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Optimization of backfill pellet properties

ÅSKAR DP2

Laboratory tests

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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. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Abstract

Bentonite pellets are planned to be used as a part of the backfill in the Swedish spent nuclear fuel deep repository concept KBS-3. This report describes testing and evaluation of different backfill pellet candidates. The work completed included testing of both pellet material and pellet type. The materials tested were sourced from India (ASHA), Greece (IBECO, 2 products) and Wyoming USA (MX-80 clay). The majority of the tests were completed on the ASHA clay as well as the IBECO-RWC-BF products, with only limited testing of the others. The pellets tested were manufactured using both extrusion and roller compaction techniques and had different sizes and geometries. The following tests have been performed and are presented in this report:

1. **General tests.** Water content, bulk density and dry density have been determined for both the pellet filling and the individual pellets. The compressibility of the pellet filling was tested with CRS-tests and the strength of the individual pellets was tested with a special compression test. The water content varied from 11.3% to 18.7% and was highest for the extruded pellets. The dry density was somewhat higher for the roller-compacted pellets and their compressibility was lower. The strength of the individual pellets was generally higher for the extruded pellets.
2. **Erosion.** The pellet filling will be exposed to groundwater inflow when installed in the tunnel. This flow could possibly cause significant erosion on the pellet filling. Erosion tests have been performed with comparisons in erosion resistance made on the various material- and pellet-types. The influence of variations in water salinity and flow rates was also tested. The IBECO extruded 6- and 10- mm diameter rods and the compacted Posiva spec.-A pellet filling seem to have the lowest tendency to erode. It is also the IBECO extruded pellet filling that withstands variations in water salinity and flow rates best.
3. **Water storing capacity.** The pellet filling's ability to buffer the inflowing groundwater during the installation phase was investigated in two types of tests. In the first test the wetting behavior was observed at small scale in a Plexiglas tube. The second test was performed in an artificial pellet slot with Plexiglas sides. The ASHA extruded 6 mm pellet seem to be the superior in water storing capacity, though it is suggested that this result may be more related to the presence of a fine grained material within the pellet mass than the pellets themselves.
4. **Installation test.** The pellets will most likely be installed with a shotcrete machine blowing them into place. This method was tested at full scale in order to investigate how much of the pellet filling that would be crushed into fine grained material if there is no water used during their placement. ASHA extruded 6 mm was the most durable pellet type with 5% of the material being crushed. 7–8% of the IBECO extruded pellet types (6 and 10 mm) were crushed into finer grains. The least durable pellets were the ASHA compacted pellets (pillow and almond shaped) with a crushing ratio of 53 to 61%. These results may have significance in terms of subsequent water uptake behavior.

Large scale tests at repository-scale still need to be done utilizing shotcrete equipment so that more experience is obtained in how to control the installation of the pellet filling and identify the key influences on its composition and as-placed condition.

Sammanfattning

Bentonitpellets är planerat att användas som en del av återfyllnaden i det Svenska slutförvaret av använt kärnbränsle, KBS-3. Denna rapport beskriver genomförda försök och utvärdering av kandidater till pelletsåterfyllningen. Det utförda arbetet har inkluderat testandet av olika materialtyper och pellettyper. De testade materialen kom från Indien (ASHA), Grekland (IBECO, 2 produkter) samt Wyoming, USA (MX-80). Merparten av testerna genomfördes på ASHA- och IBECO-RWC-BF-produkterna. Pellettyperna som testats var framställda genom både extrudering och rull-kompaktering och gjordes i olika storlekar och former. Följande tester har genomförts och är redovisade i denna rapport:

1. **Allmänna tester.** Vattenkvot, skrymdensitet och torrdensitet bestämdes för både pelletfyllningen och den enskilda pelleten. Kompressibilitet av pelletfyllningen bestämdes med CRS-tester och hållfastheten i den enskilda pelleten testades med ett speciellt kompressionstest. Vattenkvoten varierade från 11,3 % till 18,7 % och var högst hos extruderade pelletar. Torrdensiteten var något högre hos kompakterade pelletar. De kompakterade pelletarna hade också lägst kompressibilitet. Hållfastheten i den enskilda pelleten var generellt högre hos extruderade pelletar.
2. **Erosion.** Pelletfyllningen kommer utsättas för ett naturligt grundvattenflöde när den installeras i tunneln. Detta flöde kan möjligtvis orsaka betydande erosion på pelletfyllningen. Erosionsförsök genomfördes med jämförelser av erosionsbenägenhet hos de olika material- och pellettyperna. Även påverkan av variationer i vattnets salthalt och flödeshastighet undersöktes. Den extruderade 6 och 10 mm IBECO och den kompakterade Posiva spec.-A pelletfyllningen verkar ha minst benägenhet att erodera. Det är också den extruderade IBECO pelletfyllningen som påverkas minst av variationer i vattnets salthalt och flödeshastighet.
3. **Vattenlagringskapacitet.** Pelletfyllningens förmåga att buffra grundvattenflödet under installationsfasen undersöktes i två typer av test. I det första försöket studerades bevätningen i mindre skala i en plexiglastub. Det andra testet gjordes i en konstgjord spalt med sidor av plexiglas. Den extruderade 6 mm ASHA pelleten verkade lagra vatten bäst. Dock finns misstankar om att resultatet kan vara mer kopplat till förekomsten av finkornigt material än själva materialegenskaperna.
4. **Installationstest.** Pelletfyllningen kommer troligen installeras med en så kallad shotcrete-utrustning som blåser den på plats. Denna metod testades i full skala för att undersöka hur stor del av pelletfyllningen som krossas till finkornigt material om installationen genomförs utan vatten. ASHA 6 mm extruderad var den mest hållbara pelleten, endast 5 % av materialet krossades. 7–8 % av de extruderade IBECO pelletarna (6 och 10 mm) krossades till finkornigt material. Deminst hållbara pellettyperna var kompakterade ASHA (kuddar och mandelformade) där 53 till 61 % av pelletfyllningen krossades till finkornigt material. Dessa resultat kan ha betydelse för vattenlagringskapaciteten.

Fullskaleförsök bör göras där pelletfyllningen installeras med shotcrete-utrustningen så mer erfarenhet erhålls om hur man kan öka kontrollen i installationsfasen. Därigenom kan även de betydelsefulla egenskaperna i pelletfyllningens sammansättning identifieras.

Contents

1 Introduction

This report is the result of work performed within subproject two in the SKB project ÅSKAR. The subproject is a joint project between Posiva and SKB. NWMO has also been a part of the project regarding tests of roller compacted pellets. The report describes tests performed in order to optimize the properties of bentonite pellets used as a part of the backfill in deposition tunnels for the Swedish spent nuclear fuel deep repository system, KBS-3. The KBS-3 concept includes deposition of copper canisters containing spent nuclear fuel, which are placed in vertically drilled deposition holes. The deposition tunnels will after emplacement of canisters be backfilled with both pre-compacted bentonite blocks and pellets.

The backfill blocks will be placed on a bed of bentonite pellets in the SKB concept. After the emplacement of the blocks there will be a slot remaining between the blocks and rock walls which will also be filled with bentonite pellets. The pellet filling will contribute to increasing the average density of the backfill. Another important task for the pellet filling is to, during installation of the backfill, store the inflowing water and prevent it from reaching the backfilling front where it would disturb the installation work. It is of great importance to optimize the properties of the bentonite pellet filling regarding both water storing capacity and resistance to erosion. The groundwater flow present in a deposition drift could possibly cause high erosion rates which transports significant parts of the pellet filling out of place.

The work described in this report was performed in order to evaluate pellet filling candidates in terms of their resistance to erosion and water storing capacity as well as testing the installation techniques. The approach taken to accomplish this was to test the pellet filling candidates at different scales using test procedures specially designed for the purpose.

2 Test philosophy

2.1 General

The testing done as part of this investigation was intended to identify potentially suitable pellets for use as backfill in SKB's KBS-3 repository concept. This therefore involved testing of different pellet types and source materials for their manufacture, as well as the influence of water salinity and water inflow rate.

2.2 Test types

The following investigations have been done and are presented in this report:

- **General tests.** The general tests aimed to describe the basic properties of the pellet filling candidates. Dry density, bulk density, water content, compressibility of the pellet filling and strength of the individual pellets were investigated.
- **Erosion.** Tests were performed to evaluate the resistance to water erosion of the different material and pellet types. The influence of changes in water salinity and flow rates on erosive action on pellets was also investigated.
- **Water storing capacity.** Two types of tests were performed in order to investigate the water storing capacity of pellet filling candidates. The first test type aimed to compare wetting behavior and water pressure buildup using a small vertically positioned tube-shaped confinement. The second test type simulated the pellet slot geometry at larger scale.
- **Installation tests.** The pellet filling is planned to be positioned by blowing the pellets in by use of a shotcrete-equipment. This installation method was tested in an artificial slot in order to see how the pellet filling candidates were affected.

The tests and results are described in Chapters 3 to 7.

2.3 Materials and water

Four different clay materials were used in the tests:

- **ASHA NW-BFL-L.** The ASHA bentonite material was delivered in November 2010 from Ashapura, India. It is a sodium dominated bentonite with a montmorillonite content of about 70% (Sandén et al. 2012).
- **MX-80.** A high grade sodium bentonite from Wyoming, USA with a montmorillonite content of 80% (Karnland et al. 2006). MX-80 is mainly used as a reference material in the tests.
- **IBECO RWC-BF.** The IBECO material was delivered in February 2011 from Milos, Greece. The material is described by the supplier as a natural calcium bentonite with medium montmorillonite content (Sandén et al. 2012).
- **IBECO HQ (IBECO Deponit CA-N).** An activated high quality bentonite with high montmorillonite content, 75–80%. The material origins from Milos, Greece. The pellets of this material were manufactured by AECL, Canada, and were mainly of interest for Posiva. The pellets made of this material have only been tested regarding erosion properties.

Two different water salinities (50/50 of $NaCl/CaCl_2$) were used in the tests.

- **Type 1.** 1% salinity. This was used as the standard salinity in the tests.
- **Type 2.** 3.5% salinity. This was used as the alternative salinity when investigating the impact of variations in water salinity.

2.4 Pellet manufacturing

The different pellet types that were used originated from different manufacturing methods. Three pellet types have been used in the tests:

- **Roller compacted pellets.** The bentonite material is compacted between two counter-rotating rollers containing matching hemispherical voids. The compacted pellets used in the tests were manufactured in either almond or pillow shapes from the raw materials as delivered. This pellet type was manufactured by *HOSOKAWA Bepex GmbH* in Germany (ASHA and MX-80) and also by AECL in Canada (IBECO HQ).
- **Extrusion-produced pellets.** The bentonite material is pressed through a matrix. The pellets are shaped as rods with varying lengths. The diameter of the rods can be changed. The pellets manufactured by this technique are in this report denominated as extruded. The optimum water content for this manufacturing method was determined at the manufacturer's laboratory. Most of these pellets were manufactured by *Amandus-Kahl* in Germany, but one batch was also manufactured using an identical machine at Äspö HRL.
- **Granules.** The granules consist of crushed compacted pellets from *HOSOKAWA Bepex GmbH,* with a grain size of 1–5 mm. This pellet type was included in the test plan as a reference with small grain sizes.

A compilation of the pellet types used is shown in Table 2-1. The different materials are named with the trade names and to this are added the year when the batch was delivered. In order to facilitate the work, each pellet type has been given a name which then has been referred to in the test descriptions. Observe that the pellet type "Posiva spec" only has been tested regarding the erosion properties.

Photos of all tested pellet types are provided in Figure 2-1 to 2-11.

Table 2-1. Compilation of the different pellet types used in the tests and their denomination. The pellet types that have been manufactured and tested are printed in black. The grey printed pellet types are not manufactured for this study but could be possible candidates for future tests.

Material	Roller compaction			Extruded		Granules
	Pillow shape 1	Almond shape	Pillow shape 2	d=6, L=6-22	d=10, L=6-32	1–5 mm
ASHA NW-BFL-L 2010	Asha-11	Asha-12		Asha-13	Asha-14	Asha-15
IBECO-RWC-BF 2011	IBECO-11	IBECO-12	Posiva spec. B	IBECO-13	IBECO-14	
MX-80 2010	MX80-11	MX80-12		MX80-13	MX80-14	
IBECO HQ 2010			Posiva spec. A			


Figure 2-1. ASHA-11 compacted pillow-shaped pellets.


Figure 2-2. ASHA-12 compacted almond-shaped pellets.

***Figure 2-3.** ASHA-13 extruded 6 mm diameter rods.*

***Figure 2-4.** ASHA-14 extruded 10 mm diameter rods.*

***Figure 2-5.** ASHA-15 granules.*

***Figure 2-6.** IBECO-13 extruded 6 mm diameter rods.*

***Figure 2-7.** IBECO-14: 10 mm diameter extruded rods.*

***Figure 2-8.** MX-80-11 compacted pillow-shaped pellets.*

Figure 2-9. *MX-80-13 extruded 6 mm diameter rods.*

Figure 2-10. *Posiva spec.-A compacted pillow-shaped pellets.*

Figure 2-11. *Posiva spec.-B compacted pillow-shaped pellets.*

3 General tests

3.1 General

Some general tests were performed on the pellet fillings and the individual pellets. Dry density and bulk density were determined for the individual pellets. For the pellet filling the dry density, bulk density, water content and the compressibility were determined. The general tests were performed on all pellet filling candidates except the Posiva spec.-A and -B.

3.2 Method

3.2.1 Pellet filling – bulk density

The bulk density ρ_b is defined as the total material weight (including water) per unit volume (kg/m^3) and was determined by weighing of 1 dm^3 pellet filling in a graded cylinder on a laboratory balance.

3.2.2 Pellet filling – water content

The gravimetric water content w_0 is defined as mass water per mass dry substance, Equation 3-1.

$$w_0 = m_w/m_s \tag{3-1}$$

where m_w = mass water and m_s = mass dry substance

A sample was placed in an aluminum baking-tin. The sample total mass m_{tot} was determined using a laboratory balance. The sample was then placed in an aired oven at 105°C and after 24 hours the dry substance mass, m_s, was determined by once more weighing the sample. The original mass water m_w could then be calculated according to Equation 3-2.

$$m_w = m_{tot} – m_s \tag{3-2}$$

Finally the water content was determined with Equation 3-1.

3.2.3 Pellet filling – dry density

Having both the pellet filling bulk density (see 3.2.1.) and water content (see 3.2.2.) the dry density ρ_d could be determined using Equation 3-3.

$$\rho_d = \frac{\rho_b}{(1+w_0)} \tag{3-3}$$

3.2.4 Individual pellets – bulk density

The bulk density of the individual pellets was determined using the paraffin oil method based on the Archimedes principle. The bulk mass m_b was determined by weighing the sample freely suspended in air. Then the weight of the sample lowered in paraffin oil, $m_{bp,}$ was determined and the volume was calculated with Equation 3-4.

$$V = \frac{m_b – m_{bp}}{\rho_p} \tag{3-4}$$

where V is the sample volume and ρ_p is the paraffin oil density

Finally the bulk density of the sample was determined using Equation 3-5. The test was repeated three times for every pellet type and an average value was calculated.

$$\rho_b = \frac{m_b}{V} \tag{3-5}$$

3.2.5 Individual pellets – dry density

Having both the individual pellet bulk density (see 3.2.4.) and the water content (see 3.2.2.) the dry density ρ_d was determined using Equation 3-3.

3.2.6 Compressibility of the unsaturated pellet filling

The compressibility of the unsaturated pellet filling was evaluated using a CRS-test (constant rate of strain). A photo of the test arrangement is seen in Figure 3-1. The tests were performed at the following conditions;

- The pellet filling sample was placed in a steel cylinder with an internal diameter of 101 mm. At the bottom of the cylinder there was a fixed steel plate with a small hole in the center, through which air could escape. At the top of the sample there was greased piston (Figure 3-1).
- A *Wykeham Farrance Tritech 50kN* press was used in order to get a constant deformation of 1 mm/min, pushing the piston down to compress the sample.
- The pellet filling sample had an initial height of 80 mm.
- The test was run up to a maximum pressure of 5 MPa.
- Load and deformation was logged with a load cell and a deformation gauge (Figure 3-1).

Also note that the friction from the pellets on the cylinder walls was not considered in the test evaluation.

3.2.7 Strength of the individual pellets

The strength of the individual pellets was tested with a CRS-test (constant rate of strain). The test was performed using a single pellet sample. The arrangement can be seen in Figure 3-2 and was performed as follows:

- The single pellet sample was placed inside a steel cylinder. At the top of the sample a loose fitting piston was placed.
- A *Wykeham Farrance Tritech50kN* press was used for constant deformation, pushing the piston down to compress the sample.
- Load and deformation were registered by a load cell and a deformation gauge.
- The tests were evaluated by plotting the load as a function of the deformation. The load required to crush the sample could then be read from the plot. The weight of the piston was compensated for when the maximal load was determined.

The results from this kind of test should be seen as indicative and not as absolute values of the strength.

Figure 3-1. The arrangement of the CRS-tests. The load cell (1.) was placed at the top, the steel cylinder containing the pellets (2.) in the middle and the deformation gauge (3.) on the left side.

Figure 3-2. Test arrangement for the CRS-test on the individual pellets. The sample was placed in a steel cylinder (3). A piston (2) was placed on top of the sample. Load and deformation was logged with a load cell (1) and a deformation gauge (4).

3.3 Results

Table 3-1 show a compilation of the results from the tests described in Chapter 3.2.1. through 3.2.5.

Table 3-1. Water content, bulk- and dry density for pellet filling and individual pellets.

Pellet type and material	Pellet filling			Individual pellets	
	Water content %	Bulk density kg/m^3	Dry density kg/m^3	Bulk density kg/m^3	Dry density kg/m^3
ASHA-11 comp. pillow	14,5	1,083	946	2,188	1,911
ASHA-12 comp. almond	15,1	1,122	974	2,123	1,844
ASHA-13 extr. 6 mm	18,7	1,057	890	2,154	1,814
ASHA-14 extr. 10 mm	18,0	1,017	862	2,152	1,824
ASHA-15 granules	14,9	1,058	921	2,188	1,905
IBECO-13 extr. 6 mm	16,9	1,029	881	2,122	1,816
IBECO-14 extr. 10 mm	18,3	1,039	878	2,101	1,776
MX-80-11 comp. pillow	11,3	1,030	925	2,049	1,841
MX-80-13 extr. 6 mm	16,4	1,032	887	2,023	1,738

Figure 3-3 and 3-4 show the results from the tests described in Chapter 3.2.6. Figure 3-3 shows the pellet filling strain with increased vertical stress. Figure 3-4 shows the pellet filling change in dry density with increasing stress.

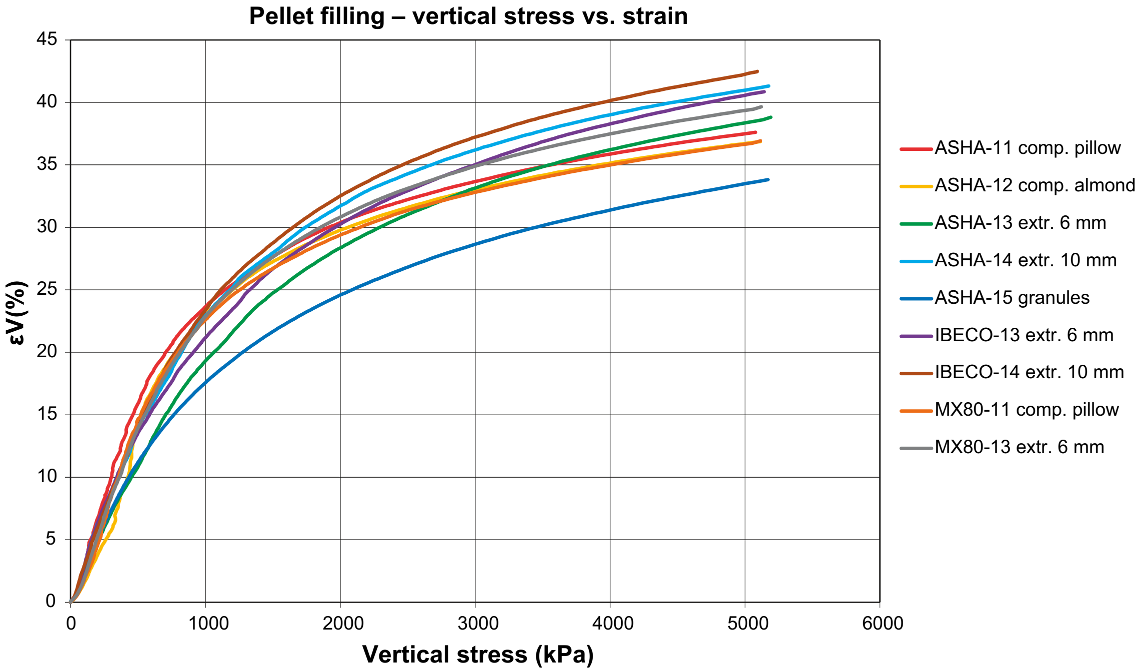

Figure 3-3. *The strain in % with increased vertical stress.*

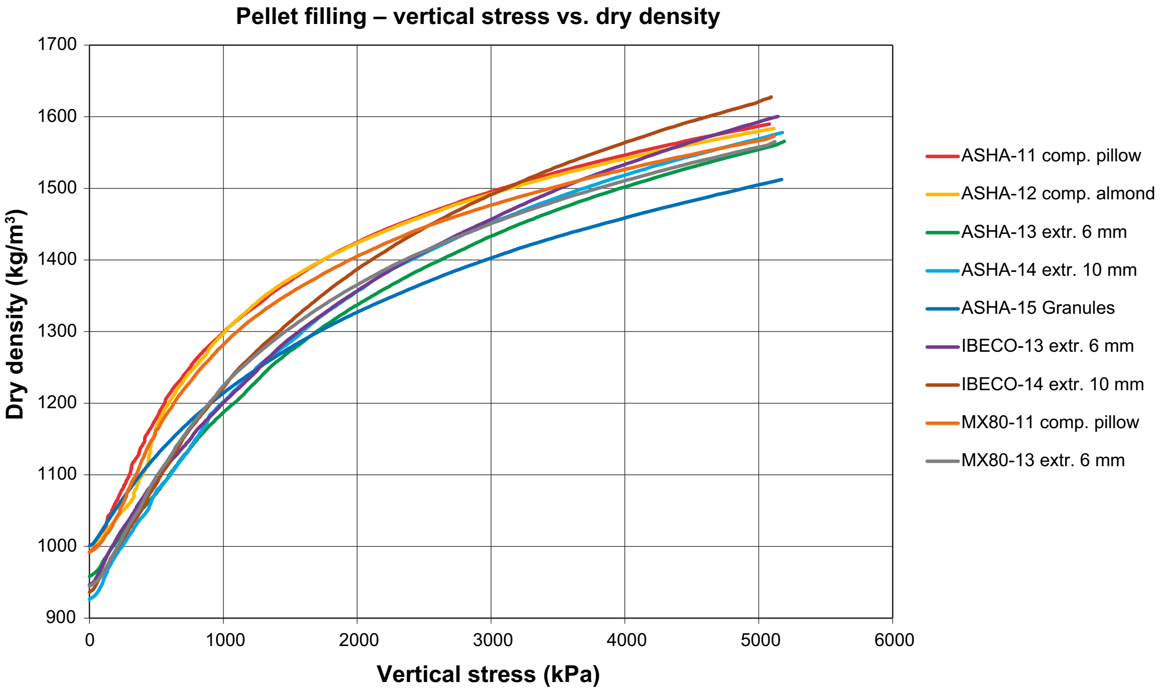

Figure 3-4. *The change in dry density in kg/m^3 with increased vertical stress.*

The results from the individual pellets strength tests described in Chapter 3.2.7 are provided in Table 3-2. The values are averages determined from five tests.

Table 3-2. The results from the tests on the individual pellets strength.

Pellet type and material	Deformation rate (mm/min)	Average max load incl. piston weight (N)	Standard deviation (N)
ASHA-11 comp. pillow	0.2	256.4	53.3
MX-80-11 comp. pillow	0.2	291.4	127.9
ASHA-12 comp. almond	0.2	141.4	26.2
ASHA-13 extr. 6 mm	0.2	231.2	17.4
IBECO-13 extr. 6 mm	0.2	300.4	21.3
MX-80-13 extr. 6 mm	0.2	251.4	34.9
IBECO-14 extr. 10 mm	0.2	336.6	37.6
ASHA-14 extr. 10 mm	0.2	453.2	86.1
ASHA-15 granules	0.05	20.4	8.8

3.4 Discussion and conclusions

The values of the water content and the dry densities were within the expected range for all pellet types and materials. The water content of the pellets varied from 11.3% for the MX-80 compacted pillow to 18.7% for the ASHA extruded 6 mm. Overall the extruded pellets have a higher water content, which is connected to the manufacturing method that requires higher water content in order to work properly. The dry density is slightly higher in the compacted pellets.

In the CRS-test the pellet filling was compacted into a brittle mass with the pellet structure still very visible. The tests showed that the compacted pellets are somewhat stiffer, especially the granules which have the lowest compressibility. The extruded 10 mm pellet materials have the highest compressibility. It was also expected that the compressibility would be lower for a pellet filling with higher dry density.

The individual pellet strength is highest for the ASHA extruded 10 mm – diameter pellets. In general the extruded pellets seem to withstand a higher load. This is probably due to a higher contact surface area for extruded rods versus the nearly-point load situation with the roller compacted pellets, since the test only measures the total load on a single pellet. The results from this of test should be seen as indicative and not as absolute values of the strength, they do however provide a basis for comparison for identically-manufactured pellet sizes.

4 Erosion tests

4.1 General

Previous tests have shown that the erosion rate in a bentonite pellet filling can vary a lot initially, but tends to decrease with time (Sandén et al. 2008). Results indicate that the pellets manufacturing method and the type of bentonite material used have a significant influence on the erosion resistance. The content of fine-grained material associated with the pellets is identified as a strong factor in the early stage of erosion and is connected to manufacturing method and material type. Also the water flow rate and salinity are parameters that seem to affect the erosion rate.

To achieve as high erosion resistance as possible, the pellet filling needs to be optimized regarding the pellet shape and material type but also regarding the impact of variations in water flow rate and salinity.

4.2 Method

The test was arranged with a Plexiglas tube (d = 0.1 m, L = 1.0 m) containing the pellet filling (Figure 4-1). One end of the tube was covered by a steel plate with a point inflow in the center. The other end was covered by a perforated steel plate. A constant flow of water was applied at the inflow point. The water pressure was logged by a transducer. In case of the water pressure exceeding the pump capacity of 1 MPa the test was stopped. Samples were taken at specific time intervals from the outflowing water and the water in the samples was removed by drying at 105°C. The eroded material dry mass was determined by subtracting the mass of the salt corresponding to the sample volume from the total dry mass. Finally the eroded dry mass was extrapolated over the corresponding time interval. The results of the tests were mainly plotted as in e.g. Figure 4-2 where the straight lines display the expected maximal and minimal erosion according to a model described by Sandén and Börgesson (2010).

In some previous erosion tests complete sealing of the flow has occurred, leading to the test being ended earlier than initially planned. This is not considered positive or negative in terms of erosivity. Conclusions from previous tests suggest that this may be an effect from the geometry of the confinement (Sandén et al. 2008). Only suspended matter in the outflow was measured in the erosion tests. Sealing and disaggregation/extrusion are treated in the water storing capacity tests.

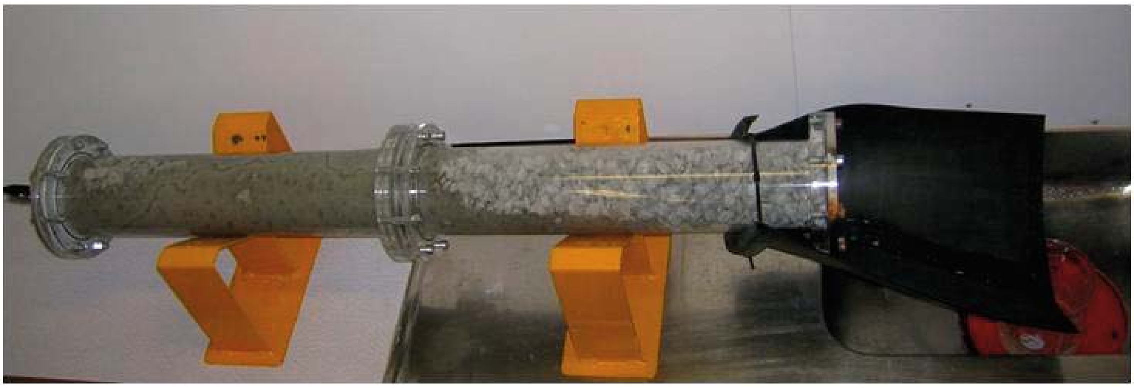

Figure 4-1. *The arrangement of the erosion tests. A Plexiglas tube was filled with bentonite pellets. A constant inflow was applied from left to right. Samples were collected at the outflow and the amount of eroded material was determined through evaporation of the water in the samples.*

4.3 Test matrix

Table 4-1 shows the planned full test matrix. Pellet type is compared at 0.1 l/min – 1% salinity. Material type is compared for the extruded 6 mm pellets at 0.1 l/min – 1% salinity and 1 l/min – 1% salinity. The influence of water flow rate is compared for 1% salinity at 0.01, 0.1 and 1 l/min for the 6 mm extruded pellets. Impact of water salinity is compared at 1 l/min for 1% and 3.5% salinity. All tests are run to an accumulated flow of 180–300 liters. In addition to this the 1% – 1 l/min tests are duplicated with a second series run to approximately 900 liters accumulated flow.

4.4 Results

4.4.1 General

A total of twenty erosion tests have been completed. The results are presented so that the influence of different pellet types, the influence of different material, the influence of different water salinity and the influence of different water flow rates can be seen.

4.4.2 Influence of pellet type

Figure 4-2 shows the results of erosion tests completed using an inflow rate of 0.1 l/min and a 1% TDS salt solution. The tests were run to about 300 liters accumulated inflow. The comparison of the results can be summarized as follows:

- Roller compacted ASHA-pellets (ASHA-11 and ASHA-12) generate three to four times more eroded material than the extruded 6 mm and the granules (ASHA-13, ASHA-15).
- Roller compacted ASHA-pellets exhibited approximately ten times more material removal than was observed for the extruded 10 mm diameter material (ASHA-14).
- Extruded pellets manufactured from MX-80 bentonite (MX-80-13) give about two times more erosion than the roller compacted product (MX-80-11).
- ASHA extruded 6 mm diameter materials (ASHA-13) experience approximately two times more erosion than the extruded 10 mm diameter product (ASHA-14) produced from the same source material.
- IBECO extruded 6 mm diameter materials (IBECO-13) give slightly more erosion than the extruded 10 mm diameter materials produced from the same source material (IBECO-14).
- The roller compacted pillow Posiva spec.-A has the lowest final accumulated erosion observed in this study.
- The roller compacted, pillow-shaped Posiva spec.-B has about six times the accumulated erosion observed for the roller compacted, pillow-shaped Posiva spec.-A pellets.

Table 4-1. The planned test matrix for the pellet filling erosion test.

Pellet type	Pellet name (material)	1% salinity			3.5% salinity
		0.01 l/min	0.1 l/min	1 l/min	1 l/min
Compacted pillow	ASHA-11		X		
Compacted almond	ASHA-12		X		
Extruded 6 mm	ASHA-13	X	X	X	X
Extruded 10 mm	ASHA-14		X		
Granules 1–5 mm	ASHA-15		X		
Extruded 6 mm	IBECO-13	X	X	X	X
Extruded 10 mm	IBECO-14		X		
Compacted pillow	MX-80-11		X		
Extruded 6 mm	MX-80-13	X	X	X	X
Compacted pillow	Posiva spec.A		X		
Compacted pillow	Posiva spec.B		X		

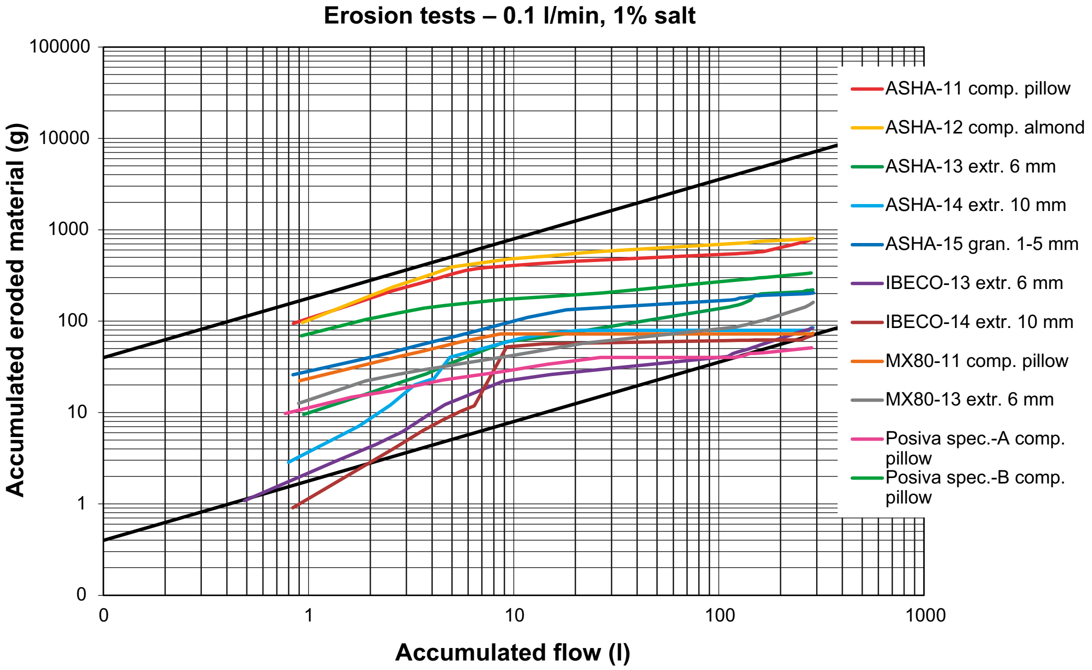

Figure 4-2. Accumulated eroded material and flow at 0.1 l/min – 1% salinity. Compacted pellets seem to have a generally higher erosion rate than extruded pellets. The straight lines show the expected maximum and minimum erosion according to a model described by Sandén and Börgesson (2010).

4.4.3 Influence of material type

Figure 4-3 shows a comparison of the three material types at 0.1 l/min and 1% salinity. IBECO only has approximately half as much accumulated erosion as ASHA and MX-80 at 300 liters accumulated inflow.

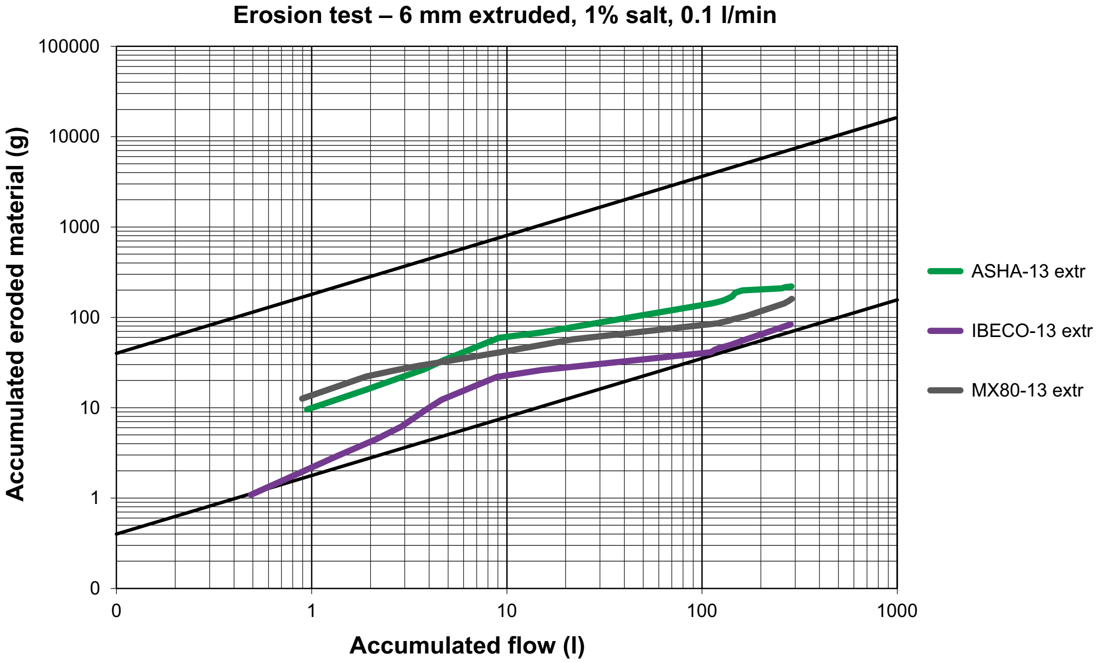

Figure 4-3. Comparison of the three material types at 0.1 l/min and 1% salinity. ASHA seem to have the highest erosion rate and IBECO the lowest.

Figure 4-4 shows both test series done at 1 l/min and 1% salinity. ASHA and MX-80 have initially high erosion rates that decrease with time. IBECO tend do have initially low erosion with temporary increase at approximately 50–100 liters accumulated flow. At 900 l accumulated flow the total erosion is in the same order of magnitude for all three materials.

4.4.4 Influence of water salinity

Figure 4-5 compares 1% and 3.5% salinity at 1 l/min for the 6 mm extruded pellets. ASHA and IBECO do not seem very affected by the salinity of the water. However the increased salinity seems to increase the erosion rate of the MX-80-pellets significantly.

4.4.5 Influence of water flow rate

The tests performed at 0.01 l/min flow and 1% salinity were ended shortly after initiation due to sealing of the IBECO material and cessation of measurable flow. Comparison of erosion behavior is therefore limited to 0.1 and 1 l/min flow rates. Figure 4-6 shows 6 mm extruded pellets at 0.1 and 1 l/min at 1% salinity. Initially there seem to be an influence on the ASHA and the MX-80 pellets, while IBECO is less affected by the increased flow rate. However, after about 50 liters accumulated flow the IBECO 1 l/min showed a brief increase in erosion. By the end of the test the influence of flow rate on erosion seem to be the same for the three materials with about 5 times more erosion resulting from a factor of 10 increase in flow rate.

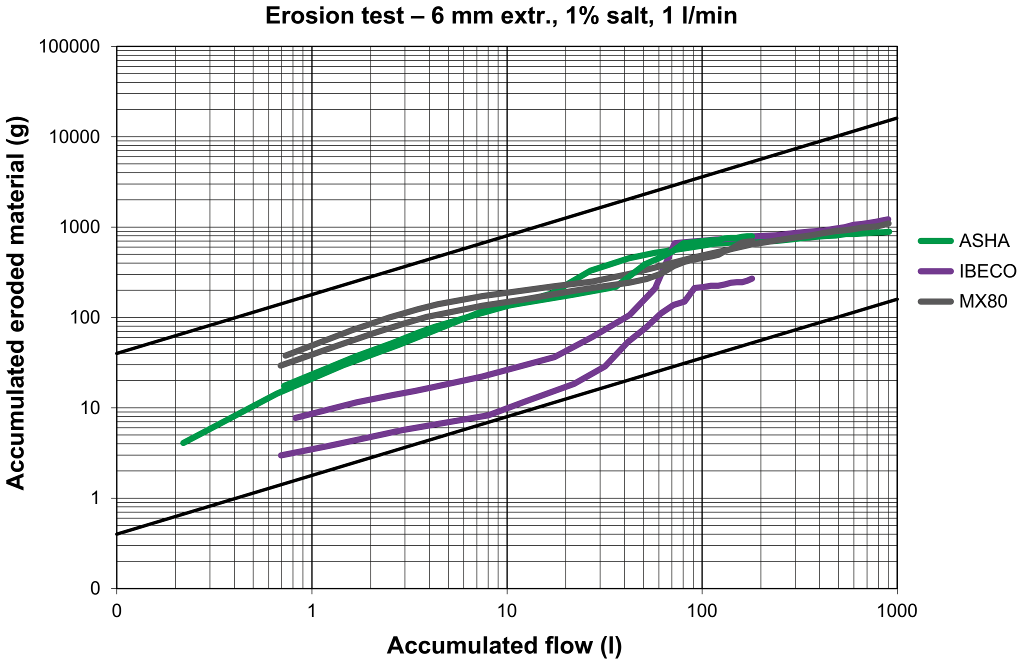

Figure 4-4. Comparison of the three material types at 1 l/min and 1% salinity. The tests are duplicated with a second series at a higher accumulated flow. For the shorter test series IBECO has the lowest total erosion. In the longer series the accumulated erosion is in the same order of magnitude for all materials.

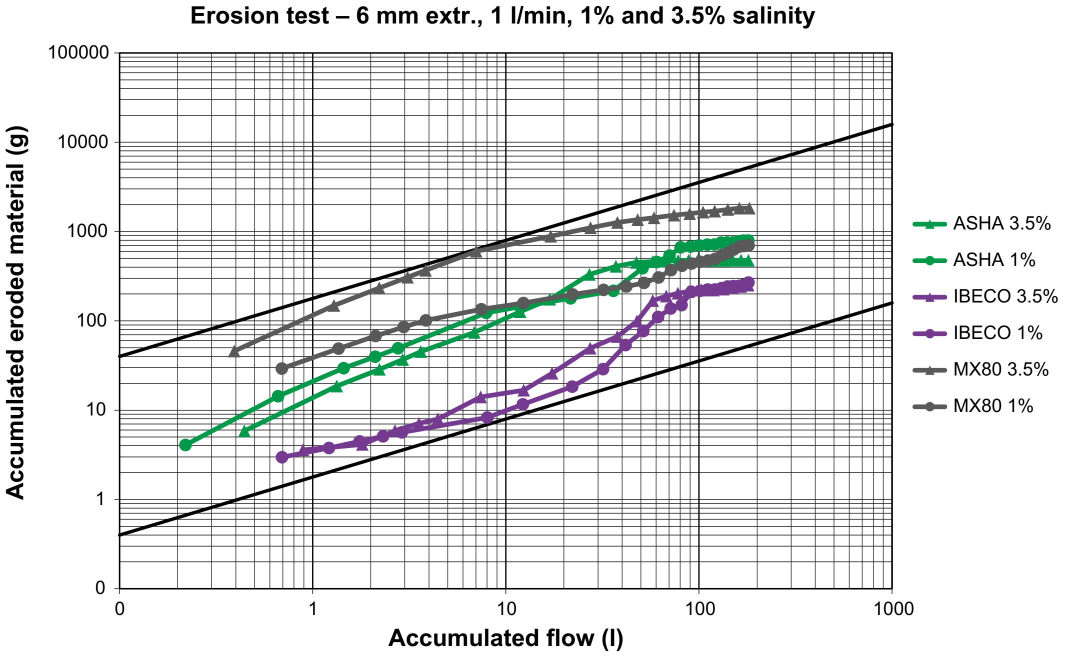

Figure 4-5. Comparison of 1% and 3.5% salinity at 1 l/min for the extruded 6 mm pellets. Only MX-80 seems to be affected by the increased water salinity.

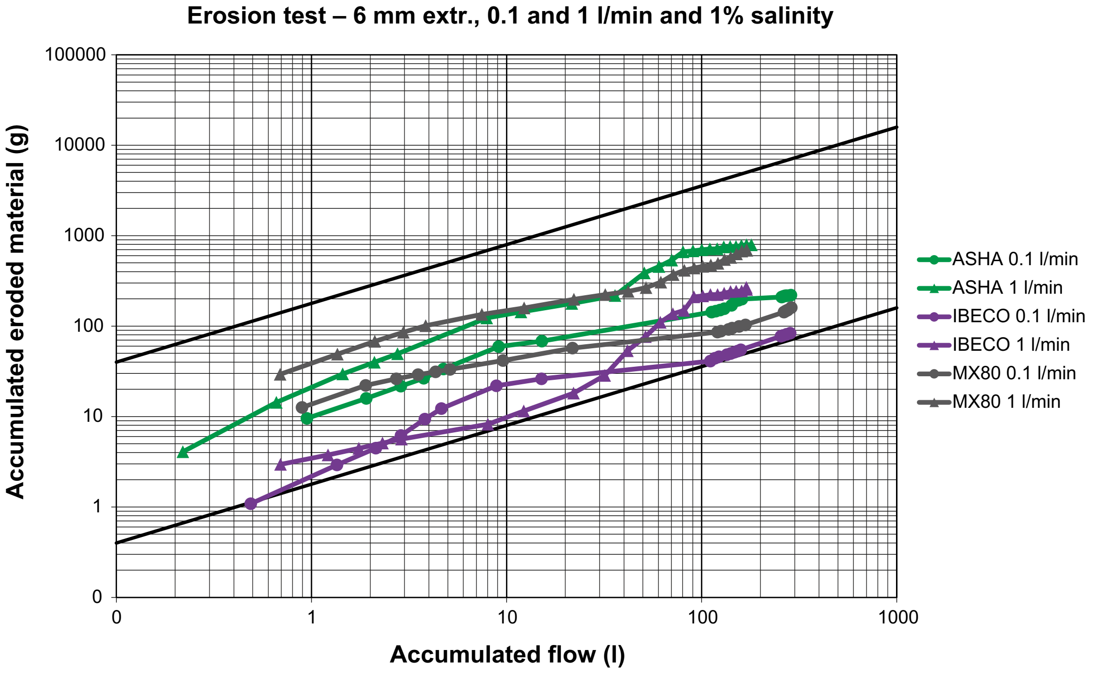

Figure 4-6. Comparison of 0.1 and 1 l/min flow at 1% salinity for 6 mm extruded pellets. Initially only ASHA and MX-80 seem to be influenced by the increased water flow rate. IBECO have a temporary increase in erosion at about 50 liters accumulated flow. By the end of the test there is no significant difference in the flow rate influence.

4.5 Discussion and conclusions

The erosion resistance of the various materials and products have been examined and can be summarized as follows:

- When comparing the ASHA pellet types it is clear that the extruded pellets have a higher resistance to erosion than the roller compacted materials.
- For the MX-80 pellet types the relation is the opposite but with less difference.
- The extruded 10 mm give less erosion than the 6 mm for both ASHA and IBECO.
- Posiva spec.-A compacted pillow has the lowest accumulated erosion while Posiva spec.-B compacted pillow has the third highest.
- For the Posiva spec.-pellets there seem to be a material influence, since the manufacturing method, shape and size is the same for the two pellets.

In general the test results indicate that the extruded 10 mm pellet type is the most resistant to erosion, followed by the 6 mm extruded.

The material type comparison indicates that IBECO is the least erosive. However it seems as IBECO have a tendency to temporarily increase the erosion rate after about 50–100 liters accumulated flow at 1 l/min flow rate. This temporary increase is most likely connected to the forming of a main flow channel. Figure 4-7 shows the forming of such a channel after about 80 minutes of 1 l/min flow rate, which corresponds to 80 liters accumulated inflow. The pictures are taken from the shorter erosion test (total of 180 liters accumulated inflow at 1.0 l/min flow rate, see Figure 4-4), which confirms this observation with a temporary increase of erosion. Figure 4-8 and Figure 4-9 show the flow channels in the 6 mm extruded ASHA and MX-80 pellets under the same test conditions. In both cases the channels are formed early and remain almost unchanged for the rest of the test. This early channel-forming could be the reason why ASHA and MX-80 have initially higher erosion rates than IBECO. This means that a significant part of the erosion could be induced by the actual forming of the channel and once the channel is stabilized the erosion rate decreases.

***Figure 4-7.** 6 mm extruded IBECO pellets at 1 l/min and 1% water salinity. In this test the flow channels are formed and stabilized after about 80 minutes, which corresponds to 80 liters accumulated flow.*

Figure 4-8. 6 mm extruded ASHA pellets at 1 l/min and 1% water salinity. A main flow channel is formed early and stays unchanged for the remainder of the test.

Figure 4-9. 6 mm extruded MX-80 pellets at 1 l/min and 1% water salinity. Several minor flow channels are formed early and stay unchanged for the remainder of the test.

Based on the results and the discussion above the erosion test conclusions are listed below:

- **Pellet type:** In general the extruded pellets are the most resistant to erosion. The 10 mm extruded seem somewhat better than the 6 mm extruded.
- **Material type:** The material type with the overall lowest erosion rate is IBECO.
- **Water salinity:** MX-80 is the only material which is clearly sensitive to water salinity changes.
- **Water flow rate:** No significant differences are observed for three tested material types.

In addition to this it should also be mentioned that almost all test results where within the limits of the model described by Sandén and Börgesson (2010) with exception of IBECO extruded 10 mm which was slightly below the expected erosion rate at the initial stage and the Posiva spec.-A sample where the accumulated erosion is less than the expected at the end of the test.

5 Water storing capacity tests, type I

5.1 General

The optimal water storing capacity properties of the pellet filling would be to slow the movement of the wetting front of the inflowing water as much as possible by taking up the inflowing water evenly over the entire pellet filling volume. In previous small-scale erosion tests some different phenomena affecting the water storing capacity have been observed (Sandén et al. 2008, Johannesson et al. 2010). These phenomena are e.g. the forming of flow channels and the buildup of water flow resistance that sometimes lead to complete sealing. Water flow resistance can be regarded as positive since it will decelerate the water front and force the flow in new directions, making the inflowing water utilize a larger part of the pellet filling volume. On the other hand total sealing of the pellet filling contributing to a clear water pocket is considered negative since the breaking of such a sealing would cause a high point flow. Also the forming of channels leading the water directly out through the pellet filling is obviously considered as negative.

The water pressure buildup in the pellet filling is influenced by many factors such as granule size distribution and void size, type of material, water salinity and water flow rate (Johannesson et al. 2010). The granule size distribution and the void size are connected to the manufacturing method (also referred to as pellet type), material type, as well as the as-placed state of the pellets. The test series described below is intended to identify which pellet type and material type is the superior in water storing capacity and also the most resistant to changes in water salinity and flow rate. The results of these tests will assist in making the test plan of the water storing capacity II tests.

5.2 Method

The concept of the test was to apply a constant flow rate to a pellet filling, observe the wetting behavior and log the resistance to water inflow (water pressure).

The test equipment consists of a Plexiglas tube (d = 0.1 m, L = 1.0 m) that was oriented vertically, see Figure 5-1. The total volume of the tube was 7.85 liters and the available void space (pellet internal voids excluded) in the tested pellet fillings was between 3.63 and 4.03 liters with an average value of 3.83 liters. The pellet filling in the tube was held in place by perforated steel plates, through which the flowing water could easily pass. The point inflow was placed at the center of the tube cross section at mid-level (0.5 m). A ruler was placed next to the tube for height reference. Results were documented through notes and photos at specific time intervals. The upper and lower water fronts were defined as the highest and lowest points where wetting could be detected visually on the tube surface. Sealing of the system was defined as the time at which the water front level ceased to advance or if the outflow stopped. A transducer was used to register the water pressure needed to maintain the defined inflow rate. The test was stopped when no more changes were observed, for example if the downward flow had sealed and the upward flow was running straight through the tube. The test was also stopped if sealing caused the water pressure to reach the pump capacity of 1 MPa.

5.3 Test matrix

Table 5-1 shows the test matrix for the water storing capacity, type I tests. Pellet type was compared for both 1% and 3.5% water salinity at 0.1 l/min flow. Material type was mainly compared for the extruded 6 mm pellets at 0.1 l/min flow and 1% salinity. The influence of the water flow rate and the water salinity was compared for all three materials using the 6 mm extruded pellet type. Finally some tests with water flow rates up to 1 l/min were done on the extruded 6 mm IBECO and ASHA pellets in order to determine if and at which flow rates stabile channels would be formed.

Figure 5-1. Arrangement for the water storing capacity type I tests. A point inflow was applied at mid-level. The inflow tube was led through the connector ending at the tube cross-section center in the middle of the pellet filling. The wetting of the pellet filling was visually surveyed and the water pressure logged by a transducer.

Table 5-1. The test matrix for the pellets water storing capacity type I tests.

Pellet type	Pellet name (material)	1% salinity					3.5% salinity	
		0.01 l/min	0.1 l/min	0.5 l/min	0.75 l/min	1 l/min	0.01 l/min	0.1 l/min
Comp. pillow	ASHA-11		X					X
Comp. almond	ASHA-12		X					
Extr. 6 mm	ASHA-13	X	X	X	X	X	X	X
Extr. 10 mm	ASHA-14		X					
Gran. 1–5 mm	ASHA-15		X					
Extr. 6 mm	IBECO-13	X	X	X	X	X	X	X
Extr. 10 mm	IBECO-14		X					
Comp. pillow	MX-80-11		X					X
Extr. 6 mm	MX-80-13	X	X				X	X

5.4 Results

5.4.1 General

A total of 26 tests have been performed with this test equipment. The results are not entirely consistent but are very indicative regarding the different pellet types wetting behavior. The results are presented so that the influence of different pellet types, the influence of different material, the influence of different water salinity and the influence of different water flow rates can be seen. The wetting fronts are marked with an orange line in the figures.

5.4.2 Influence of pellet type

In both Figure 5-2 and 5-3 we can see that the resistance to water inflow seems generally higher for the extruded pellets with a water flow rate of 0.1 l/min and a water salinity of 1% and 3.5%.

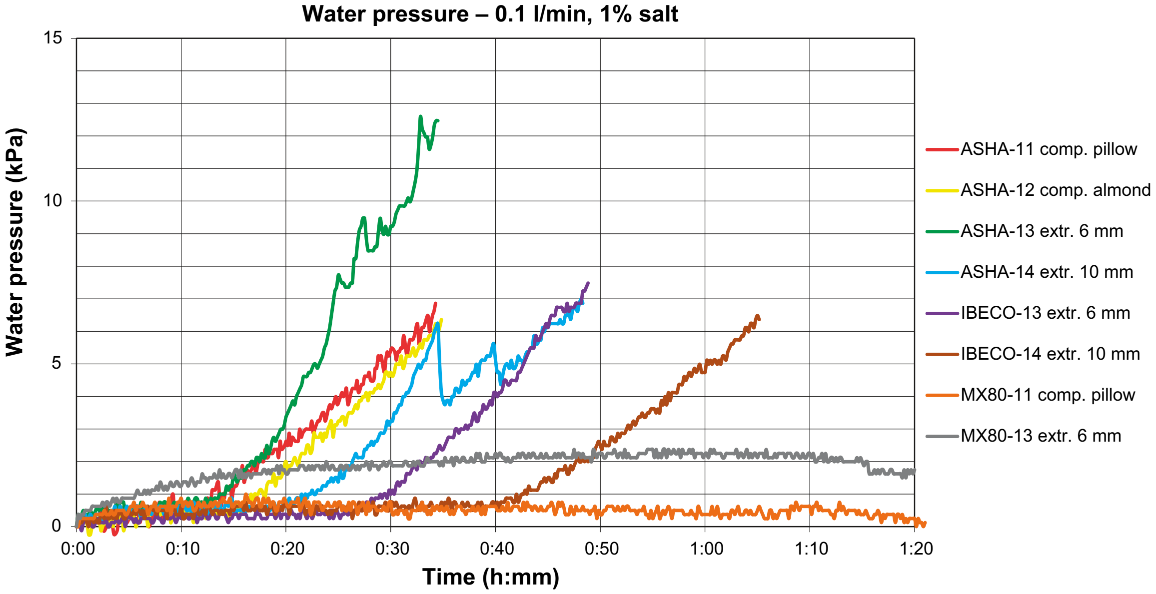

Figure 5-2. *Water pressure comparison at 0.1 l/min inflow and 1% salinity. The ASHA-15 granule values are excluded from the figure since the water pressure reached the maximum value of 1 MPa within 14 minutes.*

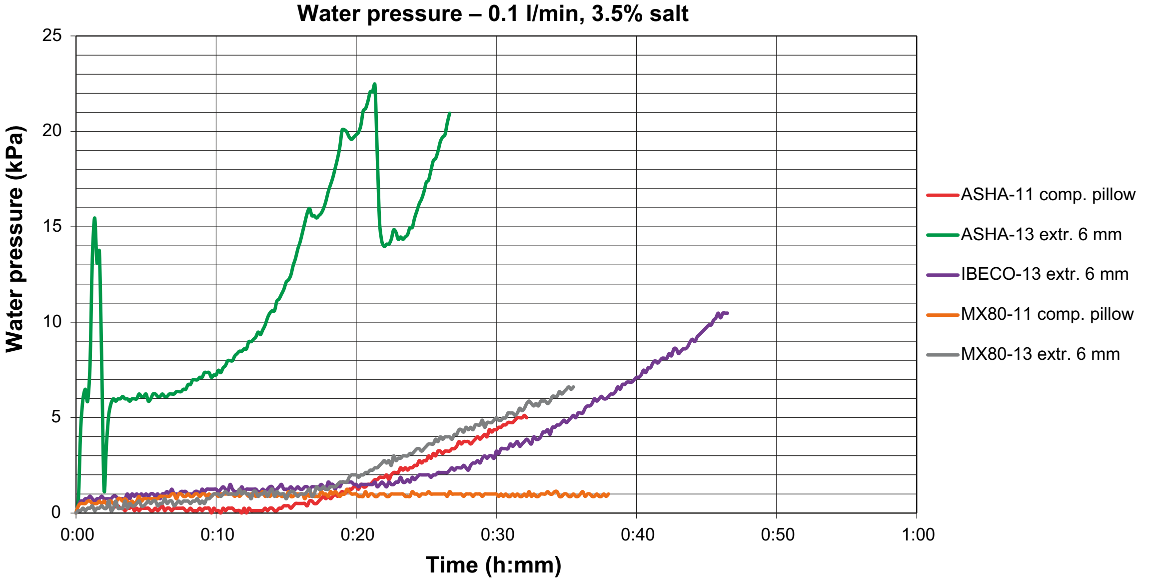

Figure 5-3. *Water pressure comparison at 0.1 l/min inflow and 3.5% salinity.*

The results for the ASHA-15 granules are excluded from the figure showing the behavior of the extruded and roller compacted pellets due to the extremely fast sealing of the system at the point of water inflow (Figure 5-4). Figure 5-4 also shows the formation of a clear water pocket in the ASHA-15 granules at 0.1 l/min and 1% salinity. The test was stopped when the water pressure reached the pump capacity of 1 MPa after about 14 minutes. The instant sealing is most likely related to the small grain size of 1–5 mm. Once this seal formed, the water accumulating in the gap acted as a hydraulic piston, compressing the materials above and below it and a corresponding increase in the size of the water-filled gap developed.

Further on Figure 5-5 and 5-6 displays the visible water front level heights plotted over time at 0.1 l/min flow and a salinity of 1% and 3.5% respectively. Eventual sealing of the water inflow occurred and the wetting to that time is marked with X in the figures. The black inclined lines show the water front progression if all the available void spaces would be used optimally for water storing and the entire flow would be in upward or downward direction respectively. In both Figure 5-5 and 5-6 it seems as the compacted pellets have a higher tendency to release the water flow downwards.

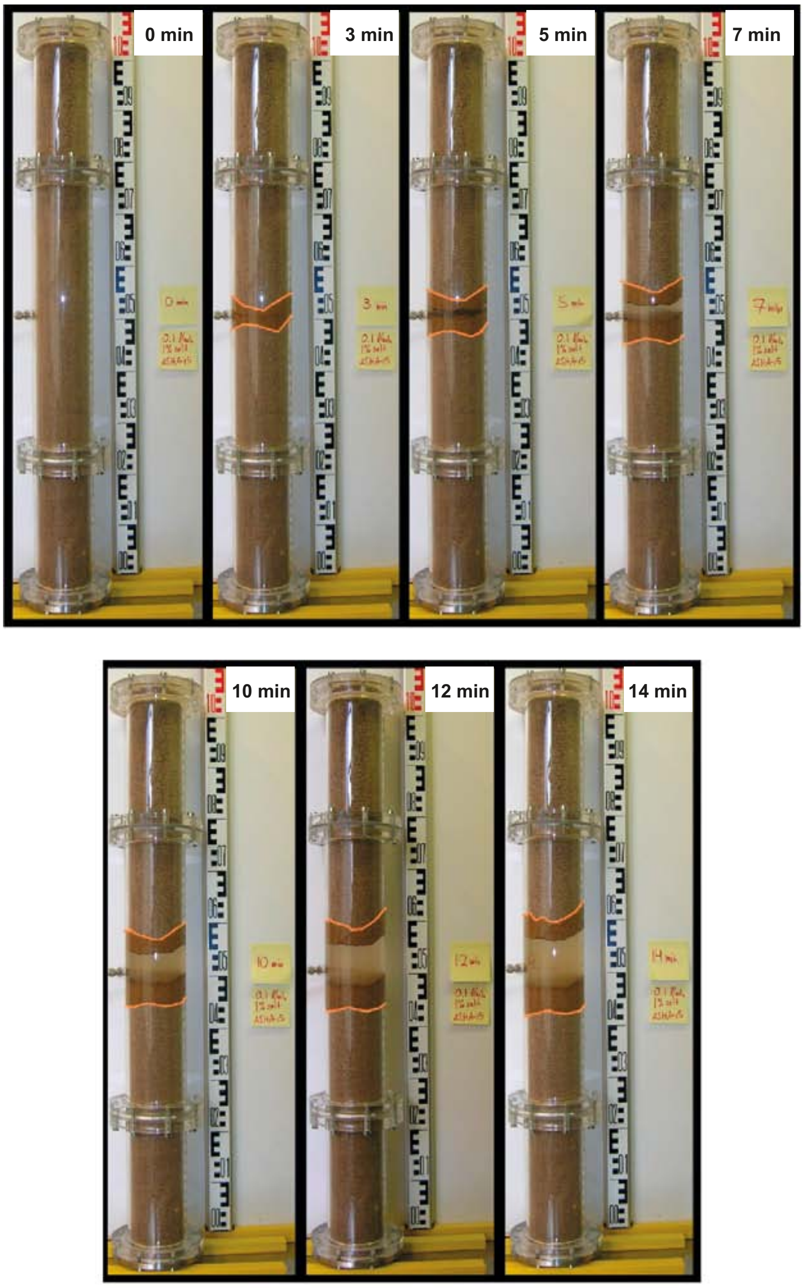

Figure 5-4. ASHA-15 granules sealed the water flow instantly and the pressure reached the pump capacity of 1 MPa within 14 minutes. A clear water pocket was formed at the inflow point.

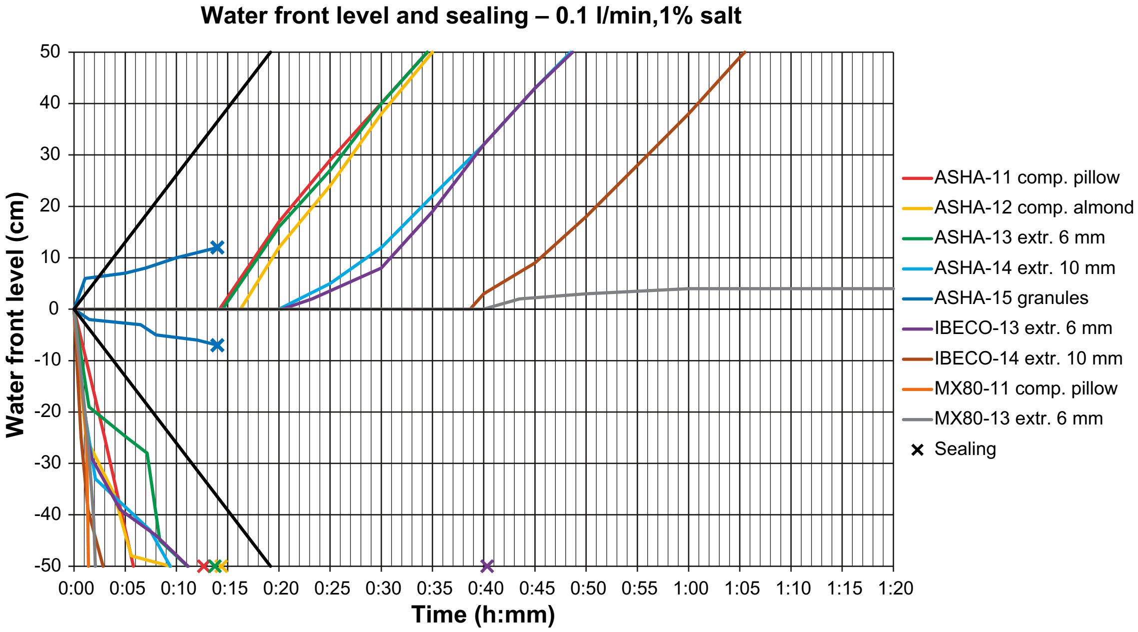

Figure 5-5. *Water front level height and sealing at 0.1 l/min and 1% water salinity. The Y-axis value displays the visible water front level in relation the inflow point. X marks the eventual sealing of the water flow. The black inclined lines show the theoretically fastest fill up of all the available void space if the entire flow would be in upward or downward direction respectively.*

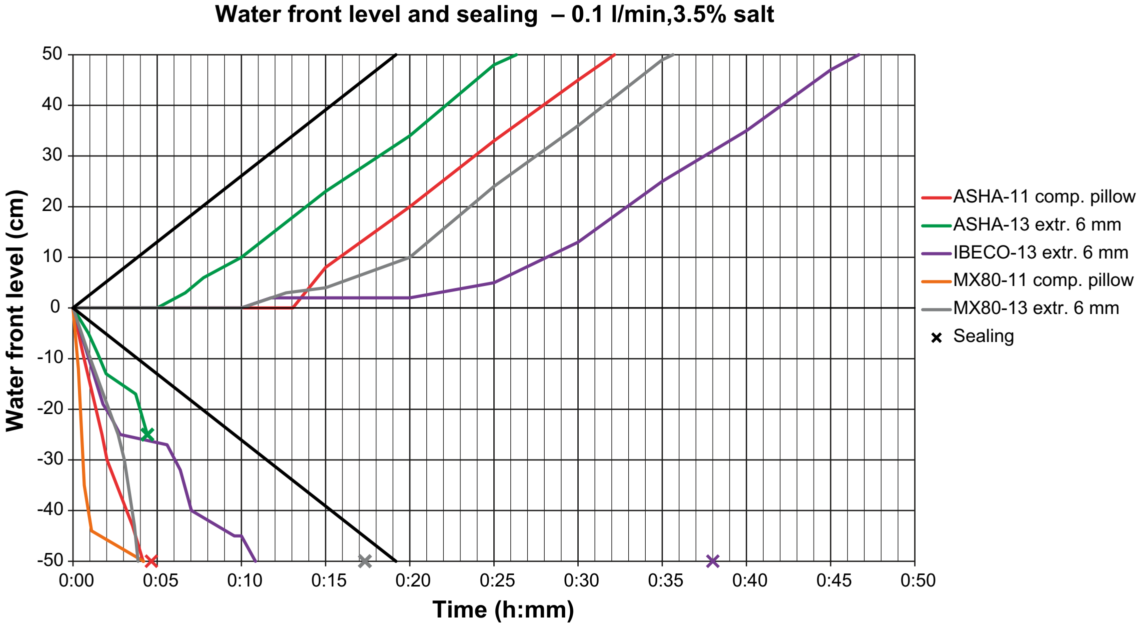

Figure 5-6. *Water front level height and sealing at 0.1 l/min and 3.5% water salinity. The Y-axis value is the visible water front level in relation the inflow point. X marks the time at which water front level ceases to advance due to clay sealing. If the water front level already has reached the outlet X marks clay sealing of the outflow. The black inclined lines show the theoretically fastest water filling rate for all the available void space if the entire flow moved upwards or downwards.*

Also the movement of the wetting fronts in Figure 5-5 are slower for the 6 mm extruded than the 10 mm extruded for both the IBECO and the ASHA materials. In both Figure 5-5 and 5-6 it is seen that the upwards movement of the wetting front occurs at the same rate as the optimal water front progression (the black inclined lines), once a sealing of the downward flow has occurred.

Figure 5-7 shows a comparison of extruded and compacted pellets for 0.1 l/min flow and 1% salinity after 30 minutes. Figure 5-8 shows compacted and extruded MX-80 after 45 minutes at the same conditions. For the pellets made from ASHA clay, the extruded seem to have a somewhat more evenly distributed wetting. For MX-80 the roller-compacted pellets have a more evenly distributed wetting, but after 45 minutes this wetting pattern had reversed (Figure 5-8). Both the extruded and the roller-compacted MX-80-11 pellets have a direct downward flow with no upward wetting of the pellet filling (Figure 5-5 and 5-8).

ASHA-11 ASHA-12 MX80-11

Compacted

ASHA-13 ASHA-14 IBECO-13 IBECO-14 MX80-13

Extruded

Figure 5-7. *Comparison of compacted and extruded pellets at 0.1 l/min flow and 1% salinity after 30 minutes.*

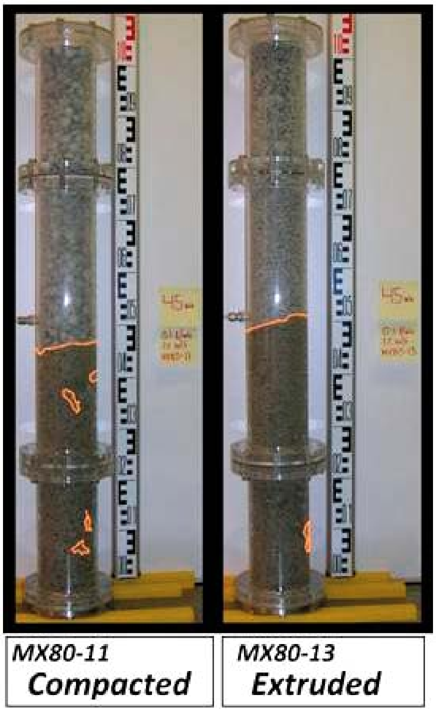

Figure 5-8. *Comparison of extruded and compacted MX-80 at 0.1 l/min flow and 1% salinity after 45 minutes of water inflow.*

In Figure 5-9 extruded and compacted pellets are compared at 0.1 l/min flow and 3.5% salinity after 25 min. It seems that the wetting is slightly more evenly distributed for the extruded pellets. However the ASHA-13 has a total sealing at height –25 cm from the inflow point, which makes part of the pellet filling's void volume unusable for water storage, see Figure 5-6 and 5-9).

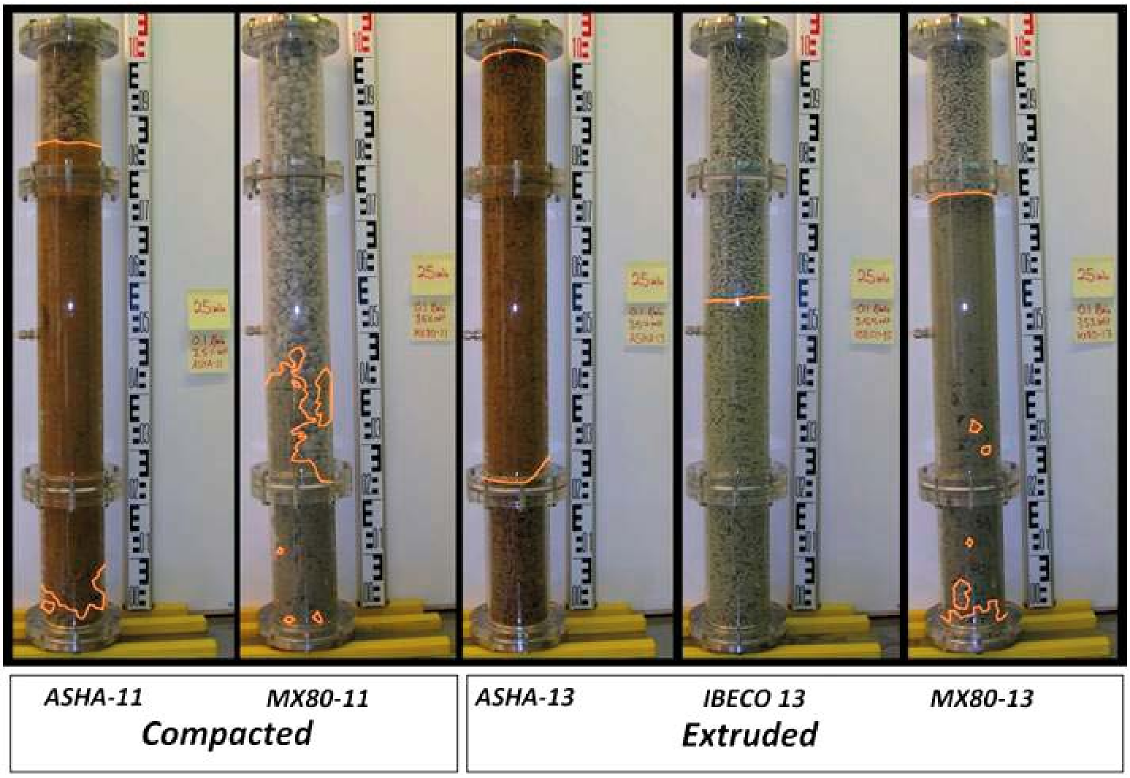

Figure 5-9. *Comparison of extruded and compacted pellets at 0.1 l/min flow and 3.5% salinity after 25 minutes of water inflow.*

5.4.3 Influence of material type

In Figure 5-5 and 5-6 it was shown that with the exception of one test (extruded 6 mm tested at 0.1 l/min flow and 3.5% salinity), pellet fill produced from MX-80 tend to allow water to move downwards with the influence of gravity. In Figure 5-5 and 5-6 it was also shown that the ASHA pellets have a tendency to swell and quickly seal off water movement in the downward direction. For the IBECO material downward sealing only occurs after the full pellet filling volume below the inflow point is wetted. At this time upwards water movement through the fill continues until the entire pellet filling is wetted.

Figure 5-10, 5-11 and 5-12 shows the initial wetting patterns of the three material types for the 6 mm extruded pellets at 0.1 l/min flow and 1% salinity. ASHA-13 seals the flow completely downwards after about 13 minutes and a part of the pellet filling lower volume is left dry (Figure 5-5 and 5-10). After about 35 minutes the water front has reached the top and all outflow occurs from the top of the cell (Figure 5-5 and 5-10).

IBECO-13 has a somewhat more even wetting behavior and a low, gradually decreasing outflow until it finally seals in the bottom after about 40 minutes (Figure 5-5 and 5-11). After 50 minutes the entire pellet filling volume is wet and all outflow occurs from the top (Figure 5-5 and 5-11).

MX-80-13 divides the water poorly over the pellet filling volume; no wetting at all occurs upwards, the downward wetting is very slow and most water seems to pass straight through the pellet filling (Figure 5-5 and 5-12). No further changes in the wetting are observed from 50 minutes and the test is stopped after 80 minutes.

5.4.4 Influence of water salinity

The impact of variations in water salinity was compared for 6 mm extruded pellets. Figure 5-13 compares water front levels for 1% and 3.5% salinity at 0.1 l/min flow. Figure 5-14 compares wetting behavior for 1% and 3.5% salinity at 0.1 l/min flow after 30 minutes (with exception of ASHA 3.5% salinity which was stopped at 26 minutes). For MX-80 with 1% salinity the flow is straight downwards and no upward wetting is observed, but at 3.5% salinity the pellet filling seals after about 17 minutes and the final outflow is upwards. ASHA is not as affected as MX-80 but seem to seal earlier when the water salinity is increased. For IBECO no impact is seen from the change in water salinity at 0.1 l/min flow.

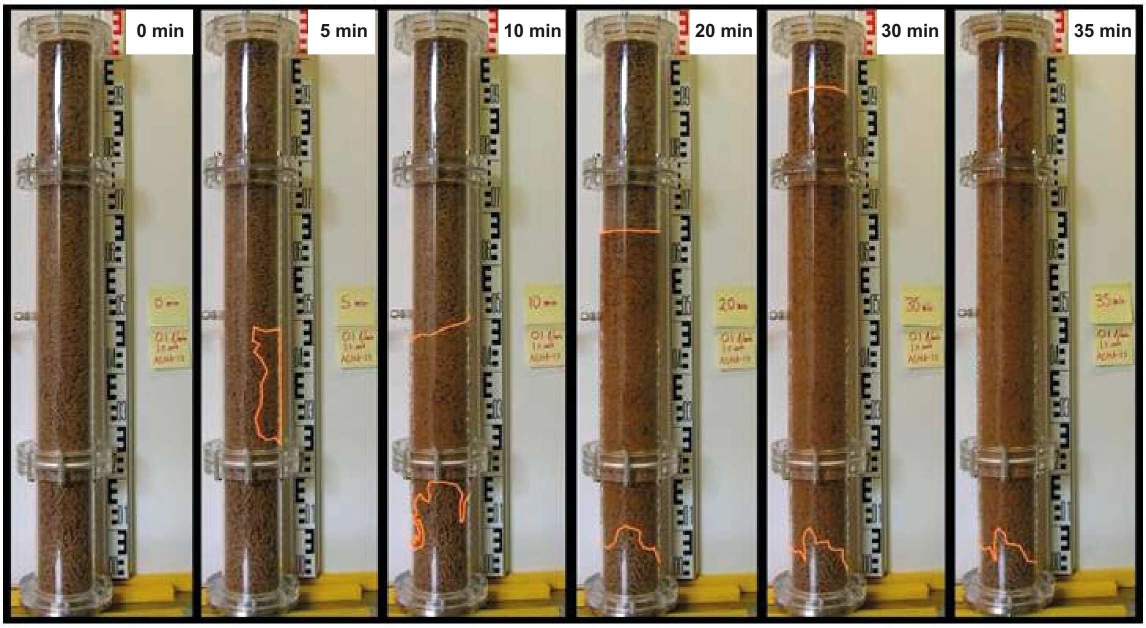

Figure 5-10. *ASHA-13 6 mm extruded at 0.1 l/min flow and 1% salinity. The wetting is initially downwards until sealing occurs after about 13 minutes. After 35 minutes the water front has reached the top and a full outflow occurs upwards.*

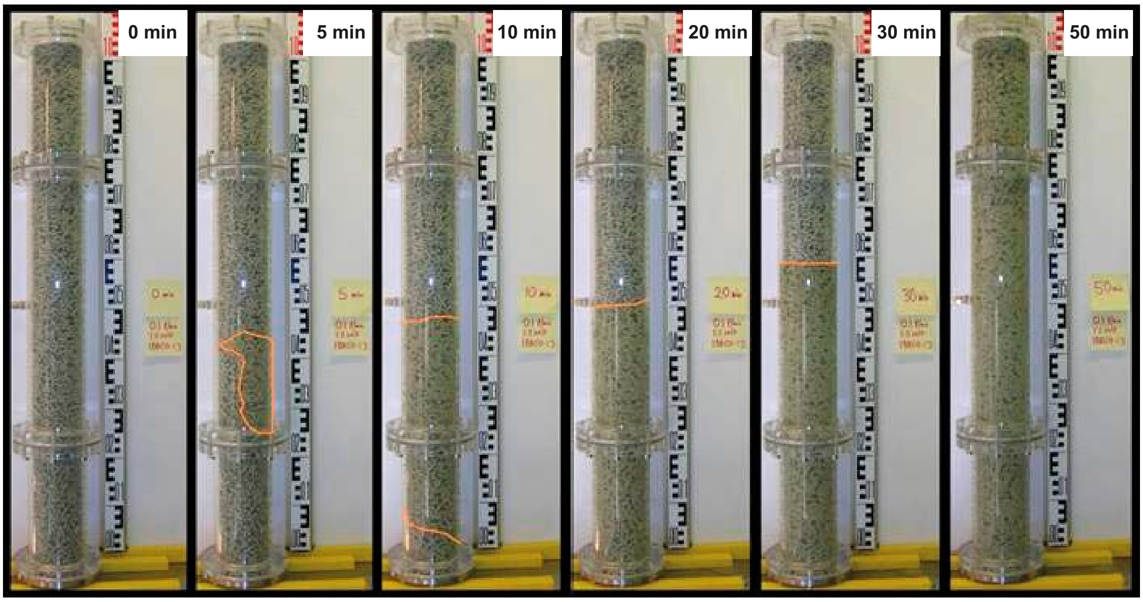

Figure 5-11. IBECO-13 6 mm extruded at 0.1 l/min flow and 1% salinity. The wetting is initially downwards and very even. After about 40 minutes the flow has sealed downwards and by 50 minutes the entire pellet filling volume is wetted and full outflow occurs upwards.

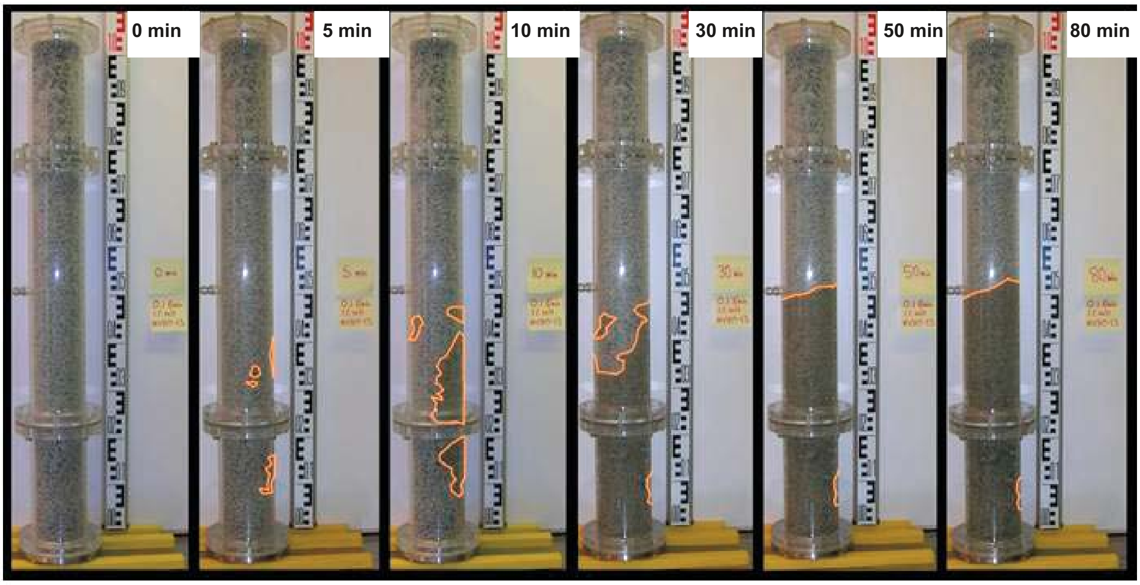

Figure 5-12. MX-80-13 6 mm extruded at 0.1 l/min and 1% salinity. The wetting of the pellet filling is poor and the water flow seems to form channels early. No further changes are seen after 50 minutes and the test is stopped at 80 minutes.

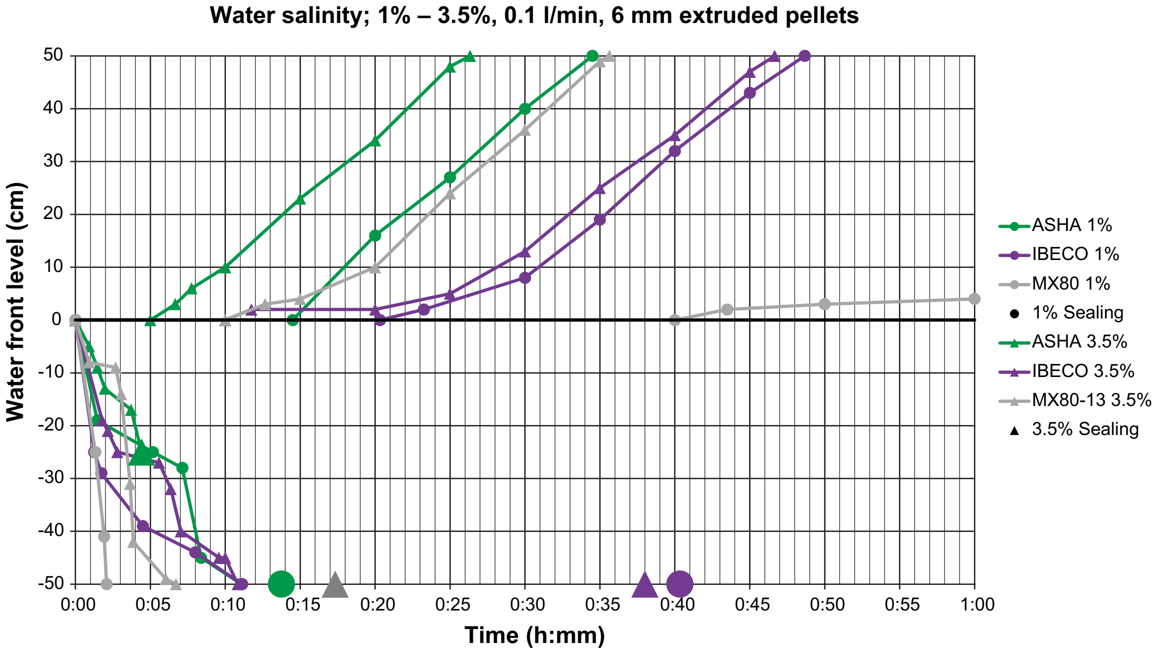

Figure 5-13. Comparison of water front levels and sealing at 0.1 l/min for 1% and 3.5% salinity for 6 mm extruded pellets.

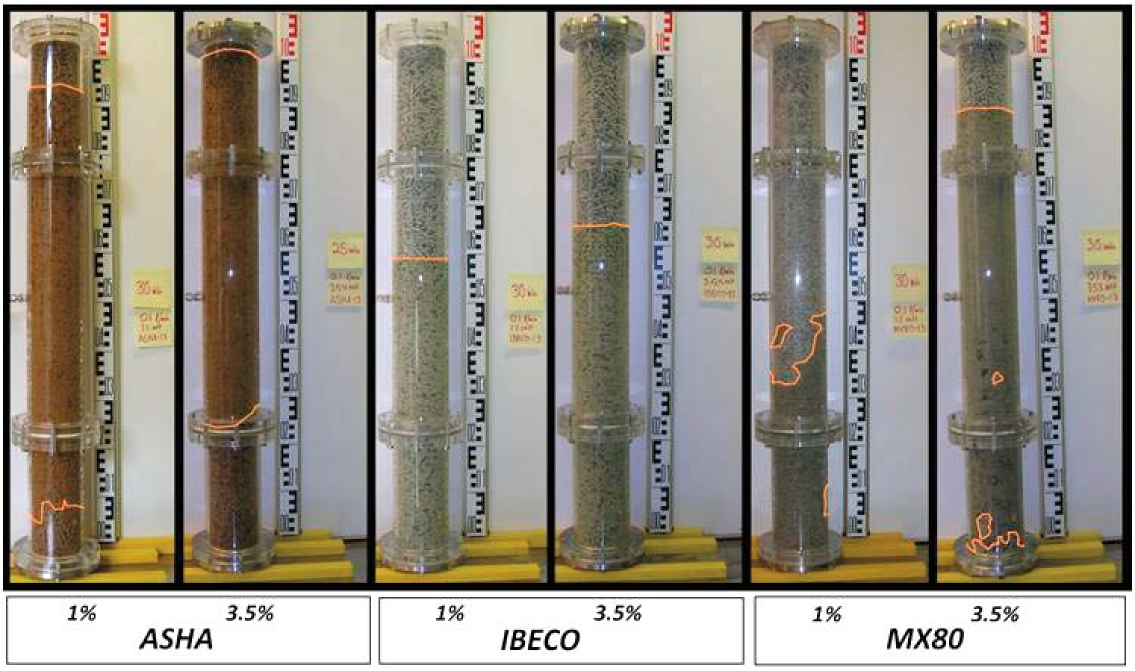

Figure 5-14. Comparison of 6 mm extruded pellets for 1% and 3.5% water salinity. Water flow rate is 0.1 l/min and pictures are taken at 30 minutes. Note that the ASHA 3.5% photo is taken at 25 minutes since the test was stopped before 30 minutes was reached.

Figure 5-15 compares water front levels for 1% and 3.5% salinity at 0.01 l/min flow. Figure 5-16 compares wetting behavior for 1% and 3.5% salinity at 0.01 l/min flow after 5 hours. All three materials have quite symmetrical wetting behavior for both salinities. The ASHA-material has sealed more slowly in the region below the inlet port and earlier above the inlet port when the water salinity was increased. IBECO goes from a quite early downward sealing for the 1% salinity to having no sealing at all for the 3.5% salinity. MX-80 has only downward sealing for the 1% salinity, but for 3.5% there is a complete sealing, with formation of a water pocket at the location of the inlet port after about 6 hours (Figure 5-16).

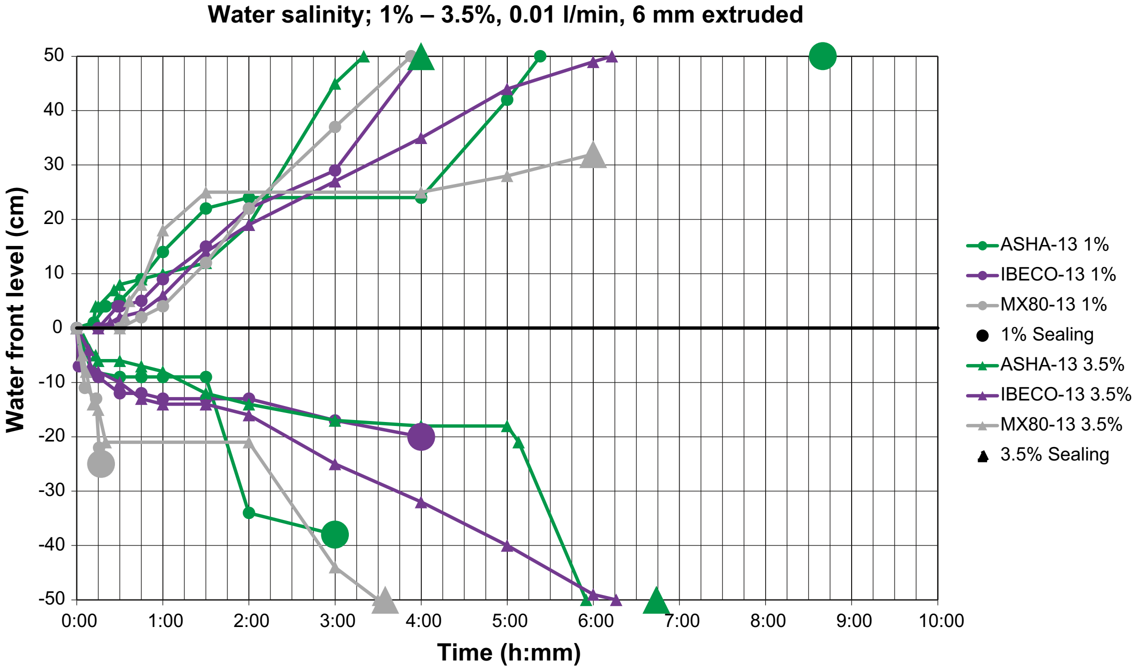

Figure 5-15. *Comparison of water front level and sealing at 0.01 l/min for 1% and 3.5% salinity for 6 mm extruded pellets.*

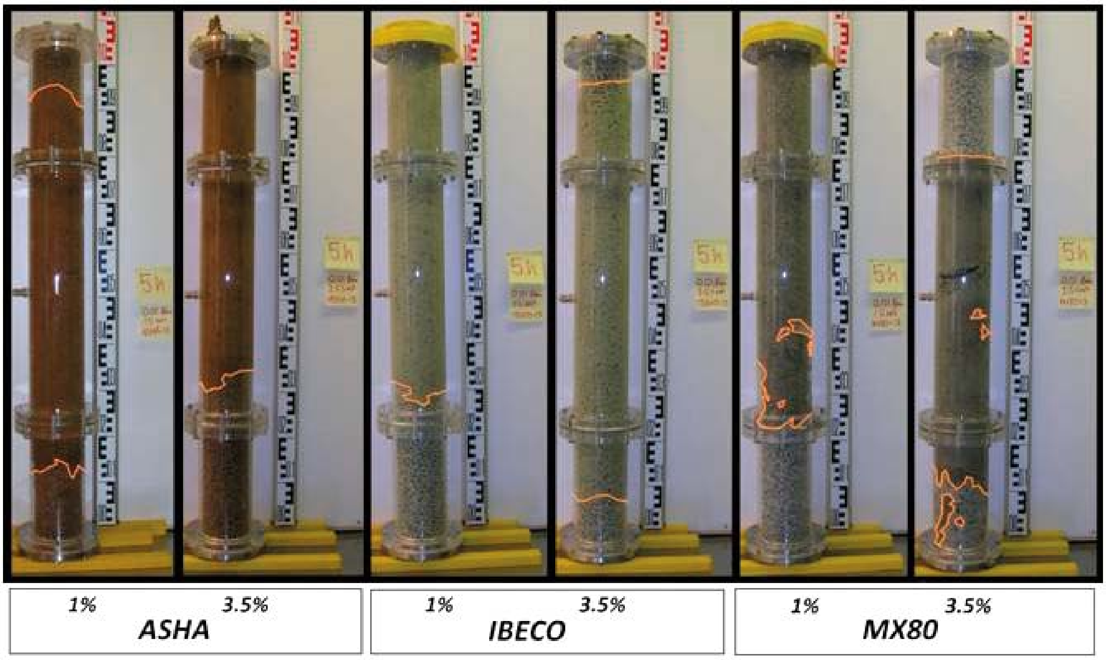

Figure 5-16. *Comparison of 6 mm extruded pellets for 1% and 3.5% water salinity. Water flow is 0.1 l/min and pictures are taken after 5 hours. The initial stage in the forming of a clear water pocket is seen for MX-80 3.5%.*

5.4.5 Influence of water inflow rate

The influence of water inflow rate was compared for extruded 6 mm pellets. Figure 5-17 shows water front level, sealing and accumulated flow at 0.1 and 0.01 l/min flow and 1% salinity (note that the x-axis now shows accumulated inflow and not elapsed time as in the previous figures). Figure 5-18 compares wetting behavior for 0.1 and 0.01 l/min at 3 liters accumulated flow and 1% salinity. MX-80 seems to be most sensitive to changes in water inflow rate. In Figure 5-17 it is seen that the water goes straight down and there is no wetting in the upwards direction at 0.1 l/min.

If the inflow rate is decreased to 0.01 l/min there is a downward sealing very early and the water goes upwards instead. In Figure 5-18 the difference in wetting behavior is very clear for MX-80. IBECO is less affected than MX-80 but still has some changes in behavior with an earlier sealing when the water inflow rate is decreased (Figure 5-17). ASHA does not seem to be very affected by the water inflow rate when comparing the water front plots in Figure 5-17 and the wetting behavior in Figure 5-18. However it is shown in Figure 5-17 that ASHA has a complete sealing in both ends when the water inflow rate is lowered.

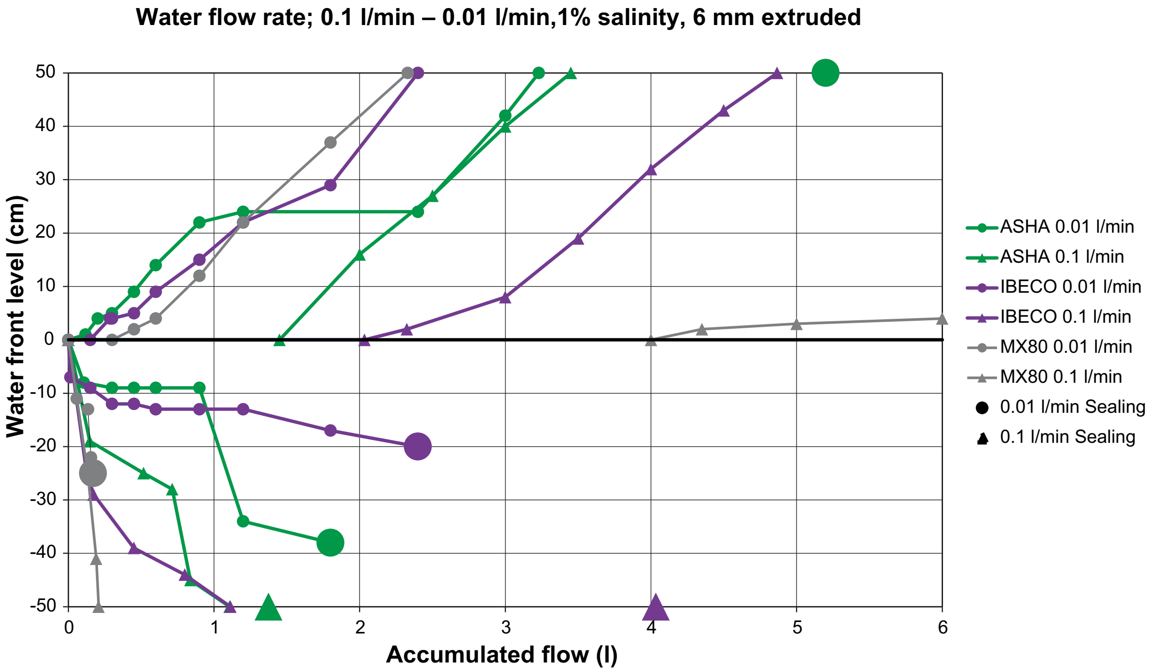

Figure 5-17. Comparison of water front levels and sealing for 0.1 and 0.01 l/min at 1% salinity for 6 mm extruded pellets. Note that the x-axis show accumulated inflow.

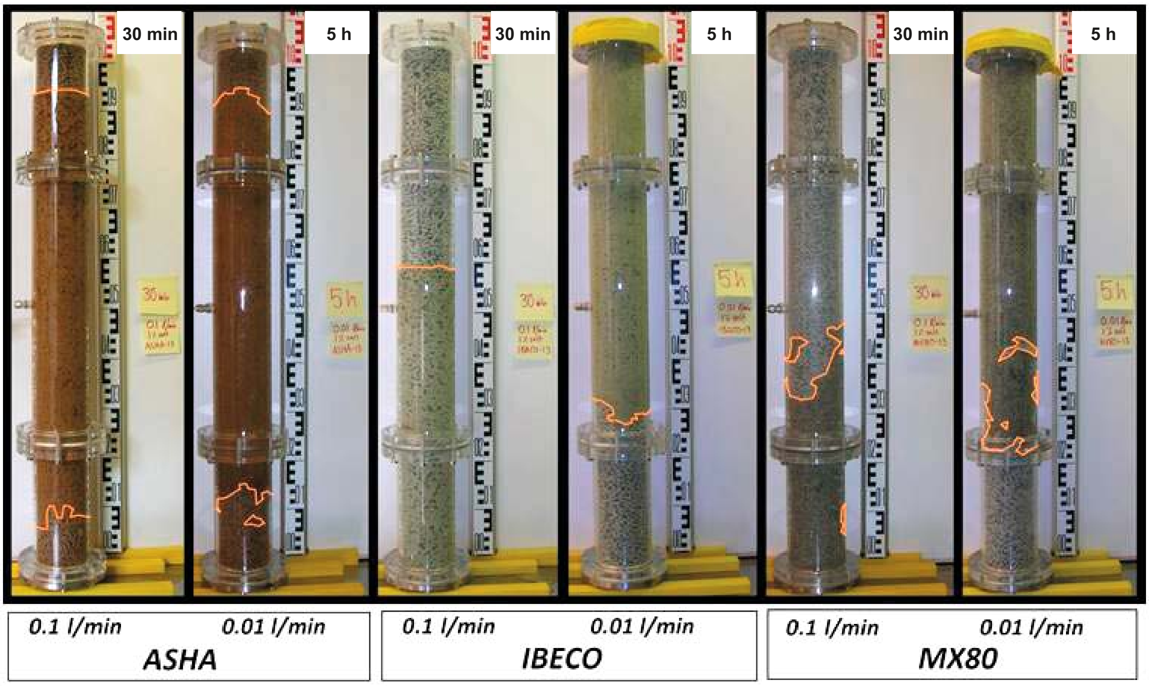

Figure 5-18. Comparison of the wetting behavior at 0.1 and 0.01 l/min with 1% salinity for 6 mm extruded pellets. All pictures are taken at 3 liters accumulated flow.

Figure 5-19 shows wetting front position and accumulated inflow at 0.1 and 0.01 l/min flow rates and 3.5% salinity (note that the x-axis shows accumulated inflow and not elapsed time as in the previous figures). Figure 5-20 compares wetting behavior for 0.1 and 0.01 l/min at 3 liters accumulated inflow and 3.5% salinity.

In Figure 5-19 it is shown that sealing for MX-80 occurs only in the lower half of the column after about 1.7 liters accumulated flow at the 0.1 l/min flow rate. When the inflow rate is lowered to 0.01 l/min there is a complete sealing in both directions and a clear water pocket is formed at about 3.5 liters accumulated flow.

ASHA shows the same behavior but has earlier downward sealing at –25 cm water front level by the time 0.5 liters of inflow had occurred at 0.1 l/min inflow. When the inflow rate is lowered to 0.01 l/min the sealing of the lower half of the pellet mass occurs later (Figure 5-19) but the downwards movement of the wetting front is much less extensive (Figure 5-20). There is finally a complete sealing at about 4 liters accumulated flow. However there is no forming of a water pocket and instead the pellet filling is homogenized and extruded through the upper end of the tube, as seen in Figure 5-20.

Figure 5-19 shows that IBECO seems to be the least affected by inflow rate change at 3.5% salinity with no sealing occurring at all. In Figure 5-20 it is also seen that the IBECO pellet filling volume is uniformly wetted with no areas having pockets of dry material.

Figure 5-21 and 5-22 shows the water front plots from the additional tests performed with higher inflow rates and 1% salinity with ASHA and IBECO. Figure 5-23 show the wetting behavior at the highest flow, 1 l/min and 1% salinity. These additional tests intended to determine the inflow rates that would give a direct downward flow with no upward wetting. The behavior for the two materials were very similar; an increase of the water flow rate caused a more direct downward outflow initially and also a delay in the start of upwards water movement. However, no channels were observed and eventually the upper pellet filling volume also saturated, even at the highest inflow rate allowed by the pump. The main difference between the results obtained was that it takes more than twice the accumulated inflow to achieve full wetting of IBECO. At higher inflow rates IBECO also exhibits an earlier outflow than ASHA.

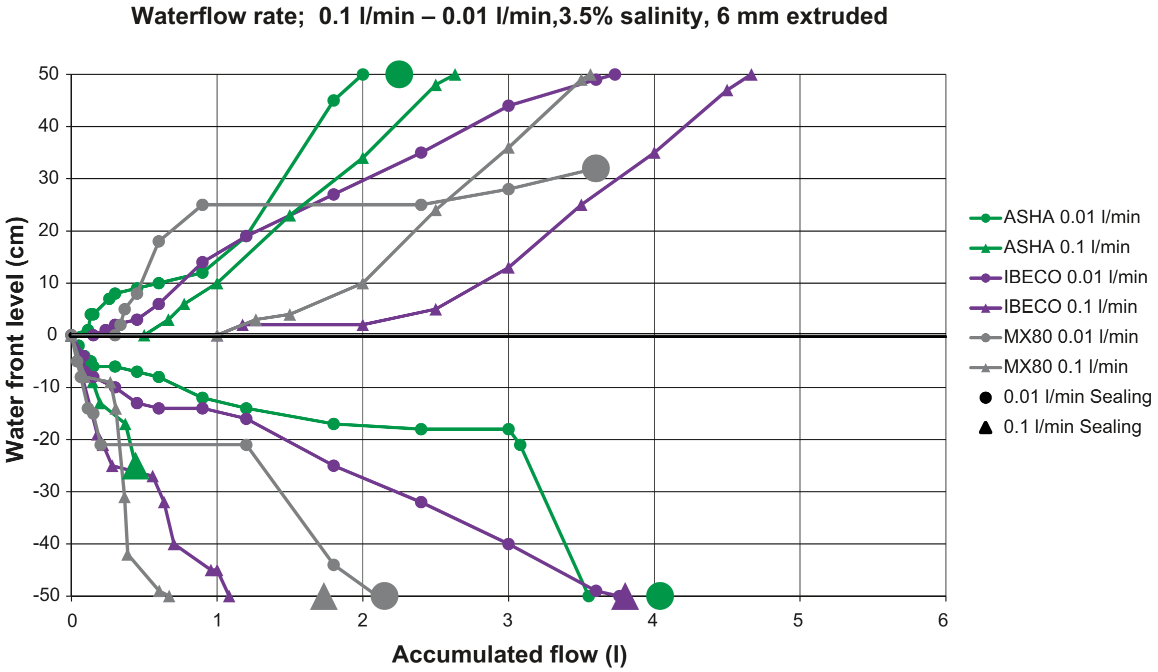

Figure 5-19. *Comparison of water front levels and sealing for 0.1 and 0.01 l/min at 3.5% salinity for 6 mm extruded pellets. Note that the x-axis shows accumulated flow.*

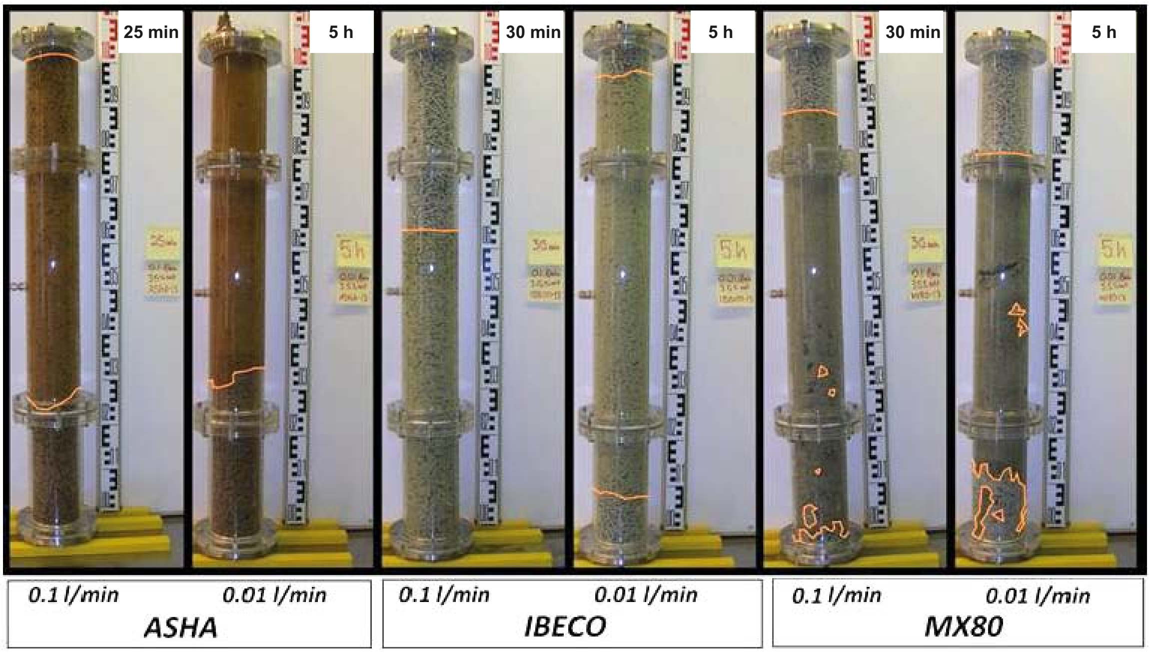

Figure 5-20. *Comparison of the wetting behavior at 0.1 and 0.01 l/min with 3.5% salinity for 6 mm extruded pellets. All pictures are taken at 3 liters accumulated flow, with exception of ASHA at 0.1 l/min which was stopped after 25 minutes (2.5 liters accumulated flow).*

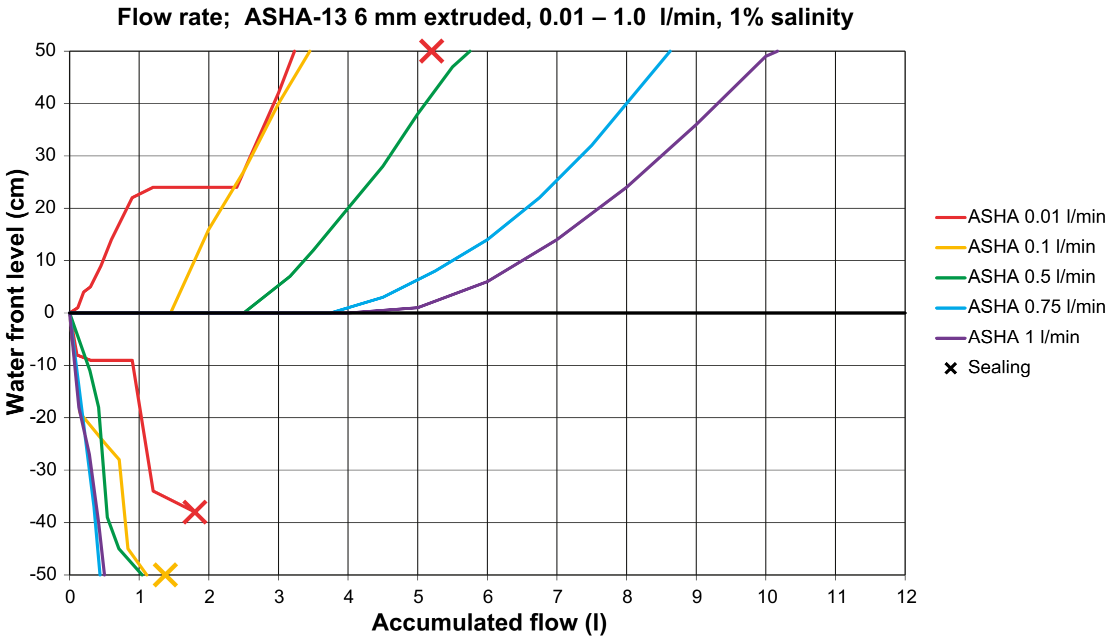

Figure 5-21. *ASHA 6 mm extruded pellets water front plot with 1% salinity and flow variation from 0.01–1.0 l/min. These additional tests were done in order to detect at what flow rate a direct downward channel is formed. The entire pellet filling volume was wetted at all flow rates and no channels were observed.*

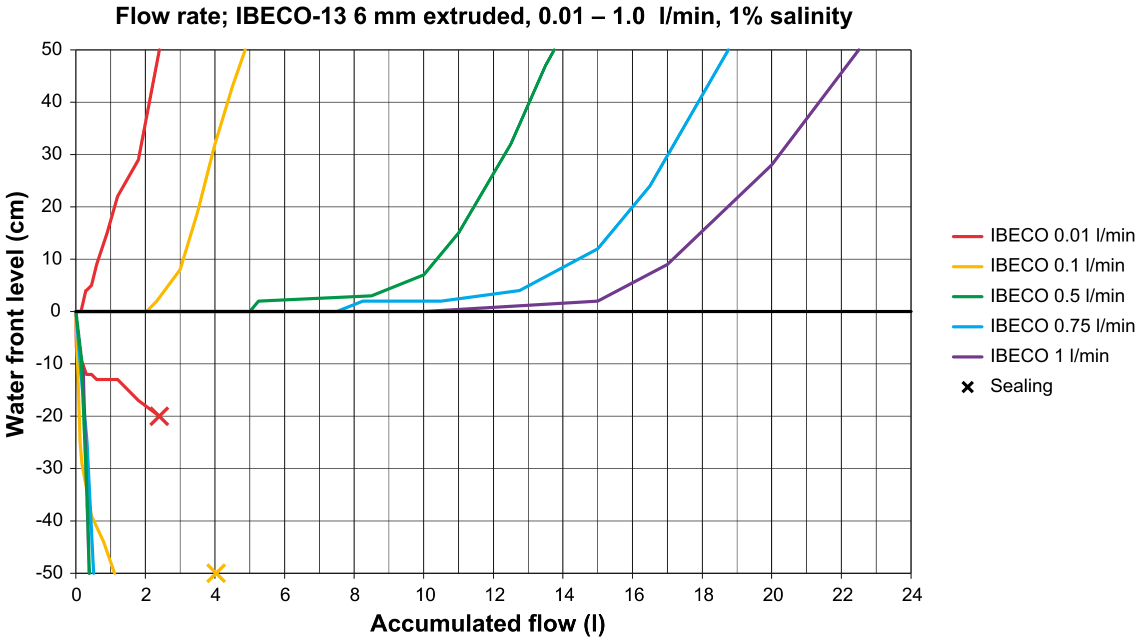

Figure 5-22. *IBECO 6 mm extruded pellets water front plot with 1% salinity and flow variation from 0.01–1.0 l/min. These additional tests were done in order to detect at what flow rate a direct downward channel is formed. The entire pellet filling volume was wetted at all flow rates and no channels were observed.*

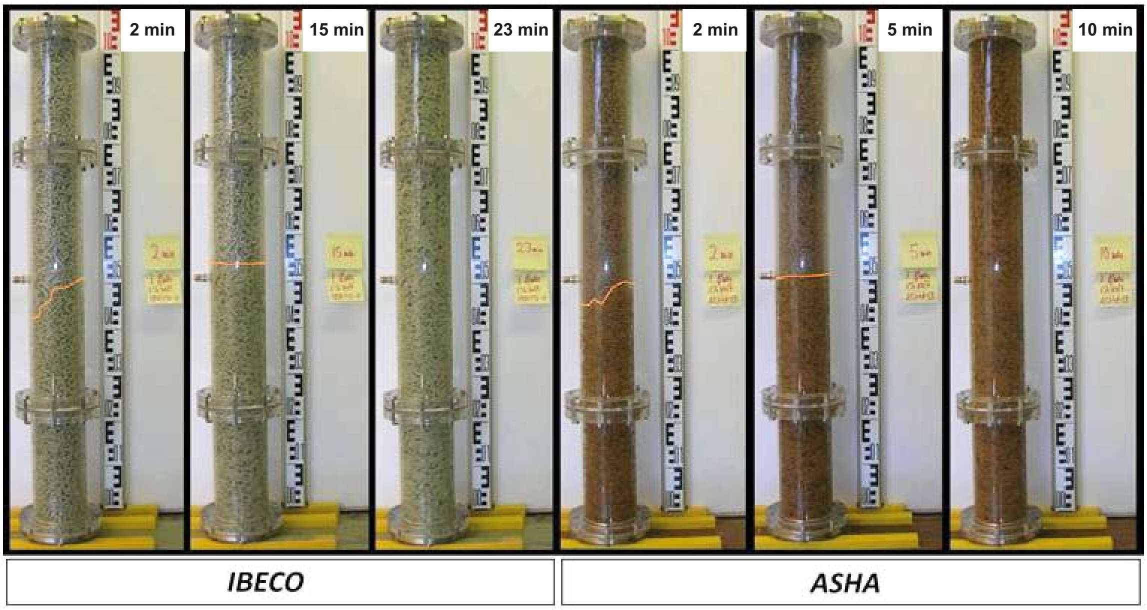

Figure 5-23. *Comparison of the wetting behavior at 1 l/min flow and 1% salinity for 6 mm extruded IBECO and ASHA. Both materials seem to have a complete wetting of the pellet filling volume, even though IBECO requires more than twice the accumulated flow.*

5.5 Discussion and conclusions

In general, the extruded pellets seem to allow for a more evenly distributed wetting than the roller-compacted materials. Also the water pressure measurements indicate that the inflow resistance is higher for the extruded pellets, which may result in a slower progression of the wetting front in the period immediately following pellet placement. The compacted pellets seem to be more liable to a direct downward outflow during the initial wetting period, which may also indicate that channels are more likely to be formed. It is suggested that this direct outflow tendency is connected to the larger void sizes in a pellet filling of compacted pellets; the compacted pellets are also large in size and therefore the void spaces between pellets are larger. When comparing the two extruded pellets sizes the 6 mm seemed to slow the initial progression of the water front slightly better than the 10 mm.

When comparing the material types MX-80 seem to form downward leading flow channels very quickly, allowing the water to move directly out of the fill. ASHA shows some tendencies to seal early, even before the water front reaches the outlet in these tests. Both these phenomenon are considered negative since the effect is that the pellet filling does not use its entire volume to store water, but the direct outflow is regarded as the worst case. In general IBECO tends to get a somewhat earlier downward outflow than ASHA, but IBECO clay is the only material whose pellets allowed the entire pellet filling's void volume to be flooded.

The influence of water salinity is strongest on MX-80, which completely changes its wetting behavior when the salinity is changed. For example at 0.1 l/min MX-80 goes from a direct downward outflow and no upward wetting to early complete downward sealing and full upward outflow when the salinity is increased. MX-80 is therefore considered the material most sensitive to changes in water salinity. It is harder to evaluate the water salinity influence on ASHA and IBECO, but the latter seem somewhat less affected having slightly more similar water front plots for the different salinities.

MX-80 is also the most sensitive material to changes in water flow rate. At 1% salinity and 0.01 l/min inflow rate there is a downward sealing early, but when the flow rate is increased to 0.1 l/min there is a direct downward outflow, probably due to channel forming. The additional tests with higher inflow rates on IBECO and ASHA showed no actual channel forming. However it was seen that IBECO is much less capable of slowing movement of the wetting front at higher flow rates and more than twice the accumulated flow was required to achieve full wetting of the pellet filling.

Based on the results and the discussion above the conclusions from the water storing capacity type I test are listed below:

- **Pellet type:** The 6 mm extruded seem to be the best pellet type for water storing capacity.
- **Material type:** IBECO or ASHA seem to be the best material type. Overall IBECO has the most even wetting behavior but ASHA seem to decelerate the water front better.
- **Water salinity:** IBECO seem to be the material with least impact from water salinity changes.
- **Water flow rate:** IBECO and ASHA are considered equal to changes in the water flow rate. At higher flow rates ASHA is superior in decelerating the water front and at lower flow rates IBECO has a more even wetting behavior.

Worth mentioning is that the geometry of the confinement could influence the test outcome. When the entire cross section of the tube is wetted the possible directions of the water front are limited to upwards and downwards. This could possibly be a factor that induces complete sealing of the pellet filling and also affects the tendency to a direct downward outflow. It is therefore of importance to further evaluate these phenomena in other test geometries (water storing capacity tests type II) where a large slot is used and the geometry of the confinement is much more similar to the actual backfill tunnel scenario, see next chapter.

6 Water storing capacity tests, type II

6.1 General

The basic idea of the water storing capacity tests are described in Chapter 5.1. In order to further investigate the water storing capacity of the pellet filling, a number of tests were performed with materials selected from those examined in the previously completed type I water storing capacity tests. The type II tests aim to test the pellet filling in an artificial slot, more closely simulating the geometry that will occur in between the backfill blocks and the rock wall in a full scale deposition drift.

6.2 Method

A simulated pellet-filled slot with a point inflow was used to observe the pellet filling's wetting behavior and the inflow-outflow linkage. Figure 6-1 shows the simulated slot consisting of two Plexiglas walls fixed on a steel frame. The slot dimensions were 1.0×2.0×0.1 meters. The total volume of pellet filling in the slot is estimated to about 110 liters. In the tests a constant water flow was applied in a point placed 0.3 meters from the slot side at 0.5 meters height. The water pressure (resistance to water inflow), that was built up, if any, was registered during the test time. The outflow of the slot was at the bottom of the right side in Figure 6-1. A ruler was placed next to the inflow point for height reference. Results were documented through notes and photos at specific time intervals. The outflow was determined by weighing all exiting water/clay material and subtracting the eroded material. The erosion was estimated by determining the mass of the sediments in the sampling vessel, using the same evaporation method as in the erosion tests (Chapter 4.2.). Water pressure was logged every minute by a transducer. The tests were run to an accumulated flow of about 105 liters.

Figure 6-1. The slot used for the water storing capacity 2 tests. A point inflow was applied to the pellet filling in the slot at mid height. The wetting behavior, the inflow-outflow linkage and the water pressure was then registered.

6.3 Test matrix

The test plan was based on the conclusions from the water storing capacity type I tests (Chapter 5.5.). One conclusion from these earlier tests was that the extruded 6 mm pellets seemed to be the superior pellet type. The evaluation of the type I tests concluded that ASHA and IBECO were the most suitable materials and therefore the test plan was focused on these. One test was also performed with MX-80 in order to have the third reference material included for comparisons. Worth mention also is that the ASHA-13 and IBECO-13 pellets made by Amandus-Kahl in Germany had run out before the start of the type II tests. They were replaced by pellets of the same type, but instead manufactured by SKB in Äspö HRL. An identical machine delivered by Amandus-Kahl and material from the same batch as the earlier manufactured pellets were used when manufacturing the replacement pellets.

Table 6-1. The planned test matrix for the water storing capacity type II tests.

Pellet type	Pellet name (material)	1% salinity	
		0.25 l/min	0.5 l/min
Extruded 6 mm	ASHA-13*	X	X
Extruded 6 mm	IBECO-13*	X	X
Extruded 6 mm	MX-80-13		X

*The Germany-manufactured ASHA-13 and IBECO-13 ran out and were replaced by pellets manufactured by SKB at Äspö with an identical machine and material from the same batch.

6.4 Results

A total of six tests have been performed. In the first test performed (IBECO-13 with 0.5 l/min water flow rate) some leakage occurred that was judged to influence the result somewhat and this test was therefore repeated. However, the registered water pressures and the inflow-outflow linkages from that test are still included in the figures for comparison.

The water pressures plotted against accumulated inflow are shown in Figure 6-2. ASHA gives the highest flow resistance and IBECO the lowest at both flow rates. The sharp changes in water pressure are most likely the result of the piston cycling of the pump used to supply the water. By taking the mean of each cycle a good indication of pressure change can be determined.

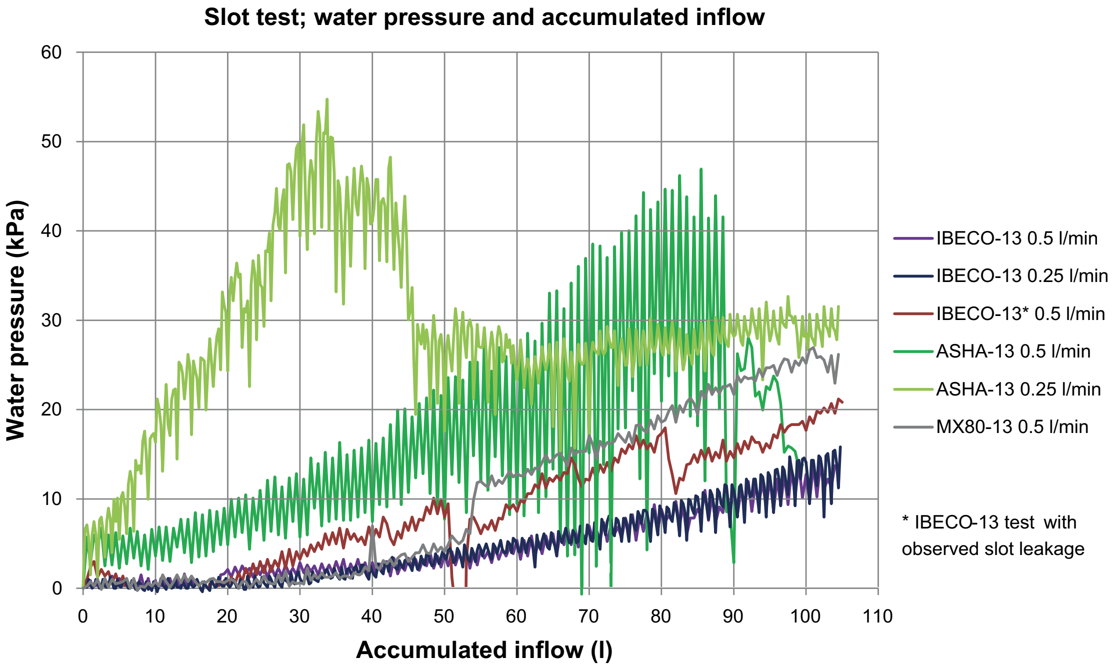

Figure 6-2. Water pressure plotted against accumulated inflow for all slot tests. ASHA has the highest flow resistance and IBECO the lowest at both flow rates.

Figure 6-3 and 6-4 show a comparison of the wetting behaviour for all tests at 45 liters and 105 liters accumulated inflow respectively. The total volume of the pellet filling void space for a pellet filled slot is calculated to about 54 liters (from a total pellet volume of 110 liters and a porosity of 0.49). The water fronts are marked with an orange line.

At 45 liters accumulated inflow (Figure 6-3) ASHA has stored most water at both flow rates. At the higher flow rate the wetting is downwards, but at the lower inflow rate the pellet filling seems to seal downwards and the water front moves upwards. IBECO have a similar behaviour at both inflow rates; straight downward wetting from the inflow point which spreads in both directions over the bottom. MX-80 is similar to ASHA in wetting behaviour at 0.5 l/min.

At 105 liters accumulated inflow (Figure 6-4) practically the entire pellet filling is wet for ASHA and MX-80 at the higher inflow rate. For the lower inflow rate ASHA is entirely wet around the inflow point and upwards, but a large volume below the inflow point has remained dry, probably due to early sealing. IBECO experienced somewhat more wetting above the inflow point at the lower flow rate but most of the upper pellet filling volume remained unused for water storage for both IBECO tests.

In Figure 6-5 the inflow-outflow linkage for all slot tests are displayed. The figure shows accumulated inflow on the x-axis and accumulated outflow on the y-axis. The dotted line shows inflow = outflow if no storing of water would occur. The continuous black lines points out inflow = outflow for the test which it is connected to. In the figure it is seen that inflow = outflow for ASHA at the end of both the 0.25 l/min and the 0.5 l/min tests, which means that no more water is stored. For MX-80 it seems as the outflow rate is increasing and starts to get close to the inflow rate by the end of the test. For IBECO the outflow starts very early but the pellet fill stores water throughout the whole test and by the end of the test the outflow rate has still not reached the inflow rate. It is also seen that the ASHA 0.5 l/min test has stored most water by the end of the test (together with the IBECO 0.5 l/min test with observed slot leakage) followed by MX-80.

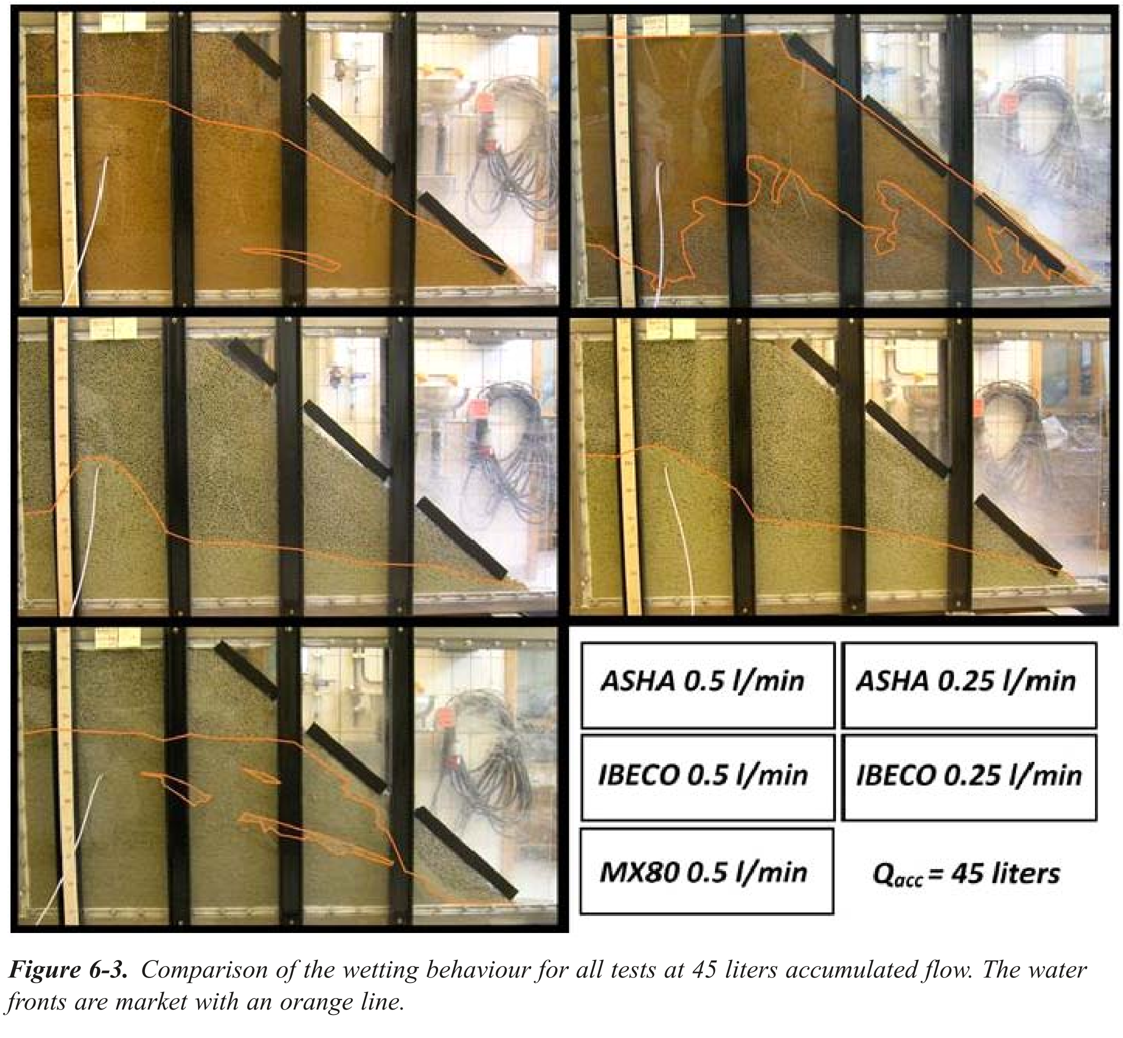

Figure 6-3. *Comparison of the wetting behaviour for all tests at 45 liters accumulated flow. The water fronts are market with an orange line.*

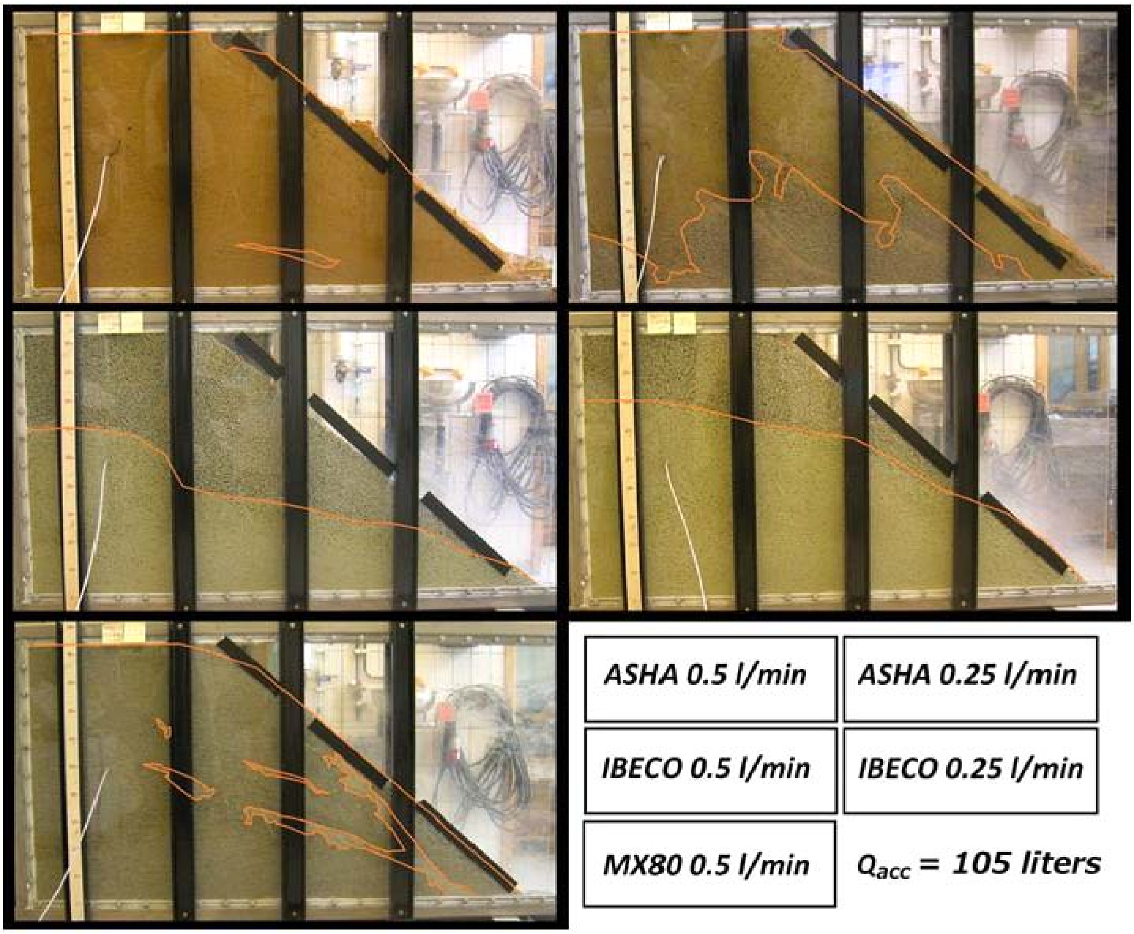

Figure 6-4. *Comparison of the wetting behaviour for all tests at 105 liters accumulated flow. The water fronts are marked with an orange line.*

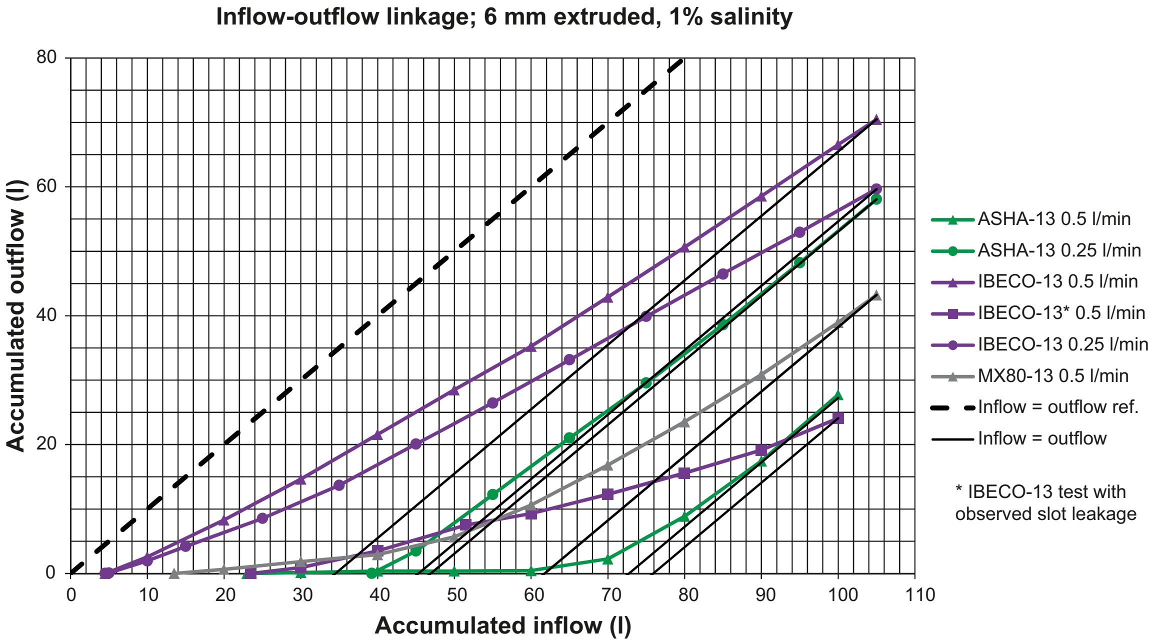

Figure 6-5. *Slot test inflow-outflow comparison for all tests. The dotted line shows inflow = outflow if no storing of water would occur. The continuous black lines show inflow = outflow for the test which it is connected to.*

6.5 Discussion and conclusions

It seems as the IBECO material has a generally low flow resistance. In Figure 6-5 it is shown how the water front reaches the slot outlet already after 4.5 liters accumulated inflow at both flow rates. This is very early in comparison with the other materials. For ASHA the outflow starts after about 23 and 39 liters accumulated inflow for the high and the low flow rate respectively. The outflow for MX-80 occurs after 13.5 liters accumulated inflow. Despite the early start of the outflow IBECO is still storing water at an almost constant rate throughout the entire test. IBECO is however the material that has stored the least water by the end of the test (with exception of the 0.5 l/min test with observed slot leakage). ASHA seem to be the superior material in decelerating the water front. If the 0.25 l/min ASHA and IBECO tests are compared it is seen that the accumulated outflow is practically the same for both tests, however the outflow from the ASHA test starts much later than in the IBECO test. The idea of a high water pressure causing an increased flow resistance which in its turn decelerates the water front is confirmed by the water pressure measurements provided in Figure 6-2.

One observation is also made that could make a great difference in the wetting behavior and the water storing capacity of the pellet filling; most of the sealing that occurred in the ASHA and MX-80 tests seem to be in areas were very much fine grained material is present. The ASHA and MX-80 pellet filling was taken from the bottom of their respective Big Bags. It is possible that more fine grained material was present in the samples due to stratification. The IBECO samples were taken from the top of a Big Bag and no fine grained material was observed. This can be hard to observe in Figure 6-3 and 6-4, but in Figure 6-6 an example of water front sealing is shown where it seems as it mainly occurs around the fine grained materials.

Also worth to mention is that the pilot slot test at 0.5 l/min, which was repeated due to leakage in the slot, used IBECO-13 6 mm extruded pellets taken from the bottom of the last Big Bag with Germany-made pellets. In Figure 6-7 it is shown that fine grained material was also present in this test. Two string shaped layers of fine grained material are observed at mid height between the third and the fourth iron beam. It seems as the water front at 60 liters accumulated flow has the same orientation as the upper fine grained layer, which indicates that this could be an effect of these fine grained layers. However this result must be interpreted with caution since significant leakage was observed through the slot.

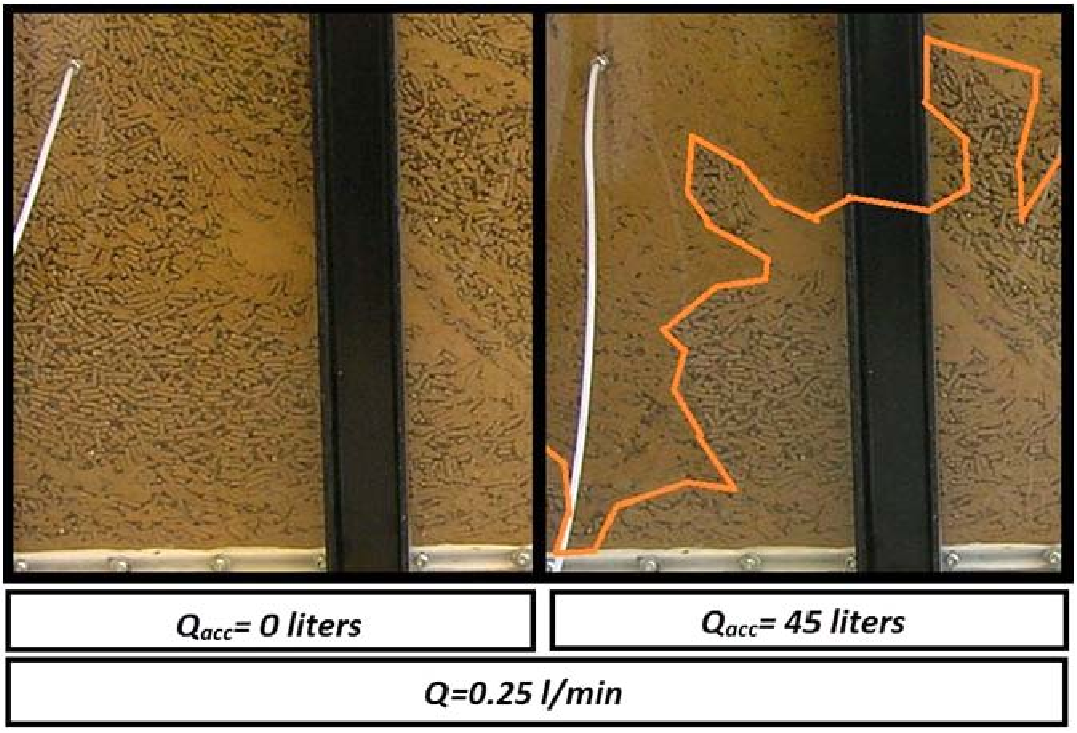

Figure 6-6. *ASHA at 0.25 l/min flow. The presence of fine grained material seems to induce sealing in the pellet slot.*

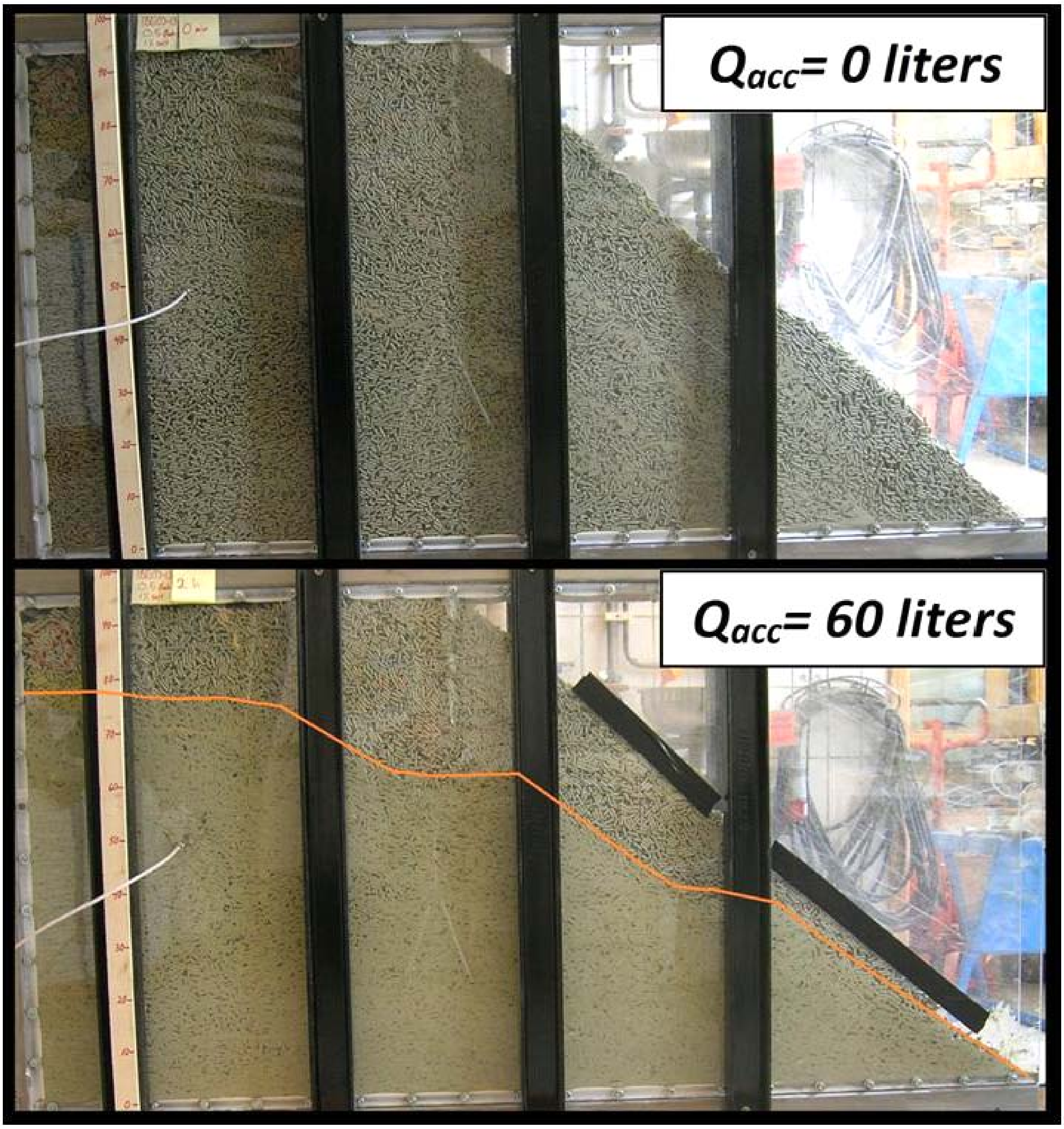

***Figure 6-7.** The pilot slot test was made on IBECO material taken from the bottom of a Big Bag. At 0 liters accumulated flow layers of fine grained material are observed. At 60 liters accumulated flow the water front seem to have taken the same orientation as the upper layer. It is suspected that an increased presence of fine grained material has decelerated the water front. The result must however be interpreted with caution since the test was discarded due to leakage in the slot.*

Based on the results and the discussion above the conclusions from the water storing capacity type II tests are the following:

- The time of the outflow breakthrough and the water flow resistance indicates that ASHA is the superior material in decelerating the water front and storing water.
- The presence of fine grained material will play a significant role in slowing the advance of the wetting front. Results indicate that this could have a stronger influence than the actual material type.

7 Installation tests

7.1 General

The pellet filling installation method most probable to be used in full scale is to blow the pellet filling into the slot between the tunnel wall and the backfill blocks. This procedure can be performed with shotcrete equipment (originally used to spray concrete, but demonstrated to be able to install pellet materials). Past experience with pellet placement using this machine indicates that it is likely that the pellet filling will be crushed to some extent during its placement. To investigate exactly how the pellets are affected by the installation procedure, an installation test was performed in an artificial slot.

7.2 Method

An artificial slot with dimensions similar to the slot between the backfill blocks and the rock wall was constructed using plywood. The shotcrete equipment and the artificial slot constructed from plywood and Plexiglas boards are shown in Figure 7-1.

About 40–70 kg of pellet filling was used for every test. The slot and the nozzle were covered with a tarpaulin to avoid spreading of recoiling pellets fractions and dust (Figure 7-2). The pellet filling was first screened through a 4 mm sieve to separate all finer material from the whole pellets. After weighing, the pellet filling was placed in the shotcrete machine's hopper and then blown into the slot. Finally the pellet filling was collected and once more weighed. After screening through the 4 mm sieve the fractions of fine and coarse material where determined. Also the loss of material was determined to have an idea of how well the pellet filling was recaptured.

7.3 Test matrix

The results from the previous erosion and water storing capacity tests excluded the use of granules from the test matrix. All the remaining pellet types were tested. Worth to mention is also that the ASHA-13 pellets made by Amandus-Kahl in Germany ran out. The pellets were replaced by pellets of the same type, but instead manufactured by SKB at Äspö HRL using an identical machine delivered by Amandus-Kahl. The material used was from the same batches as the material used for the previously manufactured pellets.

Figure 7-1. *The shotcrete-equipment to the left and the shotcrete nozzle and the artificial slot to the right.*

Figure 7-2. *The arrangement was covered with a tarpaulin to avoid spreading of recoiling pellets fractions and dust.*

7.4 Results

The test results are presented in Table 7-1. The performed weighing is presented in the first four columns where $m_{in\ tot}$ is the total weighed in material mass, $m_{out\ tot}$ is the total recaptured material mass after the test and $m_{>4\ mm}$ and $m_{<4\ mm}$ is the material mass with grain sizes larger and smaller than 4 mm respectively. The next column, $diff_{installation}$, is the material mass change at installation and the last column shows the amount of material that is crushed to a grain size smaller than 4 mm due to the installation technique.

Table 7-1. Data and results from the installation tests.

Pellet	Pellet Description	$m_{in\ tot}$ (kg)	$m_{out\ tot}$ (kg)	$m_{> 4\ mm}$ (kg)	$m_{< 4\ mm}$ (kg)	$diff_{installation}$ (%)	loss to < 4 mm (%)
ASHA-11	Roller compacted	48.80	48.15	22.35	25.60	–1.33	53.17
ASHA-12	Roller compacted	55.55	54.55	21.10	33.40	–1.80	61.23
ASHA-13	6 mm extruded	55.90	55.53	52.84	2.77	–0.66	4.99
ASHA-14	10 mm extruded	47.45	47.35	37.20	10.15	–0.21	21.44
IBECO-13	6 mm extruded	69.94	69.24	64.16	5.10	–1.00	7.37
IBECO-14	10 mm extruded	69.86	69.37	64.17	5.24	–0.70	7.55
MX-80-11	Roller compacted	50.30	50.10	45.85	4.25	–0.40	8.48
MX-80-13	6 mm extruded	43.15	42.33	27.99	14.59	–1.90	34.47

7.5 Discussion and conclusions

The most durable pellet type seems to be ASHA-13 6 mm extruded. Also the extruded IBECO pellets (IBECO-13 and IBECO-14) have a low rate of loss to finer grains. As for MX-80 the compacted pillows MX-80-11 seem much more durable than the extruded 6 mm MX-80-13. The least durable pellet types were the compacted ASHA pellets (ASHA-11 and ASHA-12) were more than half of the mass was lost to finer grain sizes. However, it is also worth to mention that the test was performed in two sets with different operators, why it is possible that the air pressure and feed motion was different. ASHA-13, IBECO-13, IBECO-14 and MX-80-13 were tested in the first set and ASHA-11, ASHA-12, ASHA-14 and MX-80-11 in the second. It is suggested that this technique is refined to gain more control of how the installation of the pellet filling affects its composition.

8 Summary and conclusions

8.1 General

An optimization of the pellet filling properties and placement methodology is necessary in order to increase the safety margins and facilitate the placement of a backfill of consistent quality. The performed tests show that the behavior of a pellet filling varies depending on pellet manufacturing method, pellet shape and size as well as the material used. The installation technique will probably also affect the behavior depending on how much fines that are created.

The general conclusion from the tests completed in this study is that the 6 mm extruded pellet seems to have the best overall characteristics.

This chapter summarizes the results from the laboratory tests performed to evaluate candidates for the pellet backfill in the Swedish spent nuclear fuel deep repository concept KBS-3.

8.2 Characterization tests

The results from the generic characterization tests are summarized below. The water content, dry density and compressibility were within the expected range for all candidates and are as follows:

Pellet filling – bulk density

The roller-compacted almond- and pillow- shaped ASHA pellets had the highest bulk density. The lowest bulk density was found in the extruded 10 mm – diameter IBECO. The bulk density varied from 1,017 kg/m^3 for IBECO-14 extruded 10 mm – diameter pellets to 1,122 kg/m^3 for ASHA-12, roller-compacted, almond-shaped pellets.

Pellet filling – water content

The water content was as expected highest for the extruded pellets (this is a requirement of this manufacturing method which needs the material to be wetter in order to run it through an extruder. The water content varied from 11.3% for the MX-80-11 roller-compacted pillows to 18.7% for the ASHA-13 extruded 6 mm pellets.

Pellet filling – dry density

The ASHA-13 extruded 6 mm pellets had the lowest dry density, 862 kg/m^3. The ASHA-12 roller-compacted, almond-shaped pellets had the highest dry density, 974 kg/m^3. The dry density was generally lower for the extruded and higher for the roller-compacted pellets.

Individual pellets – bulk density

The individual pellets bulk density was lowest for MX-80-13 6 mm extruded at 2,023 kg/m^3. ASHA-11 roller-compacted, pillow-shaped and ASHA-15 granules had the highest individual pellet bulk density at 2,188 kg/m^3.

Individual pellets – dry density

ASHA-11 roller-compacted pillow had the highest individual pellet dry density at 1,911 kg/m^3 and MX-80-13 6 mm extruded had the lowest at 1,738 kg/m^3.

Compressibility of the unsaturated pellet filling

The compressibility was lower for the roller-compacted pellet types, which was expected since they also had a higher dry density and lower water content. The ASHA-15 granules were the stiffest material tested and the IBECO-14 extruded 10 mm the softest.

Strength of the individual pellets

In general the measured load required to fail the individual pellets is somewhat higher for the extruded pellets. The results from these tests should not be seen as indicative since the method does not take the sample surface area or area that the load is applied to into consideration. The compression tests do however provide a basis for comparison between pellets of identical shape and size.

8.3 Erosion

The erosion tests were intended to examine the ability of the various pellet filling candidates to resist the action of flowing water. Pellet types and material types were compared and the impact of variations in water salinity and flow rate was tested. The evaluation of the results led to the following conclusions:

- In general the extruded pellets are the most resistant to erosion, but the Posiva spec.-A compacted pellets had the lowest total accumulated erosion.
- The 10 mm extruded seem somewhat better than the 6 mm extruded.
- The material type with the overall lowest erosion was IBECO.
- MX-80 was the only material clearly sensitive to water salinity changes.
- No significant influence was observed in any material type from variations in water flow rate.

The main conclusion that can be drawn from the erosion tests is that the extruded IBECO pellets are the most resistant to erosion. However, almost all pellet types are within the limits of the theoretical model describing the erosion rate.

8.4 Water storing capacity

The pellet filling's ability to rapidly take in and hold water originating from the surrounding rock was tested at small scale in a Plexiglas tube and at larger scale in an artificial slot. A summary of the main conclusions from the performed tests is as follows:

- The extruded pellets have a higher flow resistance and seem to decelerate the water front better than the compacted according to the comparisons in the initial water storing tests.
- The 6 mm extruded seem somewhat better than the 10 mm extruded pellet in terms of its water holding ability.
- In the initial water storing capacity tests, ASHA and IBECO seemed similar but in the large slot tests, ASHA was the superior material type. However, there are suspicions that the observed difference in water storing capacity between the materials are more connected to the presence of fine grained material in the pellet filling than the actual material properties.
- Neither ASHA nor IBECO seem to be much affected by changes in water salinity.
- In the initial water storing capacity tests the results show that ASHA slows the advance of the water front better at higher flow rates but IBECO seem to have a more even wetting behavior at lower flow rates.
- The water storing capacity in these materials needs to be further evaluated according to the suggestions in Chapter 8.6.

8.5 Installation tests

The planned installation method for the pellet fill is to blow them into place with a shotcrete machine. This method was tested on a full scale artificial slot to see if and to what extent the pellet filling was crushed. All pellet types except the ASHA-15 (granules) were tested. ASHA-13 (6 mm extruded pellets) was found to be the most durable of the pellets examined. The installation method crushed 5.0% of this pellet filling to a size less than 4 mm. IBECO-13 and IBECO-14 (6– and 10 mm extruded pellets) were also quite durable with 7.4% and 7.6% respectively being reduced to < 4 mm. ASHA-11 and ASHA-12 (roller compacted pillows and almonds) were the least durable pellet types with a crushing rate of more than 50% (53.2% and 61.2% respectively). It is suggested that this technique still needs to be refined in order to gain more control of how the installation of the pellet filling affects its composition.

8.6 Further work and recommendations

In the large slot tests some concerns were raised with regards to the effect of the grain size on the pellet filling's sealing behaviour and also on its water storing capacity. It was observed that the pellet fill tends to seal in areas where finer grained materials are concentrated. It is suggested that further studies be made on this phenomenon where ASHA and IBECO extruded pellets could be further evaluated using the large slot test equipment. The following tests are suggested:

- **Large slot test equipment**. Tests should be done using a pellet filling with no presence of finer grains. This can be performed by separating all finer grains from the pellet filling before placing it in the test slot.
- **Large scale and full scale tests**. A practical problem with performing tests in laboratory scale with material that have gone through the installation process is that when collecting the recaptured material in e.g. a big bag, a separation of the material will immediately occur, resulting in that the main part of the fines is accumulated in the bottom of the big bag. It will probably be very difficult to install representative material in the laboratory equipment. In order to test the behavior of a pellet filling after exposure to the installation equipment, where a quantity of fines will be created, it will probably be necessary to perform tests in large scale e.g. using the steel tunnel equipment at Äspö or using a part of a full scale deposition tunnel. These kinds of tests are planned to be performed within the Åskar project.

It would also be of interest to do erosion tests on no-fines materials. By using pellets where all fines are removed, it will be possible to evaluate the erosion properties of the pure pellet filling and it will also be easier to compare the results obtained from different sized pellets. It is also suggested that more parallel testing is performed in both erosion tests and water storing capacity tests to see scattering in the results and obtain higher confidence in the evaluation.

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