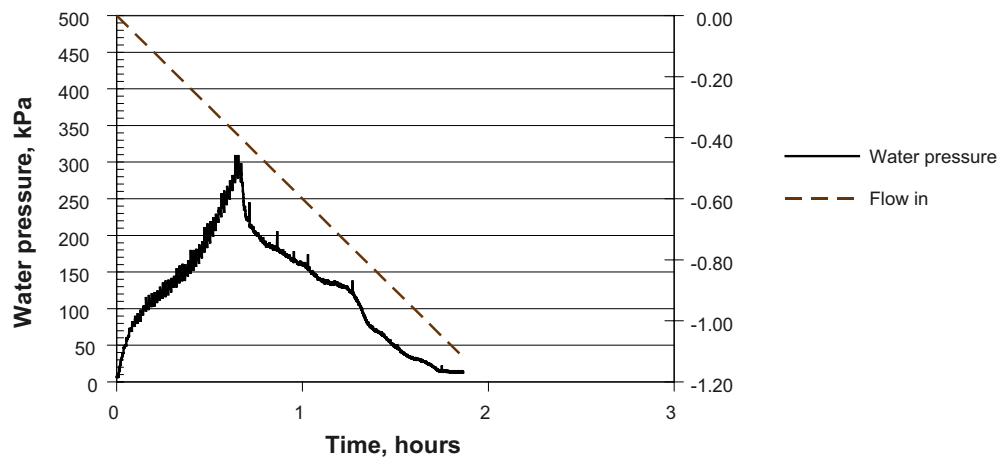


Figure A24-1. The measured inflow and the water pressure plotted vs. time.

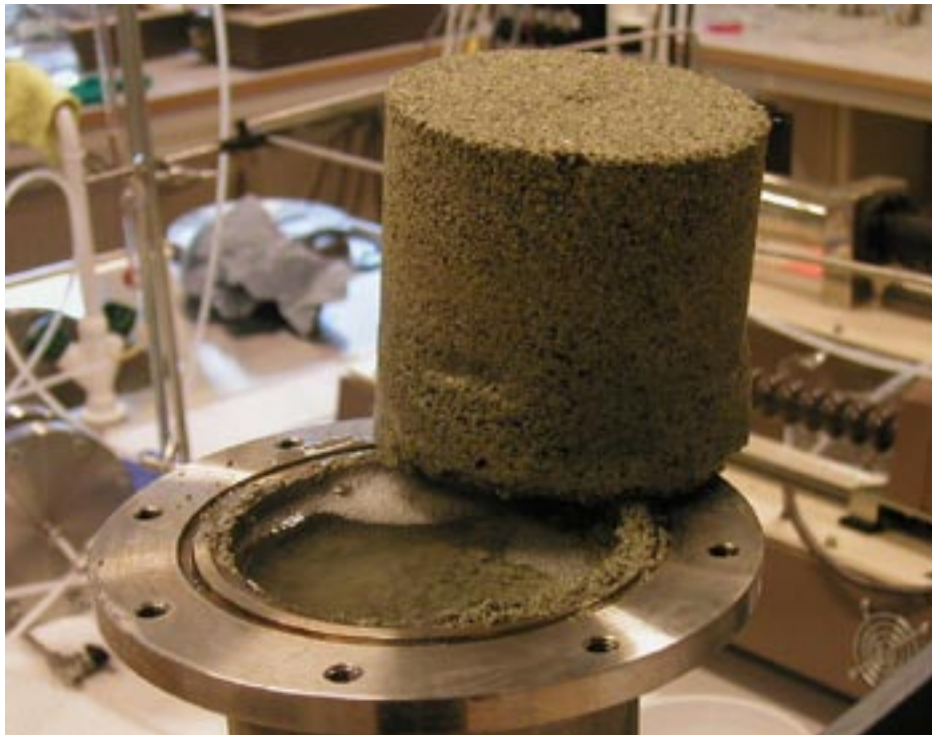


Figure A24-2. Photo from the test. A homogenous cylinder was pushed out. When lifting it away from the sample holder, the free water volume beneath could be seen.

Test E:22 Pellets in slot

Sample	Material	Water type	Flow	Test type
E:22	MX-80 Pellet	1% salt	0.01 l/min	Slot (1×2×0.1 m)

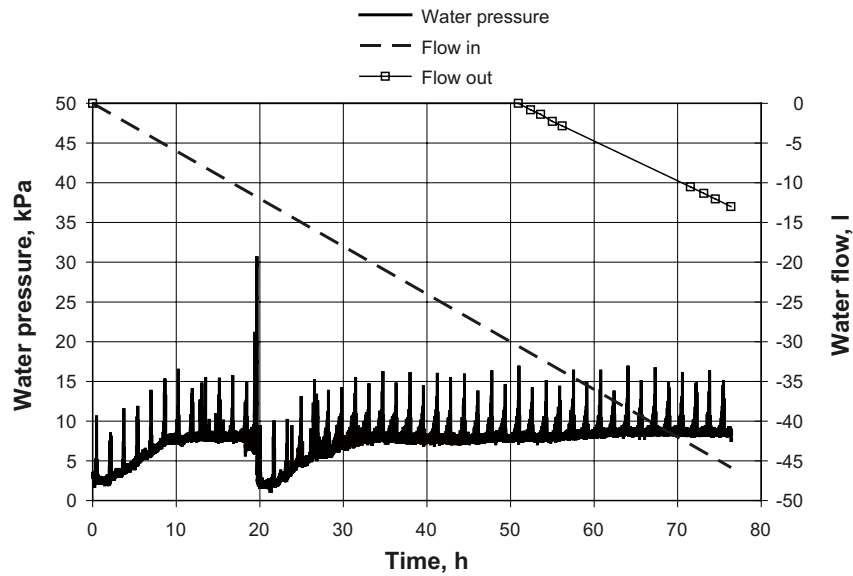


Figure A25-1. The measured inflow, the outflow and the water pressure plotted vs. time.

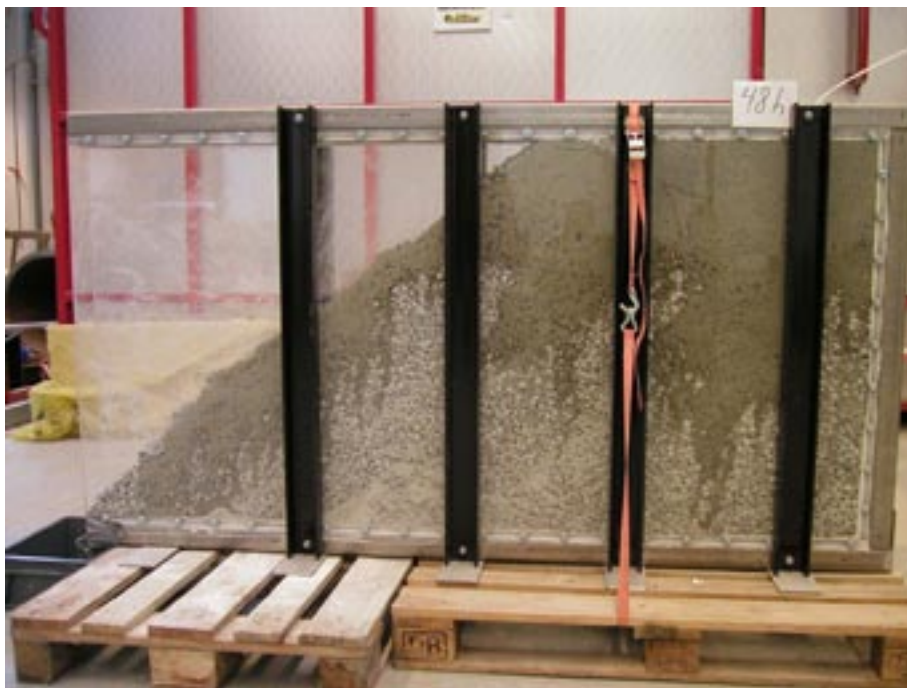


Figure A25-2. Pictures from the test. The picture shows the situation after 48 h. The water has only affected the upper parts of the volume and the water flows out on the surface of the slope.

Test E:23 Pellets in slot

Sample	Material	Water type	Flow	Test type
E:23	MX-80 Pellet	1% salt	0.1 l/min	Slot (1×2×0.1 m)

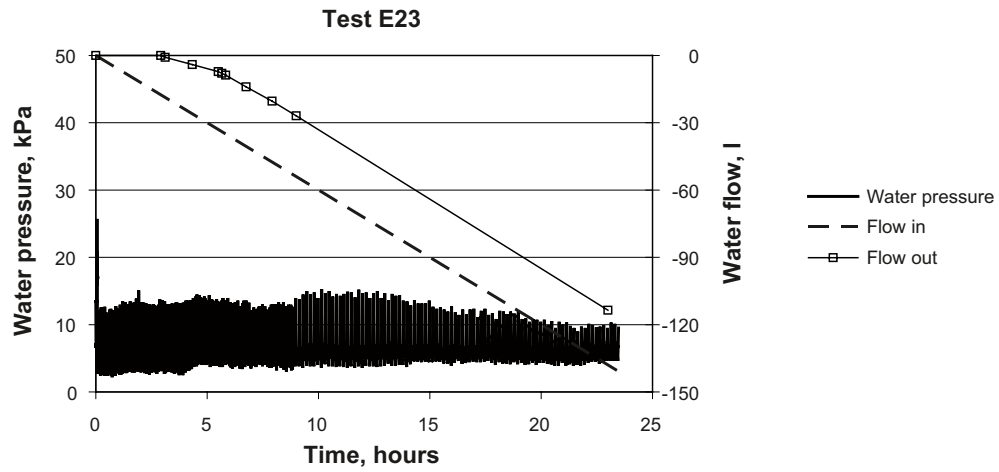


Figure A26-1. The measured inflow, the outflow and the water pressure plotted vs. time.

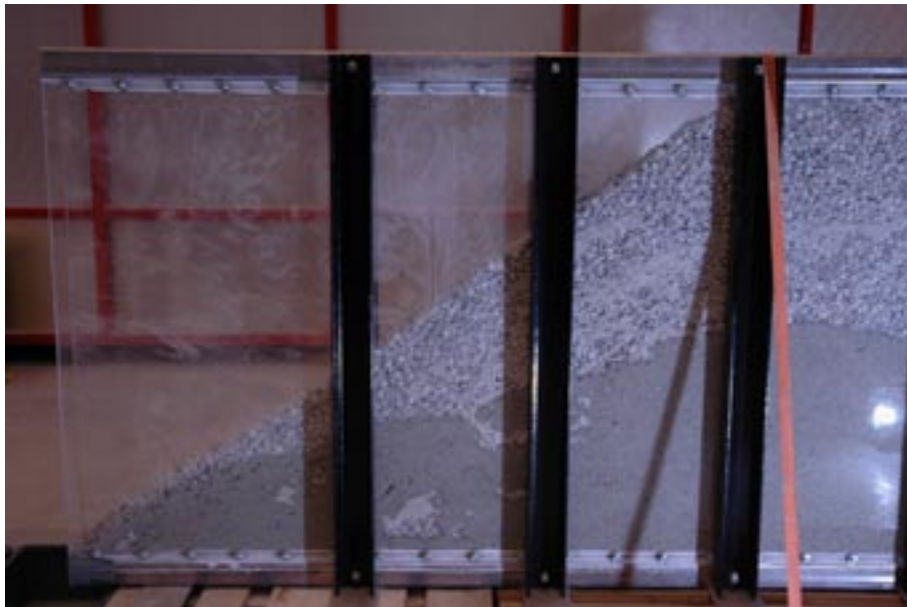


Figure A26-2. Pictures from the test. Only the lower part of the pellets volume is affected.

Test E:24 Pellets in slot

Sample	Material	Water type	Flow	Test type
E:24	MX-80 Pellet	1% salt	1 l/min	Slot (1×2×0.1 m)

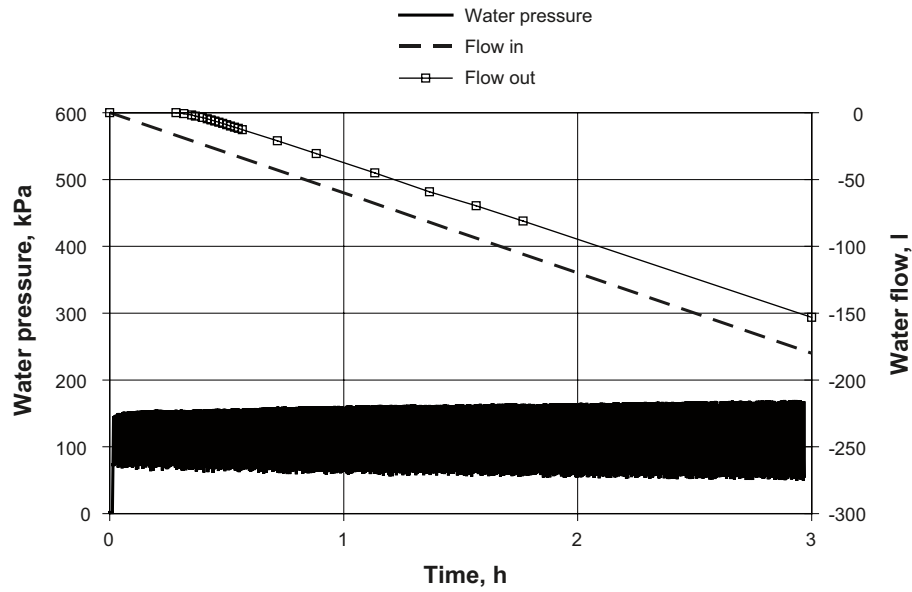


Figure A27-1. The measured inflow, the outflow and the water pressure plotted vs. time.

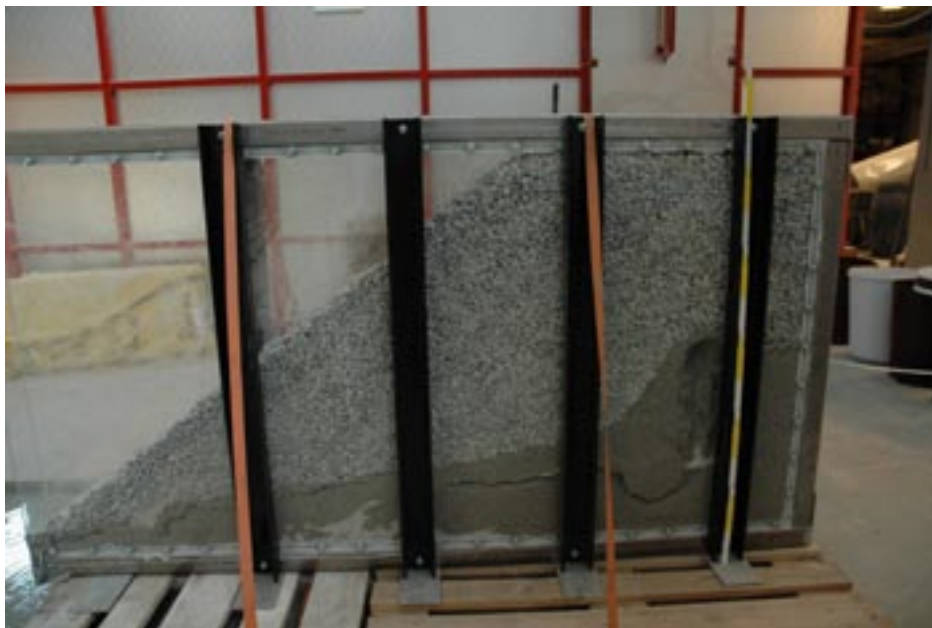


Figure A27-2. Pictures from the test. Only a part of the volume is affected. The erosion of material is evidently at the water inlet.

Test F:122 Healing ability of Bentonite/Ballast mixture

Sample	Material	Water type	Flow	Test type
F:122	Bentonite/Ballast 30/70	1% salt	0.01 l/min	Healing ability

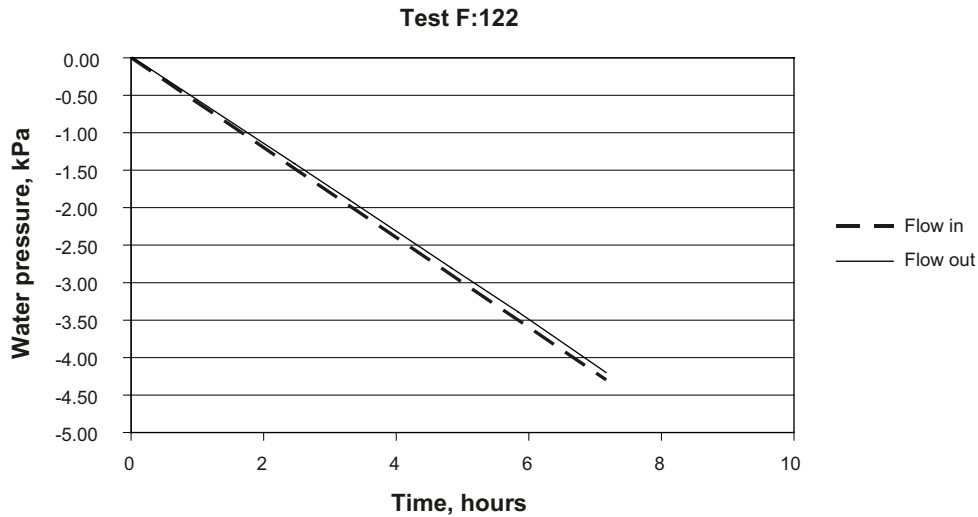


Figure A28-1. The measured inflow, the outflow and the water pressure plotted vs. time. The sample was prepared with a pre-drilled borehole, $d=3$ mm, in the middle where the water was flowing. No water pressure could be measured in this test.

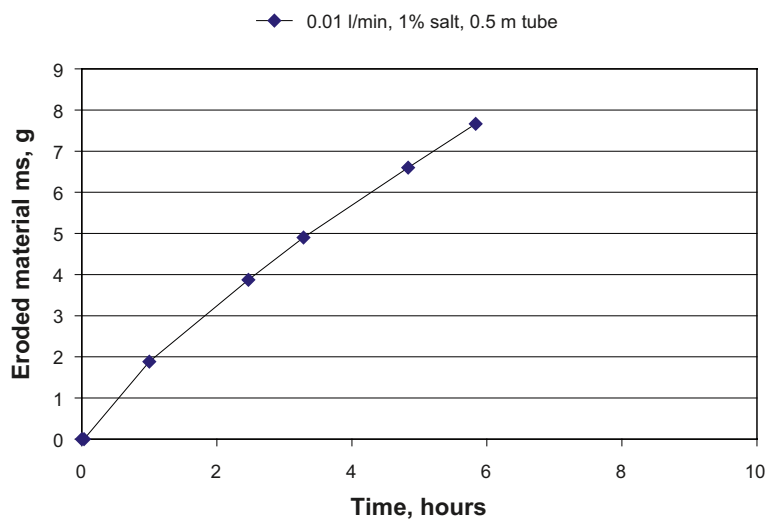


Figure A28-2. The total amount of material eroded during the test plotted vs. time.

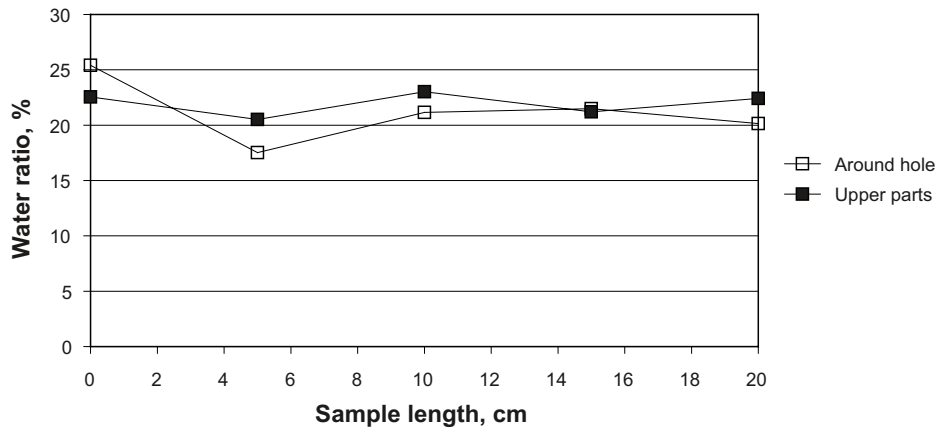


Figure A28-3. The water ratio distribution in the 20 cm specimen. A few samples were also taken in the 5 cm specimen showing water ratios between 23–25%.