International
Progress Report

IPR-06-30

Äspö Hard Rock Laboratory

Cleaning and sealing of Borehole

Report of Sub-project 3 on plugging of borehole OL-KR24 at Olkiluoto and reference boreholes at Äspö

Roland Pusch
Geodevelopment International AB

Gunnar Ramqvist
Eltekno AB

November 2006

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

Äspö Hard Rock
Laboratory

Report no.	No.
IPR-06-30	F98K
Author	Date
Roland Pusch Gunnar Ramqvist	November 2006
Checked by	Date
Christer Svemar Jukka-Pekka Salo Antti Öhberg	May 2007
Approved	Date
Anders Sjöland	2007-08-27

Äspö Hard Rock Laboratory

Cleaning and sealing of Borehole

Report of Sub-project 3 on plugging of borehole OL-KR24 at Olkiluoto and reference boreholes at Äspö

Roland Pusch
Geodevelopment International AB

Gunnar Ramqvist
Eltekno AB

November 2006

Keywords: Plugging, Sealing, Bentonite, Borehole, Concrete

Abstract

Sub-project 3 comprised plugging of an about 550 m deep hole, OL-KR24, at Olkiluoto and two 5 m deep holes at Äspö, using clay and concrete. The field work at Olkiluoto could be successfully pursued and the techniques were shown to be practical and sufficiently robust. One clay plug was inserted and is in contact with cement-stabilized quartz concrete, the reaction being investigated by examining the plugs extracted from the Olkiluoto and Äspö holes when this becomes possible.

Theoretically, the time allowed for placing the clay plug in OL-KR24 could have been as long as 8-12 hours without causing significant problems, while the actual operation was completed in less than one hour.

The clay plugs in the 5 m deep holes KA 1621G01 and KA 1621G02 at Äspö have limited access to water from the rock and will mature more slowly than in OL-KR24. This may have a greater impact on the chemical interaction between the concrete and clay because cement water will interact with the slowly formed "clay" skin around the dense clay plug and thereby affect its hydraulic conductivity and expandability.

Summary

Sub-project 3 comprised plugging of an about 550 m deep hole, OL-KR24, at Olkiluoto and two reference holes at Äspö, using clay and concrete. The field work at Olkiluoto could be successfully pursued and the techniques were shown to be practical and sufficiently robust to be recommended for application in other contexts. There were no indications of difficulties in constructing neither concrete nor clay plugs at this depth.

Clay plugs in holes of any depth will be in contact with cement-stabilized quartz concrete and interact chemically with it. This will be investigated by examining the plugs extracted from the Olkiluoto and Äspö holes when this becomes possible.

Prediction of the evolution of the plugs in OL-KR24 was made with respect to four possible impacts on the physical constitution and performance of the clay plug of "Basic" type: 1) erosion of the clay in the emplacement phase, 2) too rapid expansion of the clay, which can generate high wall friction and difficulties in placing such plugs, 3) piping due to high hydraulic gradients along the hole in the placement phase, and 4) subsequent degradation by interaction with concrete. The most important practical issue is the time required for placing plugs in deep holes. Thus, there is a risk that too rapidly increasing wall friction, caused by too quick maturation of the clay plug, can jeopardize the placement. Theoretically, the time allowed for placing the clay plug in OL-KR24 could have been as long as 8-12 hours without causing significant problems, while the actual operation was completed in less than one hour.

Modelling of the hydration and maturation of the clay has indicated that where the rock gives off unlimited amounts of water at a pressure of at 4 MPa, like in the OL-KR24 case, the clay plug will be largely water saturated in one or a few weeks. The forthcoming examination of the concrete and clay plugs, particularly where they are in contact, will reveal both deviations from the intended densities and homogeneities as well as the extents to which chemically induced changes in physical performance and mineralogical composition have taken place.

The clay plugs in the reference holes at Äspö will not be affected by any of the problems that can be foreseen in deep hole plugging but they are located in rock with lower water pressure than in OL-KR24 and have limited access to water from the rock. This may have an impact on the chemical interaction between the concrete and clay in the sense that cement water will interact with the slowly formed "clay" skin around the dense clay plug and thereby affect its hydraulic conductivity and expandability. With the recorded hydraulic conditions in the rock the clay plugs are expected to be fully hydrated in a few months.

Sammanfattning

Sub-project 3 omfattar pluggning av ett ca 550 m djupt hål, OL-KR24, i Olkiluoto och två referenshål i Äspö, med användande av lera och betong. Fältförsöket i Olkiluoto kunde genomföras framgångsrikt och de använda teknikerna visades vara tillräckligt praktiska och robusta för att kunna rekommenderas för tillämpning i andra sammanhang. Inga svårigheter vid byggandet kunde påvisas vid utförandet av varken lerpluggar eller betongpluggar på detta djup.

Lerpluggar kommer att vara i kontakt med cementstabiliserad betong och interagera kemiskt oberoende av hållängden. Detta kommer att studeras genom undersökning av pluggar uttagna från hålen i Olkiluoto och Äspö när det blir möjligt.

Prediktering av mognaden hos pluggarna I OL-KR24 gjordes med avseende på fyra möjliga slag av påverkan på tillståndet och egenskaperna hos lerpluggar av "Basic"-typ: 1) erosion av leran vid inplaceringen, 2) alltför snabb expansion av leran som kan ge hög väggfriktion och svårigheter att placera pluggar av denna typ, 3) piping som följd av hydrauliska gradienter i hålets längdled i inplaceringsfasen, samt 4) efterföljande nedbrytning genom interaktion med betong. Det finns sålunda risk för att alltför snabb mognad hos lerpluggen kan äventyra inplaceringen. Teoretiskt sett kunde tiden för detta moment ha fått vara så lång som 8-12 timmar i Olkiluoto utan att skapa problem medan den verkliga tiden var mindre än en timme.

Modellering av bevätning och mognad hos leran har visat att där berget avger obegränsad mängd vatten med trycket 4 MPa, som i fallet OL-KR24, kommer lerpluggen att vara helt mättad på en eller några få veckor. Den kommande undersökningen av betong- och lerpluggar, särskilt av de delar som är i kontakt, kommer att avslöja såväl avvikelser från de avsedda densiteterna och homogeniteterna som omfattningen av kemiskt betingade ändringar av fysikaliska egenskaper och mineralsammansättning.

Leran i referenshålen i Äspö kommer inte att drabbas av de problem som kan förutses vid pluggning av djupa hål men de är belägna i berg med lägre vattentryck än i OL-KR24 och har begränsad tillgång till vatten från berget. Det kan ha inverkan på den kemiska interaktionen genom att cementvatten kan reagera med det långsamt utbildade "skinnet" runt de täta pluggarna och därigenom påverka dess hydrauliska konduktivitet och expanderbarhet. Under de uppmätta hydrauliska förhållandena i berget kan pluggarna förväntas bli helt vattenmättade på några få månader.

Contents

1 Introduction

Sub-project 3 had two parts: 1) plugging of OL-KR24 by use of clay and concrete, and 2) plugging of reference holes with the same type of plugs for investigation of chemical reactions between clay and concrete. The work concerning OL-KR24 is the first example of very well controlled and successfully performed placing of a clay plug in a deep hole. The work concerning OL-KR24 is described in Rautio (2006) [9] and in Majapuro (2006) [8].

Clay plugs in deep holes will be in contact with cement-stabilized quartz concrete and interact chemically with it. This will be investigated by examining the plugs extracted from the 550 m deep OL-KR24 hole at Olkiluoto when this is possible but for investigating such interaction in shorter holes at an earlier occasion two holes were bored and plugged at Äspö using "Basic" plugs and cement-stabilized quartz concrete. These experiments are described in this report as well.

Potentially unstable fracture zones intersected by boreholes have to be stabilized for avoiding rock fall in conjunction with subsequent placement of clay plugs. Following the basic strategy defined in [1] such zones will be stable but not very tight and there is hence no need to effectively seal the hole where it passes through them. Stabilization is made by reaming the hole and filling it with cement-stabilized quartz concrete followed by re-drilling. The plugging operation is made by use of clay-based plugs in the parts of the hole that are located in normally fractured rock, while the parts that have been stabilized are plugged by filling them with cement-stabilized quartz concrete similar to what is used for the stabilization. It is estimated that the quartz component is chemically stable while the cement, which is of low-pH type, can possibly be dissolved and lost. This is not deemed to be critical to the performance of the fill since its gradation is such that it should not be eroded. However, the contact between the cement-stabilized plugs and the clay plugs can lead to changes in mineral composition and loss in tightness. This will be investigated by examining the plugs extracted from the 550 m deep OL-KR24 hole at Olkiluoto when this is possible, while the Äspö tests make it possible to investigate the chemical interaction at an earlier stage.

In this report the following items are in focus:

OL-KR24

- Selection of levels for plugging in the more than 550 m deep hole
- Preparation and placement of plugs
- Prediction of the maturation rate of the plugs
- Preparation of detailed plan for testing plugs that are ultimately extracted from the hole

Reference holes at Äspö

- Preparation and placement of plugs
- Prediction of the maturation of the plugs
- Preparation of detailed plan for testing the plugs

The strategy proposed in the borehole plugging project is to cast cement-stabilized quartz concrete where fractured rock is intersected, and place clay plugs where the rock is normally fractured and this principle was applied in the OL-KR24 work. The clay plugs in both field experiments were of "Basic" type, i.e. perforated copper tubes containing well fitting, highly compacted blocks of smectite-rich clay. The concrete recipe was worked out by CBI and applied in both experiments.

2 Plugging of the OL-KR24 hole

2.1 Basic conditions

Figure 2-1 illustrates the originally proposed use of the hole OL-KR24 for plugging experiments. The hole, which was core drilled in 2003 (Niinimäki 2003) [7], has a diameter of 76 mm and extends from a level some 20 meters below the ground surface (the shaft was excavated from the surface, +9.74, to the -11 level) to somewhat more than 550 m depth.

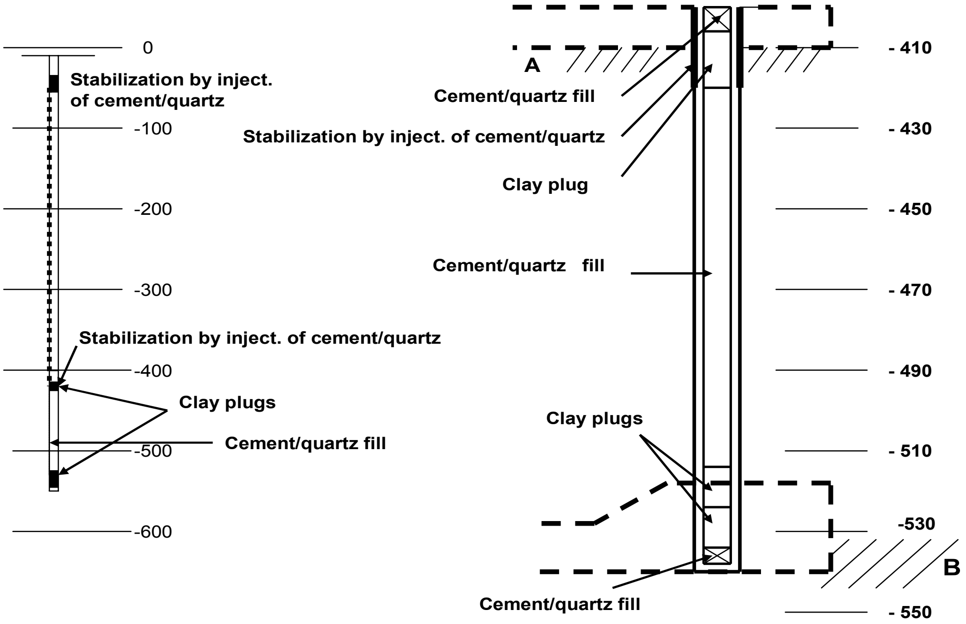


***Figure 2-1**. Schematic illustration of the originally plan for stabilization and plugging.*

2.2 Planned and performed field work at Olkiluoto

2.2.1 Original plan

The major objectives were to:

1. Investigate the applicability of the “Basic” concept, i.e. placement of segments of jointed units of perforated copper tubes filled with highly compacted Na bentonite blocks, in deep hole plugging.

2. Investigate the efficiency of stabilizing potentially unstable fractured rock that is intersected by the borehole.

3. Investigate the feasibility of filling parts of the borehole that intersect fracture zones with chemically stable quartz-based concrete.

4. Demonstrate a technique to bring down a dummy for checking the clearance of a real plug segment before installing it.

5. Demonstrate replacing natural water in the hole by tap water.

These activities were scheduled to take place at Olkiluoto before the end of October 2005. After future excavation of the ramp down to level -420, which is expected to be completed in the end of 2008, rooms or niches reaching to the hole will be made at levels -420 and -520. At these two levels the cement/quartz concrete and contacting clay plugs would be extractable.

2.2.2 Final plan

After rinsing and stabilization of the deep borehole, clay and concrete plugs were placed in the period November 8-14, 2005. The final plan, which was preceded by changes due to excavation and grouting work taking place in the nearby access tunnel causing restrictions to the timetable of the of the plugging experiment in OL-KR24. Due to the tight timetable the lower part of the hole was selected for the plugging experiment.

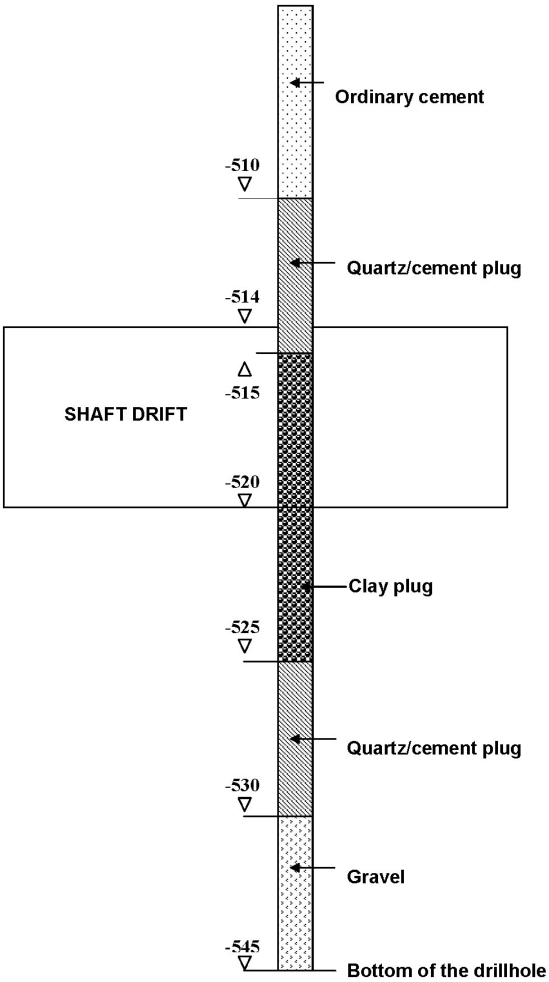


Figure 2-2. The final location of the plugs in OL-KR24.

The actual levels of different plugs are presented in Figure 2-2. The lowest part of the borehole, which extends down to the level about -545.00 (hole depth from the surface 553.94 m), could not be filled with concrete and sand was used instead. It was compacted by letting the drill string repeatedly drop on the top of the sand fill. The lower Q/C plug became became 5 m high and had its top at level -535.29. Its hardness was found to be acceptable for carrying the 10 m long clay plug, which could be placed without problems. This operation was preceded by testing of whether 2.5 m and 5 m long dummies could be moved down without difficulty in the hole. Since it was verified that even the longer ones could be brought down without hindrance the finally prepared plug segments consisted of two coupled 2.5 m long units forming 5 m long segments. Two such segments were to be inserted in the hole, hence forming a 10 m long plug of "Basic" type.

Above the 10 m long copper/clay plug ("Basic" type) locating between levels -515…-525 another 5 m long Q/C plug was casted (Figure 2-2).

The rest of the hole between levels -510…-11 was plugged with ordinary concrete.

2.2.3 Definition of tasks

The work comprised the following activities: i) Cleaning (rinsing) of the hole, ii) Selective stabilization of the hole after identifying the parts that needed to be secured, iii) re-drilling and second cleaning of the hole, iv) Characterization of the hole (optical imaging survey and calliper) from level -180 to -545 y) manufacturing of clay plugs and cement/quartz concrete for plugging, vi) exchange of water in the hole by tap water, vii) dummy testing, viii) placement of plugs, and ix) sealing of the hole above level -510 with ordinary concrete.

Posiva was responsible for items i) to iv) and vi) to ix) with the exception of viii) that was made in co-operation between representatives of SKB and Posiva. The work provided by Posiva is reported by Rautio (2006) [9] and by Majapuro (2006) [8].

In the present report focus is on SKB's parts with due reference to geological and rock investigations. They are:

- Manufacturing and storing of plugging materials
  - Copper tubes with compacted clay according to the proposed design Sub-project 1 but adapted to 76 mm holes
  - Cement and quartz materials
- Emplacement of the plugs
  - Detailed plan of preparation of clay plugs (materials, depths, samplings etc.) provided by SKB
  - Placement of clay and quartz plugs by use of a drill rig, the work being performed by Posiva under supervision and with assistance of SKB.

2.2.4 Identification of rock structure and hydraulic conditions

The various hydraulic loggings and fracture mappings, which were conducted before this experiment, gave the large-scale constitution that is shown in Figure 2-3 for the particularly interesting B-part. One recognizes fracture zones and water-bearing fracture swarms in the interval -515 to -525 where the clay plug is located. This suggests that the rock is sufficiently water-bearing to provide the plugs with water for quick maturation.

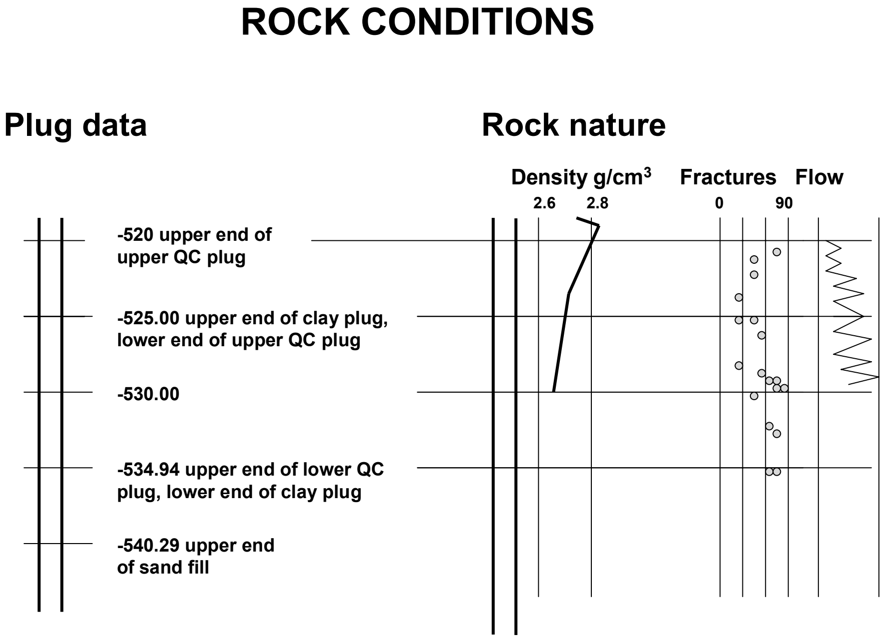


Figure 2-3. *Profile showing the plug components and basic, generalized rock data (Posiva working report; 2003-52 [7]). Fracture frequency is expressed in number per meter. Flow shown as trend.*

The selection of parts of the borehole that were judged to need stabilization was made by POSIVA, being responsible for offering borehole conditions that allowed plugging according to the project plan.

The borehole passed through some fracture zones that were considered for stabilization at the planning stage but only one depth interval was finally selected for stabilization, namely -335.63 to -338.13, where the fracture spacing was locally very high. However, stabilization of this part failed. The stabilization work is described in Rautio (2006) [9].

2.3 Construction of plugs for OL-KR24

2.3.1 Selection of materials

The present document contains a complete report on materials used in the plugging of the OL-KR24 borehole. Focus is on dimensions and compositions but some basic physical properties are reported as well. The materials dealt with are:

- Copper tubes for placement of clay components. Manufacturing. Performance
- Clay components. Manufacturing. Performance
- Cement grout for borehole stabilization. Preparation. Performance
- Concrete for plugging. Preparation. Performance

Copper tubes

The “Basic” concept implies insertion of perforated copper tubes filled with tightly fitting clay blocks in the hole. The length of a unit plug was 2.5 m and jointing can yield segments of suitable lengths, 5 m, 7.5 m, 10 m etc. Connection of adjacent segments is made on site in conjunction with the insertion of the plug in the hole. The lower part is clamped and held by the drilling rig while the next one is attached and squeezed to join the lower one.

The copper was standard ISO R1337 Cu DHP (formerly Swedish Standard SS 5015) containing 99.9% copper with the density 8930 kg/m^3. The tensile strength =60 MPa and Poisson’s ratio =0.3. The maximum tensile strenght in the copper tubes is 10 MPa for 10 m segment length.

OL-KR24 has 76 mm diameter while the outer diameter of the tubes was 72 mm. The inner diameter of the tubes, which equals the outer diameter of the clay columns, was 68 mm. No standard tubes were available so 76 mm diameter tubes had to be cut axially and welded together after removal of excess metal. The outer diameter of the completed tubes is 72 +/-1 mm. They had 50 % perforation ratio with 10 mm diameter holes uniformly distributed in straight rows with every second row displaced by half a hole distance, i.e. 6.75 mm (cf. Sub-project 1). The lowermost tube of a segment of jointed plug units of the “Basic” type must be equipped with a copper plate welded to the tube for carrying the clay blocks and this was made for the two units of the 10 m long tube segment consisting of four 2.5 m long units.

Manufacturing of plug segments

Jointing of plug units with clay blocks in them was made with the tubes hung in the drill rig. A special tool was used for connecting and releasing them from the drill string. For jointing of adjacent tube units they were brought into a short, tightly fitting outer copper tube, which was compressed radially to an outer diameter of 72 mm. At each jointing event a gripping tool connected to the rig was used for holding the already completed part of the segment for preventing it to drop in the hole (Figure 2-4). The installation procedure is described in Table 2-1. The weight in air of the jointed 10 m long clay plug, including clay and perforated copper tubes, was 45 kg. The equipment for all these purposes and the actual jointing operation was provided by Liwinstone AB.

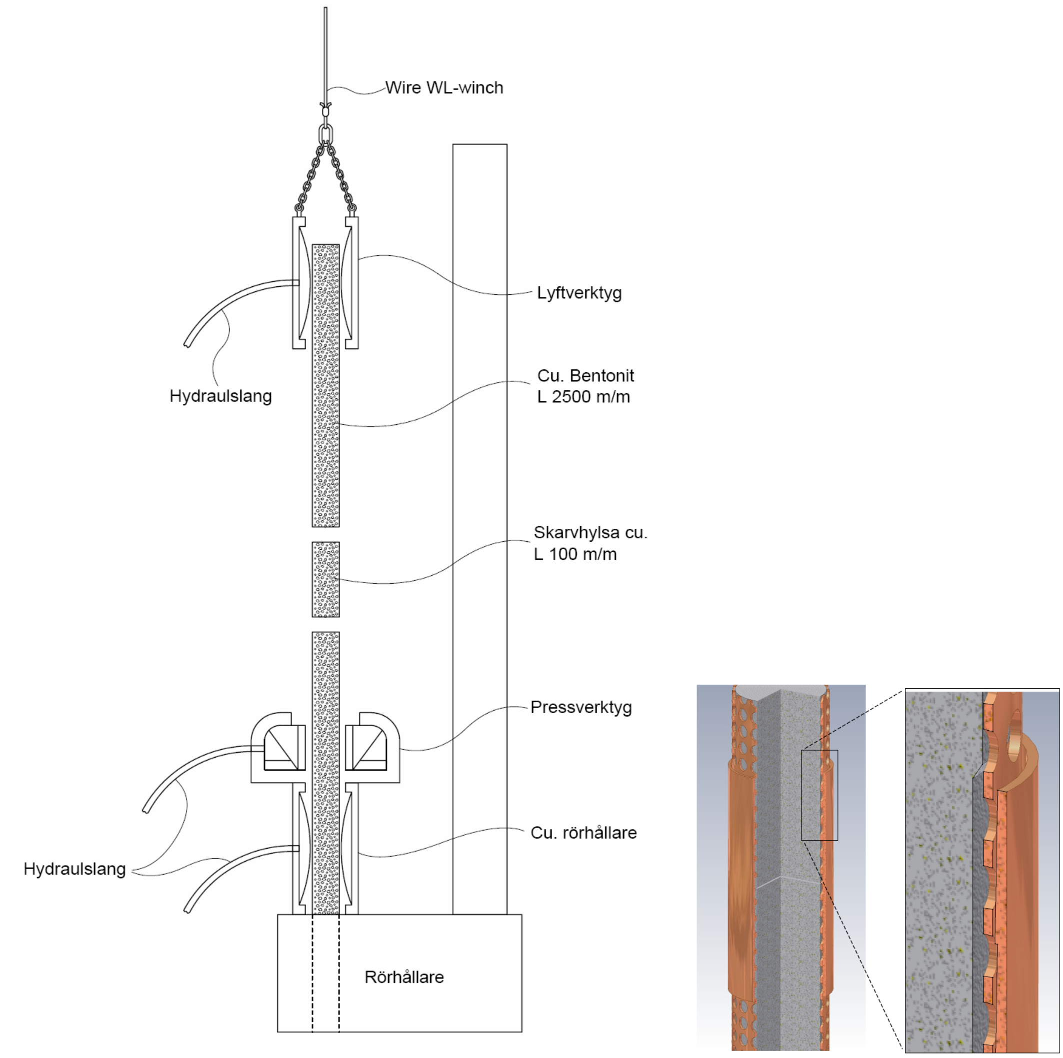


Figure 2-4. *Jointing of plug units. Left: Schematic view of the connecting tube (SWECO). Right: Jointing process [2].*

Table 2-1. Istallation work in OL KR-24.

(C=Ordinary concrete, C/Q=Cement/quartz concrete; Posiva, LL=Lars Liw, CV=Carsten Vogt, CBI), the depths must be correlated with the fixpoint.

ID	Activity	Description	Risk
1	Construction of first C/Q plug. The 5 m long plug is cast in two steps, i.e. segments with 2.5 m length; interval -520 to -515 (SKB consultants with assistance by SMOY)	Replacement of water. Preparation, mixing and casting of concrete plug.with a copper plate on top for accurate levelling and checking of bearing capacity. The procedure is: 1. Mixing of components; charging of injector tubes that are placed in the drilling machine down to the desired depth 2. Filling with water, injection pressure about 2 MPa. 3. Pumping 5 l/min under successive hoistening until stop (about 2.5 m/minute). Repeated charging etc for completing 5 m plug length	Incomplete filling and slow-hardening cement
2	Testing of bearing capacity (SKB consultants with assistance by SMOY)	1. Inserting drill string. 2. Recording level and loading to reaction	Insufficient bearing capacity requiring rinsing and new construction
3	Placement of first clay plug in interval -515 to -505. (SKB consultants with assistance by SMOY)	1. Replacement of water 2. Attaching tube holder and press unit to drill rig. (fig.2) 3. Connect rod lifter to wire line winch 4. Lowering the plug in the hole using the rod lifter 5. Locking the tube holder hydraulically 6. Attaching next tube together with the joint tube unit 7. Swaging to predecided pressure 8. Repeating the procedure for next units 9. Connecting the lowering tool to the top tube 10. Attaching first drill rod 11. Lowering the whole unit including the drill rod 12. Removing the compression device 13. Lowering the drillrods to the decided level 14. Filling drill rod string with water 15. Increasing the water pressure in the drill rods to the required level 16. Releasing drill string from the clay plug 17. For installation of next clay section start from step 2	Risk assessment: a) Holding and lowering in the plug application phase with risk of dropping the plug b) Sticking of clay plug in the insertion phase (solve by slight rotation and pressurizing)
4	Construction of second C/Q plug. The 5 m long plug is cast in two steps, i.e. segments with 2.5 m length; interval -505 to -500 (SKB consultants with assistance by SMOY)	Same procedure as for interval -520 to -515	Incomplete filling and slow-hardening cement
5	Construction and filling of interval -500 to top of hole (SMOY)	Casting of special concrete	Incomplete filling and slow-hardening cement

Clay material

The clay used for manufacturing the blocks was MX-80 bentonite with 6 % water content compacted under 200 MPa pressure. The material was delivered by Askania AB, Gothenburg, Sweden.

The preparation of blocks was made by Höganäs Bjuf AB, Höganäs, Sweden, by compacting the clay powder in cylindrical forms. The manufacturing of the clay components was completed in summer 2005 and typical data for four randomly selected pieces are shown in Table 2-2.

Table 2-2. Properties of four randomly selected clay blocks for plugging OL-KR24 (Clay Technology AB).

Sample No	Height/Diameter mm	Water content, %	Dry density, kg/m^3
1	49.01/71.20	4.05	2050
2	47.85/71.30	6.30	2023
3	48.22/71.20	6.30	2026
4	50.50/71.20	5.86	2039

Since the inner diameter of the copper tubes is 68 mm the clay columns had to be lathed for fitting exactly in the tubes. This work was made by Lars Liiv, (Livinstone AB).

The clay will exert a swelling pressure on the copper tubes and on the rock. At complete saturation with low-electrolyte water the clay, which ultimately is expected to have an average density of 2000 kg/m^3, the swelling pressure on the rock will be 1-3 MPa on the rock. This pressure, which corresponds to the density of the clay in the gap between tubes and rock (1800-1900 kg/m^3), is expected for the salinity conditions prevailing in the Olkiluoto rock, i.e. approximately 10000 ppm with Ca as dominating cation (4).

Cement material for borehole stabilization

The recipe of the cement-based material ("concrete") is given in Table 2-3 (Björn Lagerblad, CBI). A force mixer is required for homogenization of the material.

Table 2-3. Concrete for stabilizing boreholes ("lining of reamed hole", CBI).

Components	Amount (kg/m^3 concrete)	Manufacturer
White cement	514.26	Aalborg Portland
Silica Fume	342.84	Elkem
Fine ground, α-quartz M300	133.2	Sibelco
Fine ground, α-quartz M500	107.5	Sibelco
Superplasticizer Glenium 51*	8 (dry content)	Degussa
Fine quartz sand, < 250 μm	325.4	Askania
Coarse quartz sand < 500 μm	488.1	Askania
Glass fibers, 6 mm	53.6	Saint Gobain
Water	244.27	local

* Other superplasticizers can be considered as well: Set Control II, SP-40, Mighty 150

The material has paste consistency and hardens to give a compressive strength of at least 10 MPa in 24 hours, which is estimated to be sufficient for supporting the rock so that the stabilization work can proceed deeper down in the hole after one day. pH is lower than 11.

Cement material for plugging the parts of the borehole that have been stabilized

The recipe of the cement-based material ("concrete") is given in Tables 2-4 and 2-5 (CBI), [3]. The aim is to minimize the cement content for limiting pH and for maintaining physical stability of the fill even after complete dissolution and loss of the cement component. Ordinary concrete mixers can be used for the preparation.

Table 2-4. Concrete (low strength) recipe for plugging of boreholes (CBI).

Components	**Amount (kg/m^3 concrete)**	**Manufacturer**
White cement	60.0	Aalborg Portland
Silica Fume	60.0	Elkem
Fine ground α-quartz M300	200.0	Sibelco
Fine ground cristobalite M6000	150.0	Sibelco
Superplasticizer Glenium 51	4.375 (dry content)	Degussa
Granitic aggregates 0-4 mm	1700.0	Jehanders grus
Water	244.27	Local

Table 2-5. Basic components of the materials to be used for plugging and stabilization of boreholes (CBI).

Material	**Components**
White cement	CaO, SiO_2, Al_2O_3, Fe_2O_3
Silica Fume	SiO_2
Fine ground α-quartz M300	SiO_2
Fine ground α-quartz M500	SiO_2
Fine ground cristobalite M6000	SiO_2
Superplasticizer Glenium 51	Polycarboxylate solution, 35 % dry content
Fine quartz sand < 250 μm	SiO_2
Coarse quartz sand < 500 μm	SiO_2
Granitic aggregates 0-4 mm	Granitic rock composition
Glass fibers 6 mm	SiO_2, ZrO_2, Na_2O, K_2O

The material has paste consistency and hardens to give a compressive strength of 10 MPa after 7 days. The strength after 2 days is very much dependent on the temperature in the borehole and will be in the range from 2 MPa up to 4.5 MPa.. This strength is sufficient to support the load of a 10 m clay plug segment. pH is lower than 11.

Concrete filled in the borehole above the plugged parts

Since there are no chemical restrictions on this concrete ordinary cement could be used. The recipe is as in Table 2-6 and ordinary concrete mixers were used for the preparation.

Table 2-6. Approximate composition per m3 concrete based on aggregate at CBI.

Component	Mass
Cement CEM 1	350 kg
Silica fume	35 kg
Filler	150 kg
Sand 0-8 mm	1004 kg
Stone 8-18 mm	670 kg
Water	174 kg
Superplasticizer	Adjusted

The hardened concrete seals the hole and provides tightness by having low shrinkage potential for maintaining tight contact with the borehole walls. The concrete is pumpable and compacts without vibration.

2.3.2 Location of plugs

At the start of the field work the first phase would comprise casting of concrete in the hole from its lower end at about -545 level up to -530 level over which 5 m cement/quartz (Q/C) concrete would be cast to the -525 m level. After hardening the 10 m long clay plug should be placed and covered by casting a second 5 m cement/quartz concrete plug. Above this level (-510.00) ordinary concrete would be used for filling the rest of the borehole.

This plan had to be changed because it was reported on November 8 that the casting of the lowermost concrete had failed. It was decided to fill the hole with sand to the -530 level, which was also made. The day after, sounding by use of drill string showed that more sand had to be put in and the finally completed sand fill got its upper surface on level -530 (corresponding to about 540 meters of hole depth from surface). This was hence the starting level for the plug construction. The final upper level of the cement/quartz turned overlying the clay plug was reported to be -509.94, deviating from the planned level by 6 cm.

Lower concrete plug

The lower cement/quartz concrete plug, with its lower end at level -530.29 and its upper at -524.94 (the difference from the planned level -525.29 being explained by core loss), was cast successfully by use of the injection tool, which is of the “Container”-type (Sub-project 1), Figure 2-4. The 5 m high plug was cast in two steps. The physical state of the concrete the day after casting was checked by core drilling indicating stiff consistency at level -525 (hole depth about 535 m from surface). Prior to the casting a dummy test was made to certify sufficient clearance but the dummy was stuck at approximately level -500 (510 m hole depth). It was concluded that this event was not due to rock fall or concrete fragments but rather that the dummy was held by a wire making the plug sensitive to even insignificant resistance.

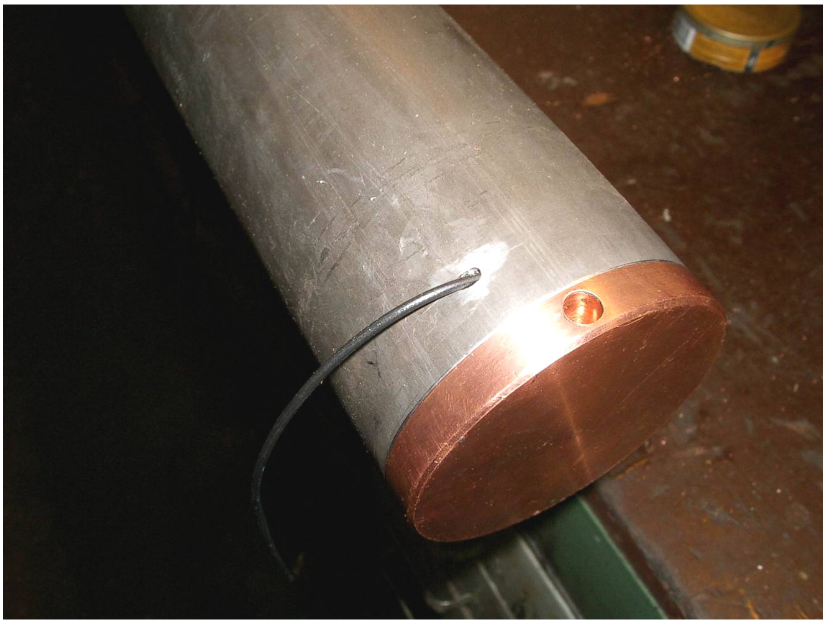


***Figure 2-4.** Copper plate at the end of the container for casting cement/quartz concrete (Livinstone AB).*

Upper concrete plug

The upper end of the clay plug was located at level -514.94, i.e. about 6 cm higher than originally planned. The casting of the 5 m high cement/quartz plug on top of the clay plug was made in two steps and could be completed without problems. The upper surface of the hardened cement/quartz plug was located at level about -509.94, i.e. about 6 cm higher than originally intended.

It is concluded that the work was made successfully and with sufficient accuracy respecting the levels.

Clay plug

The center of the hole deviates from the theoretical vertical axis by about 3 m at maximum. Assuming constant curvature the maximum lateral deviation of the axis from the theoretical center line over 25 m length is 170 mm, which means that a plug segment of this length would make contact with the rock at each end and undergo bending. While the dummy testing had indicated that a 10 m long plug would be placeable it was decided to let the clay plug consist of two parts, a lower 2.5 m unit, and an upper 7.5 m long segment consisting of three units. Each jointing of the units took about 30 minutes, which can probably be reduced by 50 % by using a properly performing winch. The entire procedure was completed without difficulties.

Caliper measurements (Majapuro 2006) [8] performed consistently showed a variation of the smoothness of the wall surface of +/- 1 mm except at certain levels that are assumed to represent major fractures with a spacing of 5-10 m. Here, the calliper was up to 78 mm and occasionally more than that. At 120 m depth there was an abrupt change by 1 mm (77 mm caliper measure to 76 mm). These irregularities were estimated to be of insignificant importance to the experiments and are believed to appear in any new hole core drilled in the area.

Figures 2-5 and 2-6 illustrate the clay plugs handling on site.

Figure 2-5. *Lower ends of clay plug units. End of segment to be placed on solid concrete plug. In the background: Plug units wrapped in tight plastic for protecting them from moisture.*

Figure 2-6. *Left: Jointing of two 2.5 m long units. Right: Hydraulic equipment for handling the copper tube during installation.*

2.4 Prediction of maturation

2.4.1 General

According to the criteria for sealing deep boreholes [1] the parts of the holes that are located between intersected fracture zones shall be at least a tight as the surrounding rock, while the fracture-rich parts shall be filled with physically long-lasting cement-stabilized quartz concrete. This principle has been followed in sealing the OL-KR24 hole at Olkiluoto in the sense that a clay plug was constructed between two plugs of cement-stabilized quartz concrete, although without paying special attention to the detailed rock structure. Still, the selection of the plugged hole interval makes the need for prediction of the maturation and final evaluation by analyzing the sampled plug materials obvious. The density and flow trends as well as the fracture frequency suggest that the rock is rich in water-bearing fractures and fissures over the clay plug length interval.

The bottom part of the hole (diam 76 mm) diameter hole has been filled with sand upon which a quartz/cement (QC) plug was cast and found physically stable. On the top of it a clay plug of basic type (perforated copper tube with well fitting highly compacted MX-80 clay) has been installed followed by a second QC plug over which ordinary concrete has been cast. What is important in the present context is to find out if the potential of the rock to provide the clay with water puts a limit to its maturation rate. This can be evaluated by theoretical analysis and the predictions compared with the results from future sampling, which will also show the physical condition of the QC plugs and their physico/chemical interaction with the clay plug.

2.4.2 Concrete plugs

The development of the cement-based material for stabilization and plugging confirmed that it fulfils the requirement to reach sufficient hardening in 24 hours. Hence, all the materials are expected to have reached a stable condition before the entire field work had reached an end.

2.4.3 Clay plug

Theoretical prediction of the maturation rate of clay plugs

The rate of maturation of clay plugs, which includes water saturation and homogenization, is of great practical importance. Thus, too quick expansion of the clay through the perforation of the perforated tubes in the emplacement phase can lead to significant erosion, while too slow expansion will leave the gap between the tube and the rock open for accumulation of debris that can jeopardize the tightness of the plug [1]. Figure 2-7 shows an example of the first phase of maturation of a dense smectite-rich clay plug.

Figure 2-7. *Growth of soft clay through the perforation of a copper tube confining a dense MX-80 clay core in an 80 mm diameter oedometer. Appearance after 8 hours when the larger part of the core is still unaffected by water [1].*

The factors affecting the rate of water saturation are:

- The hydraulic conductivity of the rock.
- The location of water-supplying fractures.
- The water pressure.
- The type, density and initial degree of water saturation of the clay plug.
- The geometrical conditions with respect to the perforation of the central tube, gap between tube and rock and between tube and clay.

The matter has been dealt with by using FEM and similar techniques for predicting the water saturation process of the clay plug in Sub-project 1, which is taken as a basis of the present document.

Expressing the potential of rock in terms of an average hydraulic conductivity the models gives the time to reach complete water saturation as shown by Figure 2-8. For rock with a conductivity equal to E-13 m/s it will take about 3 months, while for the common conductivity E-10 m/s it will take about 2 weeks.

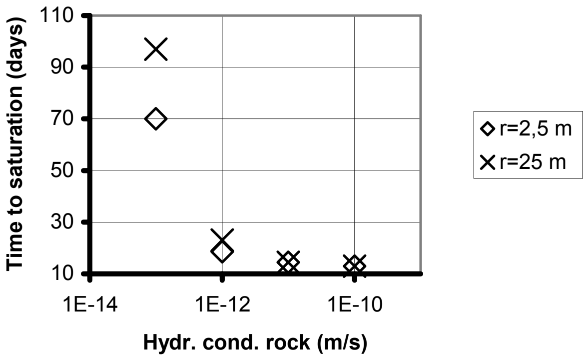


Figure 2-8. *Time to saturation of clay-plugged borehole as a function of the hydraulic conductivity of the rock at two distances to a parallel water-bearing fracture [4, 5].*

Several field experiments have given information on the rate of water saturation and maturation. One example is the plugging of a 100 m long horizontal borehole (DbH2) with 56 mm diameter in the Stripa URL by use of jointed plug units of perforated tubes with compacted clay, i.e. a slim-hole application of the "Basic" plug concept [1,6]. The evolution of the maturation of such plugs is well illustrated by this experiment, which is therefore referred to here.

The perforated tube consisted of 39 segments of 2.5 m long segments with 54 mm outer and 50 mm inner diameter. The perforation of 11 mm holes corresponded to about 50 % of the surface. The cylindrical bentonite blocks were prepared by uniaxial compaction of MX-80 bentonite powder with 11 % water content under 120 MPa pressure to a bulk density of 2110 kg/m^3. The blocks had an outer diameter of 48.7 mm and a central hole with 18.3 mm diameter for a copper pipe in which tubings were contained for testing the tightness of the plug by pressurizing filters in the clay and for subsequent recording of the build-up of natural water pressure (Figure 2-9). .

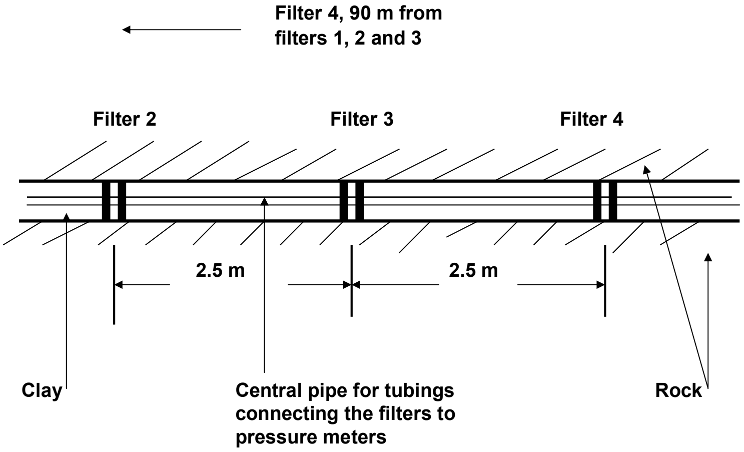


Figure 2-9. *The three filters used for testing the tightness of the clay plug segment and subsequent recording of the build-up of natural water pressure.*

A few days after placement of the plug a water pressure was applied stepwise and separately in Filters 2 and 4 while keeping the central one (Filter 3) open for allowing water to flow through the clay and be discharged. This made it possible to determine the pressure required for causing piping. After these initial tests the plug was left to mature, the only activity being to record the build-up of water pressure in the filters. The evolution of these natural piezometric pressures is shown in Figure 2-10.

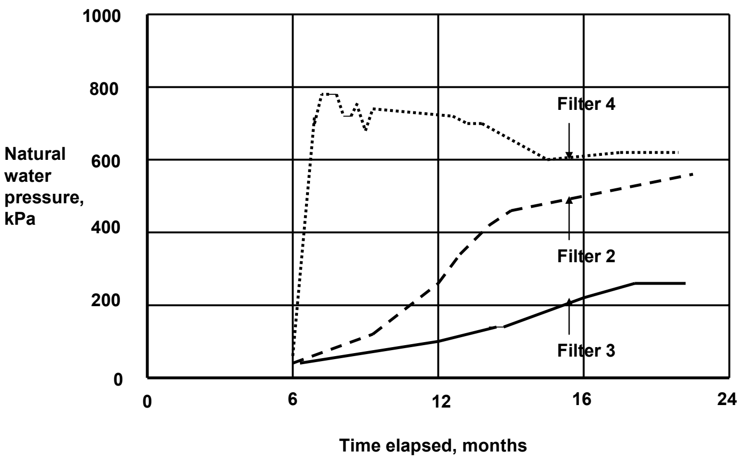


Figure 2-10. *Build-up of natural water pressure in the filters [1].*

Filter 4 reacted very quickly after completing the measurement of the critical pressure that causes piping. The subsequently measured pressure was 800 kPa, which dropped slightly with time because of the draining effect of the drift and other activities that affected the hydraulic conditions. The pressure in Filter 2 increased successively and ultimately reached almost the same level as in Filter 4. The pressure in Filter 3 grew steadily but appeared to have reached a maximum value, 250 kPa, when the test was ended by excavating the plug for sampling.

The pressure evolution can be evaluated by considering the constitution and hydraulic performance of the rock. Thus, Filter 2 was located in rather tight rock, which gave a slow rise in pressure. Filter 3 was located in a steep fracture zone that was drained via the excavation-disturbed zone around the drift and hence had a low water pressure (Figure 2-11).

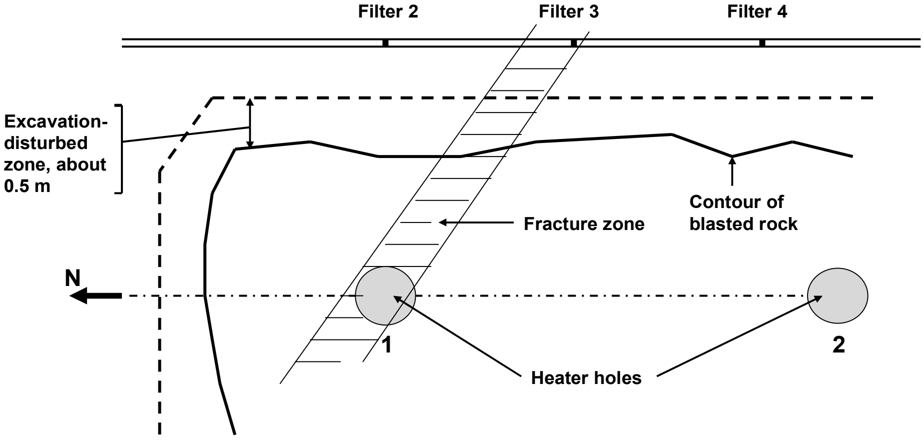


Figure 2-11. *Location of filters in the rock. Filter 2 was in tight rock, while Filter 3 was in a fracture zone. Filter 4 was in rock that is assumed to be intersected by one or a couple of major water-bearing fractures.*

The reason for the slow pressure rise in Filters 2 and 3 must have been a delay in water saturation of the filters and inflow in the clay surrounding them. This indicates that water did not primarily enter the hole in the form of uniform radial flow through the rock as assumed in the theoretical predictions, but through fractures intersecting the hole from which it migrated to the filters through the clay (Figure 2-12).

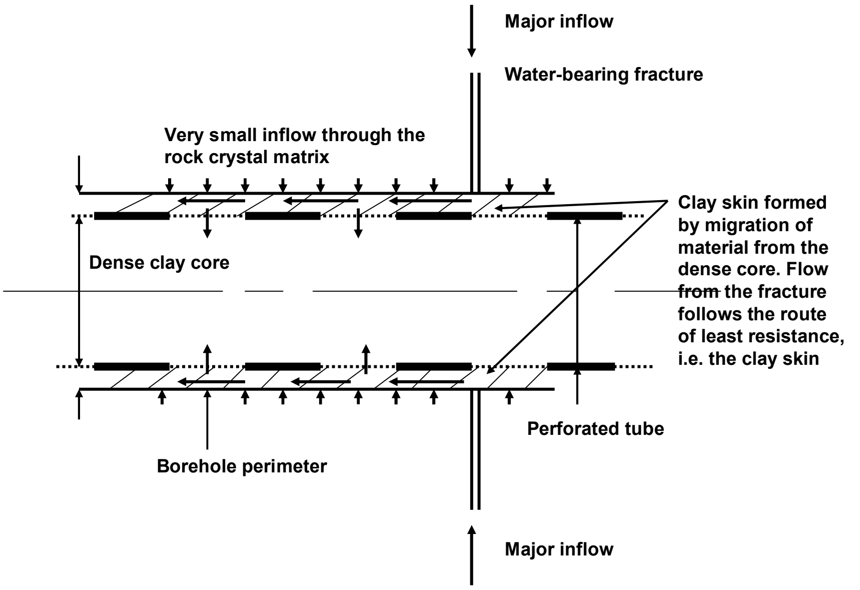


Figure 2-12. *Schematic view of the inflow path of water from water-bearing fracture. Least resistance to the flow is through the clay "skin" around the perforated tube since it is more permeable than the dense clay core for a very long period of time. The "skin" becomes denser with time.*

Most of the water flow through the clay must have taken place in the relatively soft but successively denser clay "skin" that had formed by material moved out through the perforation of the tube. Since there is practically no excavation-disturbed zone around the cored hole almost all water must have moved through the clay. Extraction after 2.5 years showed that the entire clay plug was completely water saturated and had a very uniformly distributed water content of about 33 %, the density being 1950 kg/m^3.

Applying this hypothesis to the OL-KR24 hole it can be assumed that there may be a significant delay in the saturation of the maturing plug where only few water-bearing fractures intersect the hole. However, possible delay is counteracted by the much higher water pressure in the OL-KR24 rock, i.e. about 5 MPa compared to about 800 kPa pressure at Stripa. Also, the fracture frequency and thereby the potential of the rock surrounding the clay plug to supply it with water is expected to be higher than in the tight Stripa rock. This raises the question of the impact of water pressure on the water saturation process which needs consideration of the microstructural constitution of the compacted clay.

Water is pressed into the largest open mictostructural channels and moves quickly into the clay matrix, particularly when the pressure and electrolyte contents are high [6]. For moderate pressures, like in the DbH2 case in Stripa URL, the penetration depth is limited, however, since the large channels become closed rather early at the rock/clay contact and the hydration is then totally controlled by diffusion along mineral surfaces. This is concluded from an earlier attempt to moisten air-dry, highly compacted MX-80 clay with a dry density of 1510 kg/m^3 by injecting, under a pressure of 650 kPa for 3-20 minutes, uranium acetate solution for EDX analysis for finding the pathways of the water [6]. The water content increased from initially about 9 to 11-12 % to within about 1 centimeter depth and to slightly more than 9 % at a distance of about 4 cm, the small effect being explained by the fact that the volume of the system of channels that could be filled was small (Figure 2-13).

Under very high pressure, like in OL-KR24, water is expected to penetrate more deeply in wider channels, displacing and compressing air in the voids and the unsaturated matrix. Since most of the larger voids become water-filled quickly, the average degree of saturation is raised early but the dominating subsequent hydration process is still diffusive redistribution of water from the larger channels into the clay matrix, associated with particle movements. The main difference between this case and the one of lower water pressure is that a somewhat higher degree of water saturation is reached early but that complete saturation will still be reached after very long time. A high water pressure will ultimately lead to complete water saturation.

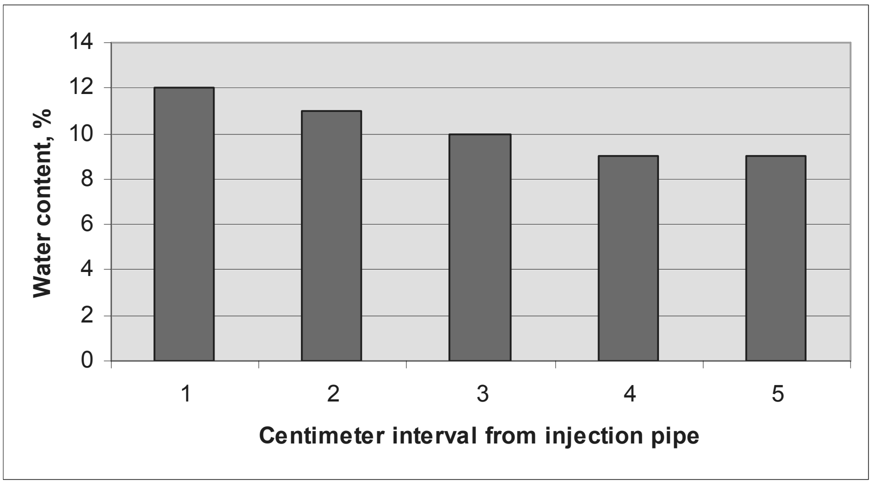


***Figure 2-13**. Water content distribution in the uranium acetate solution experiment. One notices that the water content increased from initially 9 % to maximum 12 % within 1 cm distance from the wet boundary and that pressure-induced wetting took place to about 4 cm distance from the wet boundary in 3 minutes [6].*

Expected maturation of the clay plug in OL-KR24

In the first few hours after insertion of the clay plug a successively denser, completely water saturated but not homogeneous “clay skin” was formed around the perforated tube. The high water pressure acted via this skin on the dense, unsaturated clay core confined by the tube and water early entered wider channels yielding some slight increase in water content all the way to the center of the core. The water saturated skin consolidated under the effective pressure caused by the expanding denser core which made it successively less permeable but still more conductive than the denser core, which continued to suck water from the rock via the “skin”. The least flow resistance in the system is provided by discrete water-bearing fractures in the rock and their frequency and spacing determine, in combination with the permeability of the successively tightening clay skin, how quickly the dense core will hydrate.

For adequate prediction of the saturation rate of the clay plug in OL-KR24 one has to determine if the transport of water from the fractures to and within the clay skin is higher than the diffusive transport of water from the skin into the dense clay core. It is estimated that for a spacing of water-bearing fractures of 1-2 m and a water pressure of at least 800 kPa, i.e. similar to the conditions at Stripa, inflow of water from them into and through the clay skin exceeds the diffusive transport of water from the clay skin into the dense clay core. For larger fracture spacings diffusive water transport from the rock matrix to the core is believed to dominate and yield complete water saturation of the plug in no more than about 4 months, assuming a diffusion constant of 3E-10 m^2/s (cf. Sub-project 1). Sampling after 2-3 months would have demonstrated possible heterogeneities in density and degree of water saturation, while sampling and analysis after more than a year will most certainly show complete water saturation and a density that is largely evened out.

3 Plugging of reference holes at Äspö[1]

3.1 Background

The proposed concept of sealing deep boreholes in repository rock implies that the parts of a borehole that passes through fracture zones in the rock shall be filled with a mixture of suitably graded quartz material stabilized by a small amount of low pH cement (Q/C plug). Between these fillings the hole shall be sealed by a tightly fitting plug of dense smectite-rich clay. While the larger parts of long clay plugs are believed to stay largely intact chemically for hundreds of thousands of years, the parts adjacent to Q/C plugs may undergo changes and so can the Q/C plugs. They generate such degradation, which can take the form of conversion of the clay to zeolites or amorphous silica/aluminium complexes with high hydraulic conductivity and no swelling pressure, i.e. with no self-sealing potential and no tight contact with the rock. The problem is to find out what the degradation process is and how far into the clay and Q/C plugs it extends. The latter would require that the test be conducted for an extremely long time but once the process has been identified it should be possible to derive a theoretical model that can be used for predicting the extent of the degradation over such long period of time. This is the purpose of the experiments with reference holes, which – in contrast to the OL-KR24 – are not aimed at investigating placement techniques (Figure 3-1). They were bored from the floor of a room with its floor at 220 m depth.

---

[1] The project referred to ”reference holes” but the bored holes became 5.90 and 6 m deep, respectively, and they were extended by another 15 m by percussion drilling.

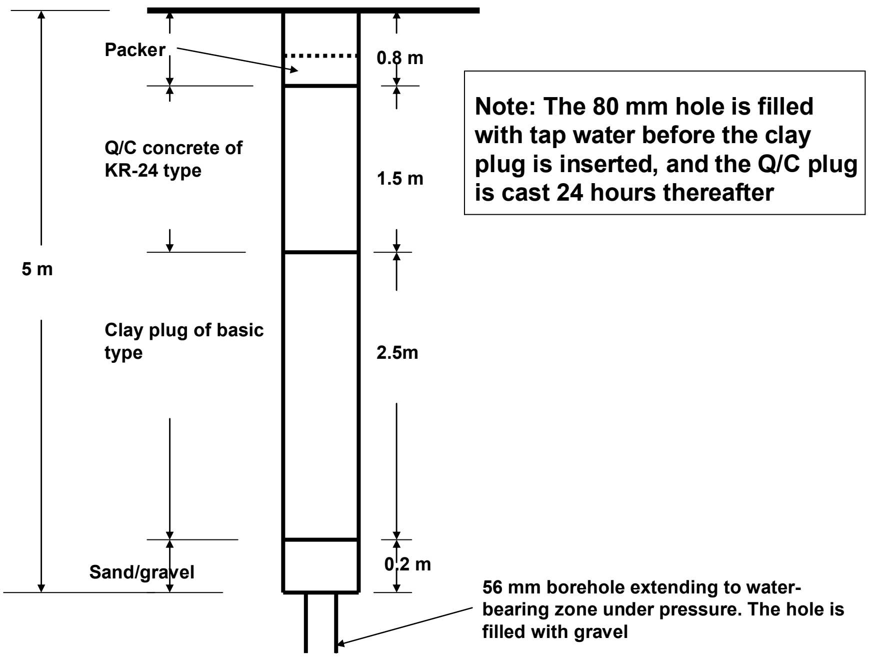


Figure 3-1. *Schematic view of two 5 m boreholes (actual depths 6.00 and 5.90 m) with 80 mm diameter for testing of the interaction of quartz/cement and clay. The upper end of the hole is sealed by a mechanical packer equipped with a manometer and a valve for recording and controlling the water pressure in the central copper pipe that extends down into the sand/gravel fill. The Q/C cement plug is the same as used for OL-KR24. The clay plug is of "Basic" type.*

The clay plug design can be different depending on the length of the holes as outlined in Sub-projects 1 and 2. Like in the OL-KR24 case the Äspö holes, termed KA1621G01 and KA1621G02, the clay plug is of *"Basic"* type and hence consists of a perforated metal tube with well fitting highly compacted columns of very dense clay. As in the OL-KR24 case the concrete plugs contacting the clay plug are prepared using the recipe worked out by CBI. The two cases are complementary and can be terminated at different times, the main differences being the water pressure, which is on the order or 5 MPa at Olikluoto and presumably up to about 1 MPa at Äspö.

3.2 Conditions

3.2.1 General

The arrangement for creating suitable conditions for investigating chemically induced changes of clay and contacting cement-stabilized quartz concrete is shown in Figure 3-1. Extracting the plugs by overcoring after a period of time that has not yet been decided will make it possible to identify possible changes in physical properties and chemical composition.

The conditions for chemical interaction of the clay and concrete depend on the rate of maturation, which is a function of the ability of the rock to give off water to the plugs, the chemical composition of the groundwater, and the temperature, which is believed to be nearly the same at Olkiluoto and Äspö. For limiting the dispersion and settlement of clay exfoliated from the dense clay core all clay-plugged boreholes must be filled with low-electrolyte water before placing the plugs. With time, electrolytes diffuse from the groundwater in the rock into the clay which yields changes in physical performance that are stronger when the water is richer in salt (more saline), as in Olkiluoto, than where the salt concentration is lower as in Äspö rock. The difference is not very important but may be detected. The access to water for maturation is the most important factor that is controlled by the rock structure and water pressure.

3.2.2 Rock structure

The structural constitution of the rock mass in which the holes were bored has not been modelled but some general features can be imagined by evaluating core photographs. The holes were core drilled with 80 mm diameter bit size to about 5 m depth after which inflow measurements were made. They indicated that the small inflow would retard the maturation of the plugs and the holes were therefore extended down to about 20 m depth below the floor by percussion drilling yielding 35 mm diameter holes. The inflow, reported below, was still not significant, indicating that rather few water-bearing fractures had been intersected and also that the two holes are hydraulically interacting through subhorizontal or moderately inclined fractures. The core photos in Figures 3-2 to 3-5 illustrate the rather low frequency of intersected fractures.

Figure 3-2. *Hole KA1621G01. The core representing the uppermost 3 meters of the hole has at least 3 water-bearing fractures.*

Figure 3-3. *Hole KA1621G01. The core representing the lower 2-3 meters of the hole has at least 3 water-bearing fractures.*

Figure 3-4. *Hole KA1621G02. The core representing the lower 3 meters of the hole has at least 3 water-bearing fractures.*

Figure 3-5. *Hole KA1621G02. The core representing the lower 2-3 meters of the hole has at least 3 water-bearing fractures.*

The visual core examination suggested that the average distance between water-bearing fractures that are intersected by the holes is 1 m in the interval 2.3 to 5 m, i.e. where the clay plugs are located.

3.2.3 Hydrology

Inflow and pressure measurements in the completed 15 m deep holes have been made. One of the holes, KA1621G01 has some insignificant water inflow that is presently being recorded and the other, KA1621G02 is even “drier”, which means that one can expect slower maturation and chemical interaction of the plugs. No water pressure can yet be measured but it is believed that with time the pressure at the plug level may rise to approximately 1 MPa.

3.3 Test arrangements

3.3.1 Bottom fill

The holes were filled with gravel up to about 5 m from the floor for providing water from the deeper parts to the plugs. The gravel was put in the hole and compacted with a rod. The uppermost part of the fill will consist of a filter of sandy gravel for avoiding migration of clay from the clay plugs.

3.3.2 Clay plugs

The clay plugs of “Basic type” were placed in the 80 mm diameter holes, similar to those used in Sub-project 2, i.e. with the following data:

- Outer and inner diameters of the copper tubes with 50 % degree of perforation are 76.1 and 72.1 mm, respectively. Their length is 2.5 m.
- The clay blocks, which were trimmed to fit tightly in the tubes, had 6 % water content and a density of 2150 kg/m^3, corresponding to a dry density of 2028 kg/m^3. The void ratio and initial degree of saturation were e=0.37 (porosity 0.27) and 45 %, respectively. The predicted ultimate density of the plugs after complete water saturation is 2078 kg/m^3.

3.3.3 Concrete plugs

The concrete plugs will be made using the same materials and technique for placement as in the OL-KR24 case. The inserted clay plugs will be allowed to mature for 8 hours before the concrete is cast. By this, the concrete cannot migrate downwards and displace the clay “skin” formed around the clay plugs On top of the concrete plugs a mechanical packer was installed for allowing the water pressure in the hole to increase.

3.4 Prediction of hydration and maturation

3.4.1 Concrete plugs

The water pressure is relatively low in the rock and saturation and maturation of the plug components will be slower than in the OL-KR24 case. Still, in a few years all major chemical processes will have proceeded far enough for making assessment of current chemical models possible.

For hydration and maturation of the concrete plug enough water is assumed to be given off from the surrounding rock and the majority of all the mineralogical processes are assumed to have taken place after one year. Earlier investigations have indicated that ordinary Portland cement gives a very high pH, which is known to degrade smectite clay that is in contact with it. Thus, theoretical considerations [5] and studies using batch tests with $KOH/NaOH/Ca(OH)_2$ at 90°C have indicated that the reaction products would be zeolites, such as phillipsite and analcime, and that they can be formed in a few months. Interstratified smectite/illite (S/I) with up to 15 …20 % illite was found when the solution contained much K^+. Uptake of Mg^{2+} in the montmorillonite crystal lattice resulted in the smectite species saponite.

The most important conclusions from these earlier studies were

- High-alkali cement degrades quicker than low-alkali cement, which deteriorates by destruction of the CAH gel. This can and will be tested by microstructural (EDX) analysis, shear testing and determination of the hydraulic conductivity of the cement within 5 cm from the clay contact.
- The dense cement paste fissures. This will be tested by microstructural (EDX) analysis.

3.4.2 Clay plugs

The fact that the hole will be filled with tap water before the plugs are inserted means that the initial phase of formation of a clay “skin” takes place within less than a day. The low density of this skin may make early chemical interaction with cement water possible to a significant distance from the contacts between the plugs. Dissolved elements and water migrate from the fresh cement paste to the smectite in the first few hours. Ca migrates from the cement to the clay causing ion exchange and change in the microstructure of the clay by coagulating softer parts. This will be documented by microstructural (SEM and TEM) analyses and determination of the hydraulic conductivity and swelling pressure of clay samples at different distances (1, 2, 3 and 5 cm) from the Q/C contact.

The subsequent maturation of the clay plugs can be estimated by applying the same simple model as used for predicting the maturation of clay plugs as described in Sub-projects 1 and 2. It requires that one can estimate the average distance between water-bearing fractures that are intersected by the holes and taking this measure as 1 m one would arrive at the same maturation rate as for the “Basic” plug in the 5 m long hole on the 400 m-level that has been studied in Sub-project 2. The conclusion would hence be that fulfilling of the condition that the inflow into the clay skin must be sufficient to feed the dense clay core also at the midpoint between intersected fractures must be about 0.2 litres for the 2.5 m long plug. For a groundwater pressure of 500 kPa (50 m water head), this would require a hydraulic conductivity K of the skin of K>3E-10 m/s, which it certainly has, especially since the Ca-uptake from the cement will cause an increase in conductivity. The most important parameter value that must be checked for verifying this estimate is consequently the water pressure. As stated under Section 3.2.3 it is quite sufficient for providing sufficient amounts of water to the clay plugs to yield maturation within a few months.

4 Program for evaluation of the evolution and conditions of the plugs

4.1 Field work

4.1.1 OL-KR24

Samples shall be taken on the -520 m level when the ramp has been excavated to this depth and a niche to the hole has been excavated, which is expected to be achieved in year 2011.

4.1.2 Äspö holes

The plugs in the holes at 220 m depth KA 1621G01 and KA1621G02 are planned to be overcored by a 200 mm borehole at a time decided later. The test program is the same as for the OL-KR24 hole and it will be based on the predictions.

4.2 Laboratory work

The samples extracted from the plugs will be examined according to the following program:

4.2.1 Cement/quartz concrete plug

Samples are carved to fit in triaxial cells for determining the i) density, ii) hydraulic conductivity, and iii) uniaxial compressive strength. The following test series is planned:

- A rock block containing a 1 m long plug is released by a series of overlapping boreholes.
- A 1 m long part of the plug is extracted and sawed into 10 pieces, representing 10 samples with 10 cm length from the contact with the clay plug.
- The density, hydraulic conductivity and uniaxial compressive strength of 5 cm long pieces sawed from the 10 cm long samples are determined.
- The remaining 5 cm long pieces of each sample are used for mineralogical, microstructural and chemical analyses.
- The part closest to the clay is analyzed with particular care focusing on the determination of the distribution of Ca from the contact with the clay.

4.2.2 Clay

The examination is intended to reveal possible erosion and effects of chemical interaction of cement/clay and copper/clay, as well as to identify and quantify possible heterogeneities in the form of different density of the central and peripheral parts of the clay columns.

Overcoring of the clay plug is made for getting an undisturbed piece of 2 m length. It is investigated with respect to the density distribution, hydraulic conductivity, swelling pressure and shear strength. The following test series is planned:

- A rock cylinder with 2 m length containing the clay plug is released by a series of overlapping boreholes. It is sawed in two equal parts and the plugs exposed by sawing them longitudinally.
- Each 1 m long part of the plug is sawed into to 10 pieces, representing 10 samples with 10 cm length from the contact with the concrete plug.
- The perforated tube is sawed longitudinally to yield two equal halves for taking samples of the clay located outside the tube, i.e. the skin, and to within half distance between the tube and the axis of symmetry, as well as of the remaining, central part. From each part smaller pieces are trimmed to fit in small-diameter oedometers for determining density, hydraulic conductivity and uniaxial compressive strength.
- From each part small specimens are extracted for mineralogical investigations, including XRD, CEC and chemical analysis.
- The part closest to the concrete plug is analyzed with particular care including determination of the distribution of Ca from the contact with the clay.

5 Discussion and conclusions

5.1 OL-KR24

The field work concerning preparation and placement of concrete and clay plugs in OL-KR24 could be successfully pursued and the techniques were shown to be practical and sufficiently robust to be recommended for application in other contexts. There were no indications of difficulties in constructing neither concrete nor clay plugs at larger depths.

The four most possible impacts on the physical constitution and performance of the clay plug of "Basic" type are 1) erosion of the clay in the emplacement phase and 2) too rapid expansion of the clay, which can generate high wall friction and difficulties in placing the plugs, 3) piping due to high hydraulic gradients along the hole, and 4) degradation by interaction with concrete after this phase. The first, third and fourth effects will be investigated at the extraction of the plug from the hole.

Early build-up of high hydraulic gradients, like in plugged holes drilled from the interior of a repository where the water pressure is low in the construction phase into the rock where the water pressure can be several MPa within a distance of a few meters, can cause piping and extrusion of the plugs. Also in deep holes like OL-KR24 the phenomenon may appear if significant differences in water pressure exist along it. A major risk is too rapidly increasing wall friction, because of too quick maturation of the clay plug. Theoretically, the time for placing the clay plug in OL-KR24 could have been as long as 8-12 hours without causing significant problems but the actual operation was completed in less than one hour.

Modelling of the hydration and maturation of the clay has indicated that where the rock gives off unlimited amounts of water at a pressure of at 4 MPa like in the OL-KR24 case, the clay plug will be largely matured in one or a few weeks.

The forthcoming examination of the concrete and clay plugs, particularly where they are in contact, will reveal both deviations from the intended densities and homogeneities as well as the extents to which chemically induced changes in physical performance and mineralogical compositions have taken place.

5.2 The Äspö holes

At shallow depth the time of maturation can be much slower depending on the frequency of intersected, water-bearing fractures, while at large depths the water pressure speeds up the saturation and makes it relatively independent of the spacing of intersected fractures. The concrete plugs at Äspö are expected to mature as in OL-KR24 despite the lower pressure.

The clay plugs at Äspö will not be affected by any of the problems that can be foreseen in deep hole plugging but they are located in rock with lower water pressure than in OL-KR24 and have limited access to water from the rock. This may have an impact on the chemical interaction between the concrete and clay in the sense that cement water will interact with the early formed "clay" skin around the dense clay plug and thereby affect its hydraulic conductivity and expandability. With the recorded hydraulic conditions in the rock the clay plugs are expected to be fully hydrated in a few months.

5.3 Evaluation of the evolution and conditions of the plugs

The proposed work comprises extraction of plugs from both test sites and laboratory investigations with respect to the physical properties and mineralogical composition of the clay and concrete plugs at different distances from their contact using available techniques for identifying possible changes and for getting a basis of conceptual modelling of identified reactions.

6 References

1. Pusch R, Ramqvist G, 2004. Borehole sealing, preparative steps, design and function of plugs – basic concept. SKB Int. Progr. Rep. IPR-04-57.

2. SWECO, 2004. Appendix 2 [ref. 1] IPR-04-57

3. CBI, Lagerblad B. & Vogt C., 2004. Concrete for plugging of deep boreholes. Int. report of Cement- och Betonginstitutet. Appendix 1 [ref 1] IPR 04-57

4. Börgesson L, Sandén T, 2005. Manufacturing of bentonite plugs with very high density. Subproject 1 IPR 06-28.

5. Pusch R, Yong R, 2006. Microstructure of Smectite Clays and Engineering Performance. Taylor & Francis, London and New York. ISBN10:0-415-36863-4.

6. Pusch R, 2001. Can the water content of highly compacted bentonite be increased by applying a high water pressure? SKB Technical Report TR-01-33. SKB, Stockholm.

7. Niinimäki R, 2003. Core Drilling of Deep Borehole OL-KR24. Working report 2003-52. Posiva Oy

8. Majapuro J, 2006. Geophysical borehole logging, dummy sonding and optical imaging of the borehole OL-KR24 at Olkiluoto 2005. Working Report 2006-26, Posiva Oy.

9. Rautio T, 2006. Borehole plugging experiment in OL-KR24 at Olkiluoto, Finland. Working Report, 2006-35. Posiva Oy.

Appendices

Appendix I

Report on evaluation of rock conditions in OL-KR24 for planning of plugging

Roland Pusch,

Geodevelopment International AB

Gunnar Ramqvist,

Eltekno AB

December 2006

1 Introduction

The about 550 m deep, vertical borehole OL-KR24 was selected for plugging experiments in 2004 using the "Basic" type clay plug concept and concrete of CBI type. The agreement between POSIVA and SKB was that POSIVA would be responsible for all required preparations, including rinsing and stabilization as well as dummy testing, before the plug installation, which SKB would perform. The most important part of the preparative work was to make sure that the hole would be stable at the start of the plugging and in the course of this activity. The present report describes how the matter of stabilization was handled.

2 Characterization of OL-KR24

2.1 Properties and parameters

Characterization of the hole was made with respect to straightness, wall surface topography, petrology (lithology), rock structure and conductivity, rock mechanical conditions, and electrical resistance as reported by POSIVA (Working Report 2003-52, and unpublished memos). The first five items were of greatest importance for the planned experiments and will be commented here. Further data of importance are:

- The hole is equipped with a mechanical packer at a depth of 25 m
- Start point of the borehole is +9.74. The depth (length) is hence not equal to the respective level, the difference being about 10 m. Thus, 320 m depth (length) is for example level -310 (approximately)
- Raise-boring, being the first phase of the shaft excavation, will start at level -410 (420 m depth) in 2008. The hole will be used for the boring, meaning that plugged parts will remain only below this level.

2.2 Straightness

The center of the hole deviates from the theoretical vertical axis by about 3 m at maximum. Assuming constant curvature the maximum lateral deviation of the axis from the theoretical center line over 25 m length is 170 mm, which means that a plug segment of this length will make contact with the rock at each end and undergo bending. This makes it necessary to check the straightness and smoothness by dummy testing. It was decided that the maximum length of plug segments of jointed tube elements was taken as 10 m.

2.3 Wall surface topography

Caliper measurements consistently showed a variation of the smoothness of the wall surface of +/- 1 mm except at certain levels that are expected to represent major fractures with a spacing of 5-10 m. Here, the caliper measure was up to 78 mm and occasionally more than that. At 120 m depth there was an abrupt change by 1 mm (77 mm calliper measure to 76 mm). These irregularities were estimated to be of insignificant importance for the experiments.

2.4 Petrology

Migmatic mica gneiss is the dominant rock type and according to the core analysis granite makes up about 13 % and tonalite about 0.5 %. Major hydraulic features seem to be associated with petrological changes. The petrological composition does not have any impact on how the hole could be used except that the nature, orientation and frequency of discontinuities (fractures and fissures) are mainly representative of gneissic rock.

2.5 Rock structure and hydrology

An early evaluation of the mapping and loggings indicated that the major discontinuities that could require stabilization were the following zones referring to POSIVA's depth designations:

- 21-23 m depth, fracture zone
- 43-48 m depth, fracture zone ("hydraulic feature")
- 76-78 m depth, fracture zone ("hydraulic feature")
- 93-95 m depth, fracture zone
- 114-116 m depth, fracture zone
- 172-220 m depth, fracture swarms
- 290-330 m depth, fracture swarms
- 304-307 m depth, fracture zone
- 330-332 m depth, fracture zone ("hydraulic feature")
- 396-398 m depth, fracture zone
- 422-424 m depth, fracture swarm/zone
- 535-540 m depth, fracture swarms (granite)

Hydraulically active, discrete fractures are frequent in all the major discontinuities and also intersect the hole with a spacing of a few meters in the depth intervals 170-220 m and 290-330 m as well as at about 400 and 420 m depths.

BIPS had revealed the small-scale structural constitution of the rock and illustrated the fundamental difference between the relatively homogeneous granitic parts, of which some are hydraulically very active like at 45 m and 330 m depths, and the strongly heterogeneous gneiss that is commonly schistose. However, in general, the BIPS are of limited value for evaluation of the mechanical and hydraulic performances of the rock mass.

2.6 Rock mechanical conditions

The rock mechanical properties are important in the sense that the stability of the hole must be guaranteed during the experiment. Two factors determine the stability: the rock stress conditions and the presence of strongly fractured or schistose parts. Critical rock stresses yielding a strongly anisotropic stress field can cause fall of larger rock pieces at inconvenient occasions, and debris can fall from schistose gneiss where plug tubes come in contact with the walls of the hole by which they may be stuck in the placement phase. The risk of spontaneous loss of stability is, however, low as demonstrated by the fact that the hole remained stable from the boring event to the time when caliper measurements were made. Stabilization by Portland cement grouting had been made in the depth intervals 298.30-308.70, and 374-384 m.

2.7 Rock stresses

The rock stresses had been reported to be moderately high but no data were provided for the OL-KR24 hole.

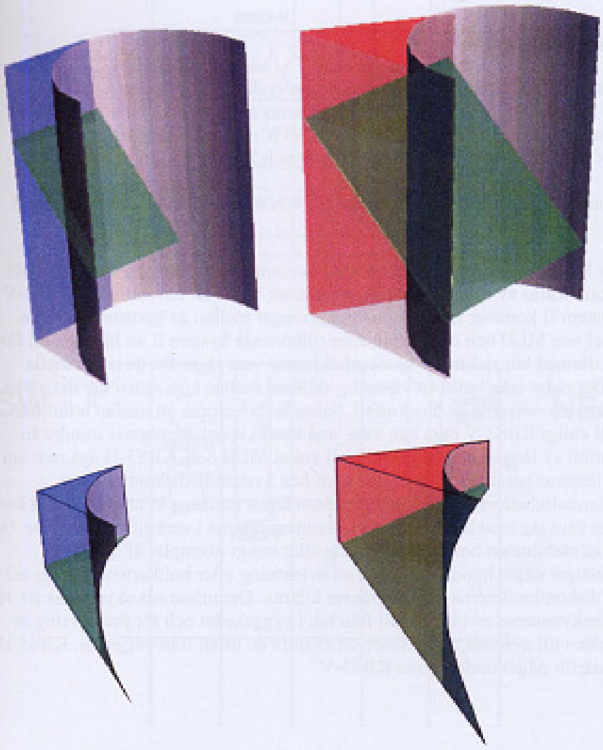
3 Selection of borehole parts for stabilization

3.1 Criteria

At a meeting at Olkiluoto on September 2, 2005, the issue of borehole stabilization was in focus with emphasis on time schedules, planning, and cost. The firstmentioned implied that the entire stabilization work had to be completed in Week 40 so that subsequent cleaning, characterization, and calliper/dummy testing could be completed before the beginning of Week 44 when plugging was scheduled to start. A second condition was that the available time and cost restrictions limited the number of zones to be stabilized to about 5.

Identification and selection of those parts that would require stabilization was proposed to be based on the following conditions:

- Where the fracture spacing and orientation is such that it can yield separation of wedges with a size that can make them drop in the hole. This depends on the interaction of critically oriented and located fractures as indicated in the first figure ("Figure 2-3"), and implies that the fracture spacing must be smaller than about 5 cm for representing critical conditions.
- Fractures or other weaknesses like biototite-rich laminae that are flatlying (more or less normal to the direction of the borehole) represent no significant risk.
- Clay or silt resulting from weathering can disintegrate spontaneously and lead to secondary fall of critically sized fragments. Such zones need stabilization.
- Stabilization will be made by reaming so that a "liner" of cement can be constructed for supporting the rock (Torbjörn Hugo-Persson, Lars Liiw, and Björn Lagerblad).



Figur 2-3 *Kritiska konstellationer hos sprickor i deponeringshål av typ KBS3-V för uppkomst av blockutfall. Övre rad: Skärning av branta plan med huvudsaklig orientering WNW/ESE och NNE/SSW samt plan med strykning nära E/W och 45° stupning. Undre rad: Form på avlossade kilar.*

3.2 Identification of parts requiring stabilization

The basis of selecting parts of the KR-24 hole that were judged to require stabilization had been worked out by Roland Pusch and Gunnar Ramqvist and presented at the meeting on September 2 ("Preliminary choice of zones for stabilization"). It was developed on the basis of data on petrology, mineralogy, fracture frequencies and hydrology collected by POSIVA, and on interpretations of POSIVA's TV-loggings made by Anders Odén, Björn Lagerblad, and Torbjörn Hugo-Persson. The zones estimated to require stabilization according to these preliminary judgements were the ones intersected at the boreholes depths (lengths) 114-118 m, 294-310 m, 328-332 m, 396-400 m, and 520-540 m.

Table 1 specifies these earlier estimates and contains a column filled in at the end of the core inspection that was made jointly on September 1. Following a brief discussion at this event there appeared to be consensus concerning the proposed borehole depths (levels). The need for stabilization was ranked, denoting the most important zones with ***, the second most demanding ones with ** and those recommended for stabilization but of presumably least important ones with *.

Table 1. Early specification of zones assessed to require stabilization.

Depth in meters/Level	**Data from profiles**	**Proposed zones for stabilization by O/L/H-P**	**Assessed on the basis of examination on Sept. 1 2005**
100-102/-90 to -92	Open fractures		No need for securing
114-116/-104 to -106	Fracture zone	Crushed rock, open fracture	No need for securing
116-118/-106 to -108	Open fractures		No need for securing
180-182/-170 to -172	Open fractures		No need for securing
184-186/-174 to -176			Fracture-rich (*), Plate I
188-190/-178 to -180	Open fractures		No need for securing
194-196/-184 to -186		Crushed rock	Crushed rock (*) Plate II
204-206/-194 to -196	Open fractures		No need for securing
294-296/-284 to -286	Open fractures		No need for securing
296-298/-286 to -288	Open fractures		No need for securing
298-300/-288 to -290		Subhor. Fractures	No need for securing
302-304/-292 to -294	Open fractures	Subhor. Fractures	No need for securing
304-306/-294 to -296	Open fractures	Subhor. Fractures	No need for securing
306-308/-296 to -298		Subhor. Fractures	No need for securing
308-310/-298 to -300	Open fractures	Subhor. Fractures	No need for securing
316-318/-306 to -308	Open fractures		No need for securing
328-330/-318 to -320	Open fractures	Crushed rock, water	No need for securing
330-332/-320 to -322	Open fractures	Crushed rock, water	No need for securing
378-380/-368 to -370		Core loss?	Needs to be checked by BIPS or similar
380-382/-370 to -372		Core loss?	Needs to be checked by BIPS or similar
382-384/-372 to -374		Plastic clastic mat.	Clay (**), Plate III
396-398/-386 to -388	Open fractures	Loose fragments	Fracture-rich (***), Plate IV
398-400/-388 to -390		Loose fragments	No need for securing
422-424/-412 to -414	Fracture swarm		No need for securing
430-432/-420 to -422		Subhor. fractures	No need for securing
432-434/-422 to -424		Subhor. fractures	No need for securing
520-522/-510 to -512	Wet, fractured		No need for securing
522-524/-512 to -514	Wet, fractured		No need for securing
524-526/-514 to -516	Wet, fractured		No need for securing
526-528/-516 to -518	Wet, fractured		No need for securing
528-530/-518 to -520	Wet, fractured		No need for securing
530-532/-520 to -522	Wet, fractured		No need for securing
532-534/-522 to -524	Wet, fractured	Subhor. fractures	No need for securing
534-536/-524 to -526	Wet, fractured	Subhor. fractures	No need for securing
536-538/-526 to -528	Wet, fractured	Subhor. fractures	No need for securing
538-540/-528 to -530	Wet, fractured	Subhor. fractures	No need for securing
545/-535 Lower end of borehole			

3.3 Recommended parts for stabilization

It was recommended that:

- Stabilization is made of four parts of the borehole in the following intervals (see Plates I to V):

- Borehole depths 184-186 m (Levels -174 to -176)

- Borehole depths 194-196 m (Levels -184 to -186)

- Borehole depths 382-384 m (Levels -372 to -374)

- Borehole depths 396-400 m (Levels -386 to -390)

- Inspection of the borehole at depths 378-382 (Levels -368 to 372) by BIPS technique or TV-logging be made for getting information on what the nature of the rock is where reported core loss took place. If the rock is richly fractured or contains clay and silt in this part it requires stabilization as well. Such inspection should also be made of the parts of the boreholes listed above for making sure that what was interpreted as "fracture-rich" parts did not originate from stress-induced disking of the core. The exact packer positions for the stabilization shall be decided on the basis of this inspection.

Plate I. *Depth 184-186 m/ (Level -174 to -176). Fracture-rich part just below depth 185 m (Level -175). Photo: R.Pusch.*

Plate II. *Borehole depths 194-196 m (Levels -184 to -186). Fracture-rich part just below depth 194.7 m (Level -184.7). Photo: R. Pusch.*

Plate III. *Borehole depths 382-384 m (Levels -372 to -374). Upper left part consists of clay/silt material. Photo: R.Pusch.*

Plate IV. *Borehole depths 396-400 m (Levels -386 to -390). Fracture-rich zone. Photo: R. Pusch.*

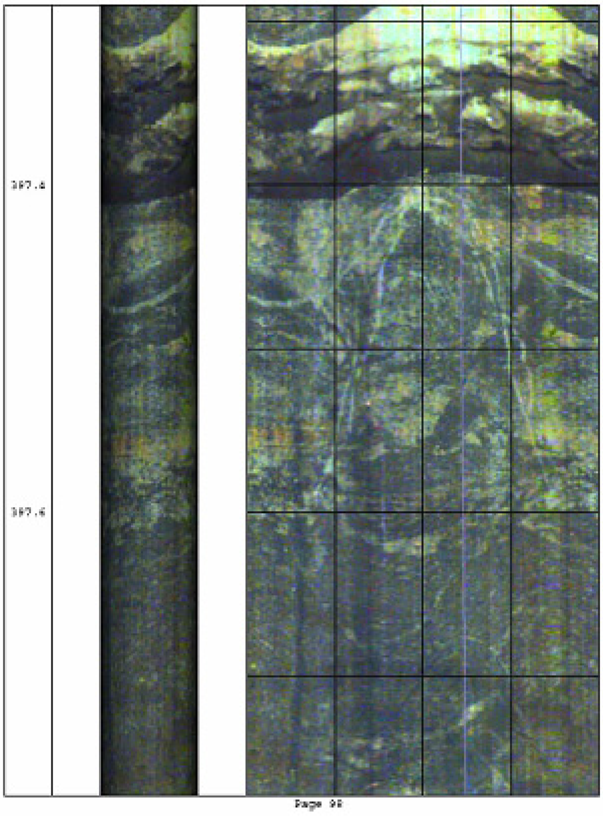


Plate V. *Borehole depths 396-400 m (Levels -386 to -390); Fracture-rich part BIPS-photographed (POSIVA).*

3.4 Planned stabilization work

The detailed planning of the stabilization work comprised the following steps:

- Decision of parts that needed stabilization
- Decision of materials and procedures

Final decision on parts deemed to require stabilization

At meetings held in Finland on October 4 and 5 (Antti Mustonen (Posiva Oy), Anders Oden (Sylog Consulting Ab) and Tauno Rautio (Suomen Malmi Oy), further exploration of the structural features and related stability issues was made, leading to a different plan for stabilization:

- Initial suggestion: Fracture zones at depths of 1) 347 m, 2) 381 m and 3) 397 m with the priority order 1>2>3. The intervals were decided to be three metres long at maximum.
- Final decision:

  - Exact interval: 345.40 - 347.90 m (Plate VI).

  - Exact interval: 379.76-382.76 m (Plate VII).

  - Exact interval: 396.70 - 399.20 (Plate VIII.

The intervals are listed in Table 2 respecting depth and levels (Z).

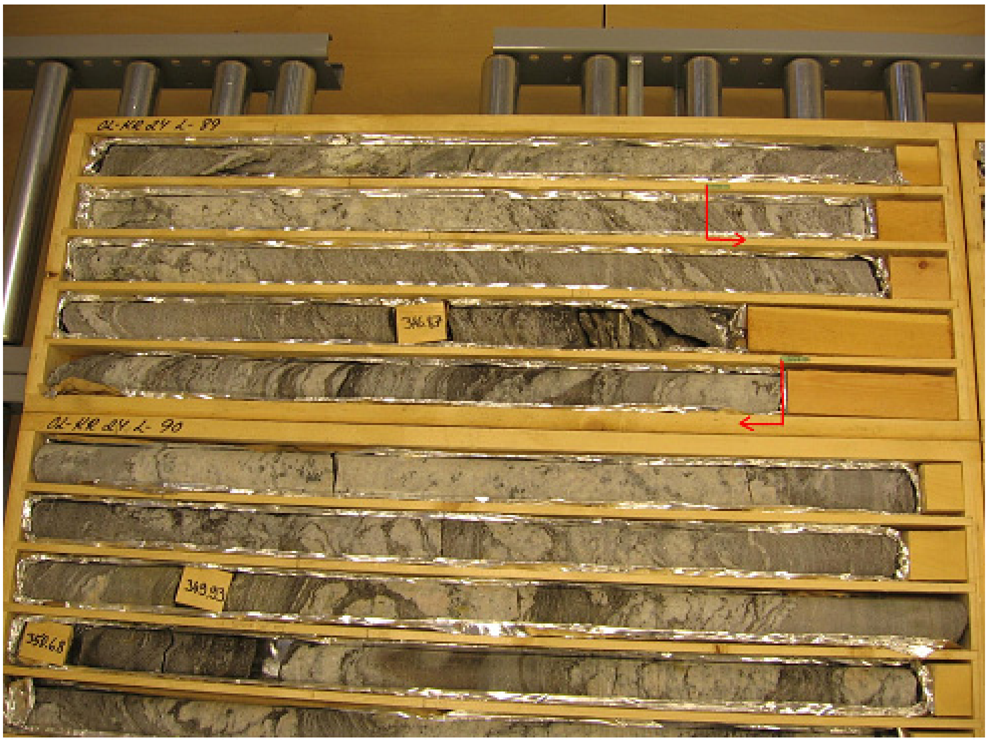


Plate VI. *First selected interval 345.40 - 347.90 m. Red arrows limit selection. Photo: A Mustonen.*

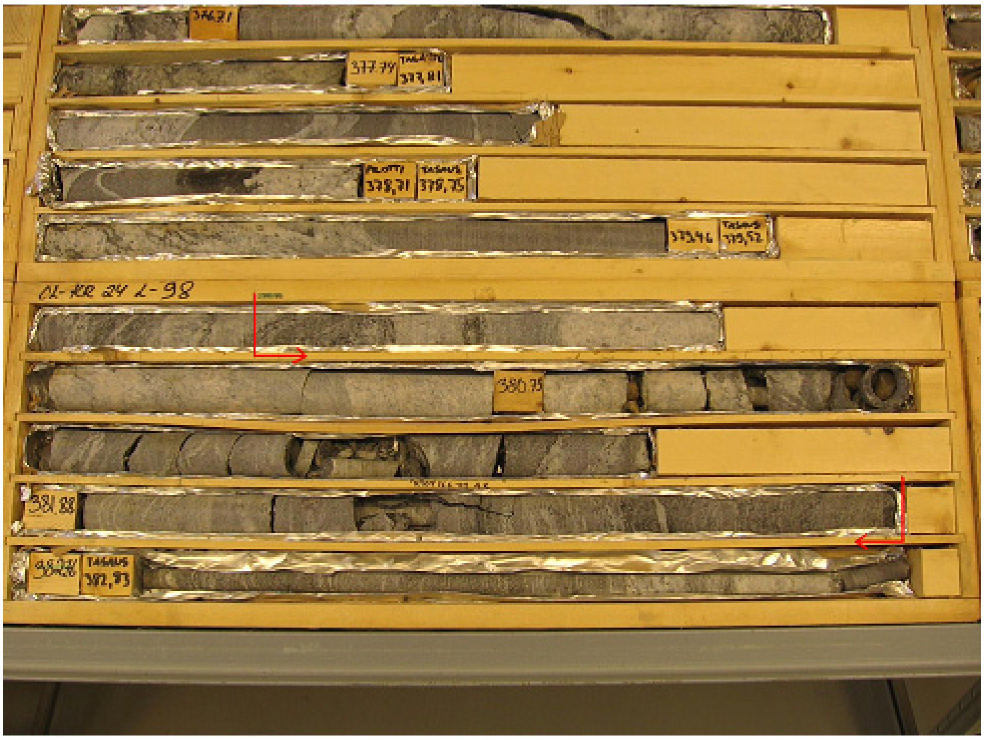
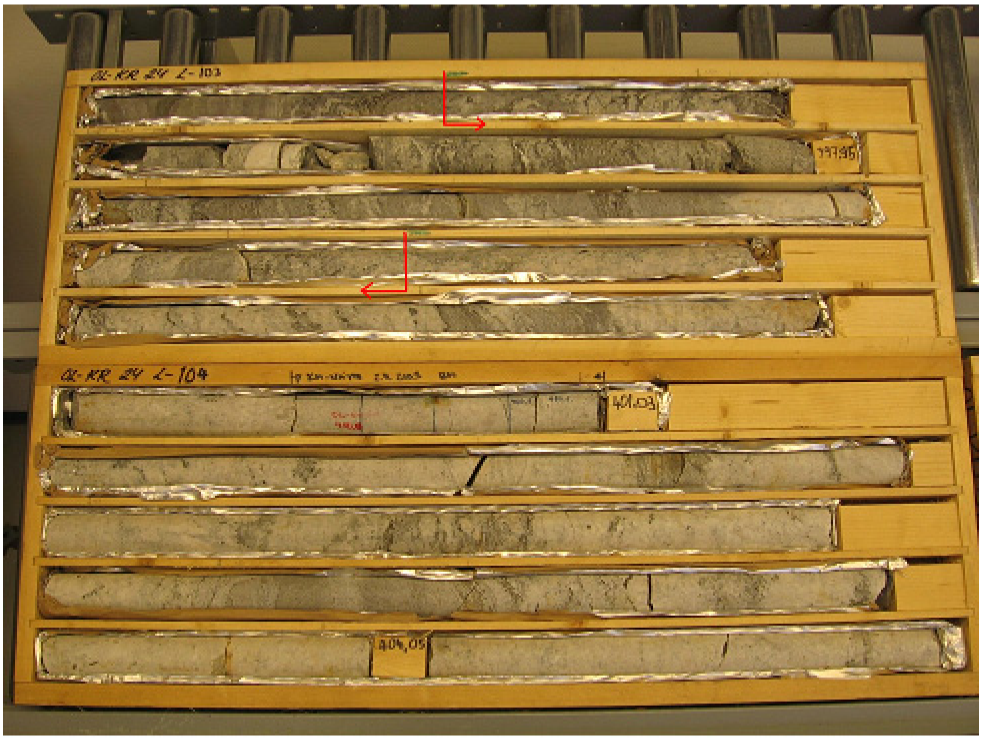


Plate VII. *Second selected interval 379.76 - 382.76 m. Red arrows limit selection. Photo: A. Mustonen.*



Picture VIII. *Third selected interval 396.70 - 399.20 m. Red arrows limit selection. Photo: A. Mustonen.*

Table 2. Selected intervals for stabilization. Depth from platform floor at site.

Original drillhole depth	Depth from platform floor	Z level
345.40-347.90	**346.00-348.50**	-335.63--338.13
379.76-382.76	**380.36-383.36**	-369.98--372.98
396.70-399.20	**397.30-399.80**	-386.92--389.42

Materials

The recipe of the cement-based material ("concrete") is given in Table 3.

Table 3. Concrete for stabilizing boreholes ("lining in reamed hole"), CBI

Components	Amount (kg/m3 concrete)	Manufacturer
White cement	514.26	Aalborg Portland
Silica Fume	342.84	Elkem
Fine ground α -quartz M300	133.2	Sibelco
Fine ground α-quartz M500	107.5	Sibelco
Superplasticizer Glenium 51*	8 (dry content)	Degussa
Fine quartz sand < 250 μm	325.4	Askania
Coarse quartz sand < 500 μm	488.1	Askania
Glass fibers 6 mm	53.6	Saint Gobain
Water	244.27	local

- *Other superplasticizers can be considered as well: Set Control II, SP-40, Mighty 150*

Procedure

Fine ground

The stabilization work included reaming and concrete casting followed by reopening by boring after hardening of the concrete.

The following steps and decisions were taken with reference to the documents in Appendix form.

- Reaming of the hole was successful
- The stabilization grout that was cast was of good quality but came at a wrong depth, i.e. 2 m higher than planned, so only the top 0.5 m of the uppermost 2.5 m long zone was equipped with concrete liner. The remaining 2 m interval could not be lined but was judged to be stable by Posiva.
- The two deeper intervals selected for stabilization were not stabilized but POSIVA took the decision not to pursue the stabilization. The hole was hence declared as ready for being plugged. It finally turned out that the hole apparently remained stable in the plugging. The final proof of this will be demonstrated when plug extraction and shaft excavation will be made.

Appendix II

Borehole plugging project in Olkiluoto – Stabilisation of borehole OL-KR24, 2005-10-06

Anders Odén

SKB

Report from first stabilisation:

October 5.

A start up meeting was held at SMOY depo, where the participants in the selective stabilisation as shown on page 5 in the AP were presented to each other. Safety rules at Onkala were presented by Antti Mustonen. Antti Öhberg, Posiva representative gave start signal for the stabilisation activity.

After the meeting Anders Odén together with activity leader Antti Mustonen went to see the core boxes to decide the exact location of the three zones we were going to stabilise. Following Zones were decided to stabilise:

1. 346,00 - 348,50 m (new zero is 60 cm higher)
2. 380,36 - 383,36 m
3. 397,30 - 399,80 m

Milling tool was lowered to 348,50 m and milling was done to 346,00 m. It went quite OK but with lower speed than planned. The reason most likely was hard rock and difficulties to know force on milling tool. Drill rig Diamec U8 is brand new for the drillers. Penetration rate was around 2 cm/min. Because of low penetration rate and water flow of 65 l/min the drillers had to stop twice to fill up the container with water. For next section SMOY will bring a second water container.

October 6.

Started by pulling out the milling tool. The bottom packer was mounted in the drill string and lowered to position below the milled section. The shear pins broke as they should and setting went OK. Rod string was pulled out of the borehole and top packer with filling tube was mounted.

Drill string with top packer was lowered into position 12 m above the milled section and was filled with water. Lower cement piston was put into drill string , which was lowered the last 12 m to position. Cement mixture was filled into drill rods above the lower piston. Just when we started to put upper cement piston into the tube we were asked to leave the site due to blasting in the tunnel.

After 20+ min we could go back and connect water swivel and start pumping. While we had to wait for blasting, the weight of the cement had pushed lower piston down, and created a section with air between cement and upper piston.

The upper piston was tight in the rods and we pumped down with 30 l/min and 15 bar, (in some rod joints pressure increased to 20 - 25 bar.) We calculated pumping time to 30 min. After 29 min pressure raise to 80 bar and we were sure lower piston was down at the packer.

Normally shear pins in the valve brake at 50 bar, but friction in upper piston could increase this value. By increasing pressure to 85 bar (max.) the pressure dropped again and we were sure the shear pins had broken and the valve was open. We pumped for 2½ min to fill the milled section. Then we locked the top packer by pulling rod string and closed the milled section.

The rod string was disconnected OK from packer and was pulled out of the hole. When 18 m remained cement mixture instead of water came out of the rods. Upper piston was placed 18 m above bottom and lower piston with unbroken shear pins was at the bottom. All cement had been remained in the drill string and there is no cement either in the section or in the hole.

What had happened was that upper piston got stuck in a narrow or bad rod joint and got loose again when pressure increased to 85 bar. And when we thought we pumped out cement we jus moved it around 10 m further down.

The reason for the upper piston to get stuck in the rod could be a combination of a narrow rod joint, the extra waiting time during blasting or a tight piston.

There is no damage to the borehole, upper packer has to be removed through drilling.

October 7.

Drillstring with Corborit bit has been lowered into borehole and drilling of upper packer is going on.

The borehole OL-KR24 is beeing prepared for a second try on Monday October 10 .

Borehole plugging project in Olkiluoto – Stabilisation of borehole OL-KR24, 2005-10-25

Anders Odén

SKB

Report of actions since last report:

Since the report 2005-10-11 the packers were drilled out and a new bottom packer was set 2005-10-13.

October 17

Before making a third attempt using the same top packer method we tested the valve in lower piston in a tube filled with cement mix horizontally on surface. The valve opened at 35 bar.

We mixed cement and set down rod string with cement at right depth and filled rods with water and started to pump. Pumping started 3 hours after we mixed the cement.

Sample at surface was still soft and possible to pump. We increased pump pressure first to 85 bar and then to 110 bar peaks, but valve did not open. Thus we had to pull back the rods again, this time we brought top packer again without drilling, after first pushing into the milled section to get rid of jaws. When rods came up we found cement mix dry and compacted above the lower piston. On surface we first connected the rod with cement to pump and tried to pump out cement but valve in piston did not open at 88 bar.

We decided to leave this method with pumping the cement mix through top packer and instead use method with transport of cement in long inner tube. This method has been used down to 345m in KAS 17 at Äspö in Hagby WL . Our equipment was modified to fit Corac N3. The inner tube takes 5 litre per 3 m. Normally it is between 12 and 24 m long depending how much cement is required. The inner tube goes through the bit and extrudes 2,5 m below bit when it has landed. In each end there is a piston and when pumping lower piston goes out at about 30 bar and upper piston push cement through inner tube.

October 18

A function test with water was made on surface and equipment was adjusted. 18 m inner tube was filled with cement and pumped into position. It went quite slow and

stopped a couple of times on way down. After 90 min it was in position and we started to pump. Lower piston left at 32 bar as it should and we pumped with 12 l/min and started to lift rod string. After one minute pressure started to increase and we lifted faster to 2 m. At 27 bar pressure dropped again. We interpreted this as upper piston had gone and stopped pumping and lifted rod string 20 m, then started pumping again now pressure increased again to 40 bar, then dropped and finally went up to 80 bar. When we pulled out the inner tube all cement had gone but upper piston was still at bottom of inner tube. This meant some cement had left in the milled section and some within 20 m above. The first indication was false, probably upper piston was stopped in a rod joint and passed when pressure increased.

October 20

We soon found that there was no hardened cement in the milled section just a soft mix at the bottom of the section.

We made adjustments to the equipment for the piston to run smoother inside the inner tube and the inner tube to run better inside the rod string. Cement was mixed in accordance with CBI manual without Carsten Vogt who left earlier.

35 l cement was filled into 21 m inner tube and pumped into position. This time it went much faster and inner tube was in position after only 9 minutes. Lower end of inner tube was just under the milled section and we started pumping. Lower piston left at 28 bar and we pumped with 12 l/min while we were lifting rod string slowly 3,5 m. Pump pressure increased to 80 bar indicating that inner tube was empty. We lifted rodstring 24 m and picked up inner tune with overshot. Inner tube was empty and upper piston had gone out. This time all cement had gone out within 3,5 m above bottom packer and cementation should be OK. 2 ref. samples were stored at 10 degrees. After 23 hour both samples were hard.

October 22

When drilling should start in the morning rod string was stuck in the borehole and it was impossible to move or turn. No water circulation. A hammer was ordered from Drillcon at Forsmark and was promised by Jetpak to be in Åbo same afternoon, but arrived one day later.

October 24-25

Trying to get rod string loose with hammer and without. Only improvement was that we got some circulation of water , although most of the water came back when we stopped pumping. After 1½ day the threads where hammer had been connected separated, and upper rod had to be replaced. It was decided to stop using the hammer and instead try jacks.

Appendix III

Report on – Removal of the drill string stuck in the borehole

Antti Mustonen

Posiva

When drilling should start in the morning on 22nd October it was noticed that rod string was stuck in the borehole. In addition there was no water circulation. It was decided to use pneumatic rod hammer to loose rods from the borehole.

Hammer arrived to Olkiluoto from Sweden on evening of 23rd. Next two days rod string was tried to loose with hammer. Only improvement was that we got some circulation of water. Most of the water pumped to hole came back through rod string when pumping stopped.

When rods stuck in hole could not be recovered with the rig and hammer, the next step was jack lifting. In jack lifting the rods were pulled with a special hole jack as long as the rods are released or the rods break at some point. The rods are under considerable tension and in the case of breakage the rods may be released fiercely. Jack lifting was started on 26th October. The rods were kept under tension two nights, but there was no mark of loosing.

On 28th October it was decided to cut drill rods inside the core barrel. The cutting planned to do with BGM drill rods and cutter. Casing cutter was lowered inside the core barrel with BGM -drill rods. The cutting blades opened with water pressure and the cutter was rotated with the rig and the BGM drill string. With first try the blades did not cut NT drill strings. The cutting depth was probed with BGM core barrel and rods and it was noticed that cutter was possible stopped in lift ring.

With second try on 30th October the NT drill rods were cut successfully and they were lifted from the borehole. Lifting of the drill rods were heavy to lifted at beginning, around the lowest rods cement was (about 20 m) noticed. After cutting there was still a core barrel, a core bit and a reamer left in the borehole.

With third try, the blades cut core barrel, but core barrel did not loose. The cutting place was 0.70 m from the upper end. It was decided to drill away rest of the core barrel.

Drilling was started on 4th November. When drilling the steel there was the basic risk that the new drilling will deviate from the original hole. Because of that, the core barrel was joined with advanced centralizer. Drilling of remaining parts was started on 5th November. When drilling was near core bit and reamer, the rest of material suddenly loosed and was lifted with retriever from the borehole.

6th November the cement and the packers were drilled away with corborit bit. During drilling it was noticed that the level of the cement was at the depth of 337.42 m.

Below the cement, at the depth of 338.07 there was a top packer. Below the packer there was eight metres of hard cement to the depth of 346.08 m. The bottom packer was found from that level. Below the bottom packer there was hard cement to the depth of 346,26 m and partly hard cement to the depth of 346.56 m. Below cement was the Van Ruth bottom packer and parts of plastic tubes. At the end of the drilling, drill rods were lowered to the bottom of the borehole to check that the borehole was completely open.

Filling of the borehole above level -510 with concrete[1]

After Borehole KR24 was plugged with quartz cement plugs and copper-bentonite plug, hole was filled with cement on 15th of November. Concrete truck loaded concrete from mixing station in Rauma and Grout-aid and retardant were added to concrete on site at Olkiluoto.

Pumping of concrete started when drill string was at depth of 500 m (level -490) i.e. 20 m above plugged interval. When 1.5 m^3 of concrete was pumped to drill string, 60 metres rods were lifted up and other 0.3 m^3 of concrete was pumped to drill string. After this all rods were lifted up.

When all rods were up, uplifting of 84/77 mm casing was started. When casing was loose, it was filled with concrete and casing was removed. After casing was removed, level of the concrete was checked. Level of the concrete was found at 25 m depth and 0.1 m^3 of concrete was added to hole. Altogether about 2.6 m^3 of concrete was use to fill borehole.

After filling demobilization of the rig started. When outer casing (114 mm) was removed level of the concrete was measured it was found 1 m below shaft floor.

---

[1] Considered as last stabilization of OL-KR24 (remark by R. Pusch)

Appendix IV

Telephone meeting regarding the borehole plugging project

Time: 13.00-14.00, November 10, 2005

Place: Telephone meeting

Participants: Christer Svemar, SKB, chair

Marina Lindén, SKB

Lars Liw, LiwInStone AB

Carsten Vogt, CBI

Gunnar Ramqvist, SKB

Timo Äikäs, Posiva Oy

Antti Mustonen, Posiva Oy

Jukka-Pekka Salo, Posiva Oy

Antti Öhberg, Saanio & Riekkola Oy, secretary

The situation in OL-KR24

- The hole is clean down to the bottom, i.e. to 550 m depth.
- The stabilization grout that was cast with good quality came at a wrong depth, 2 m higher than planned, so only the top 0.5 m of the 2.5 m long expanded zone was equipped with the concrete liner. The remaining 2 m have no cover, but was anyway judged stable by Posiva.
- The other two locations for stabilization are as well judged to be stable by Posiva without any measures.
- The try to put the bottom 30 m of concrete in the hole failed as the cement component had been washed away leaving the ballast alone at the bottom. The concrete mass had not hardened and there was no sign of cement or aggregate at the bottom of the hole. The drill string was lowered to the bottom of the hole after sonding with wire-line indicated there was no cement.
- Grouting of the ramp will in the next round probably reach the R19A, and will most certainly leak grout into KR24, and ruin the chemical conditions determined by the host rock.
- But grout may also fix the casing in the borehole KR24, which reaches down to 120 m depth, i.e. below the depth where the ramp will pass the shaft location.
- Posiva has decided to pull out the casing before the next grouting batch that is planned to start on Friday November 18th.
- This means that the bore hole is available until Wednesday only for installation of the test plug.

Proposition

Posiva proposes that instead of concrete at the bottom under Q/C only aggregates (0-8 mm) would be placed. This would be a rather fast operation. The aggregates could form a stable ground for Q/C plug. Aggregates should fill the bottom of the hole to the planned depth i.e. -530 level. The level of the aggregates should be checked every now and then during the filling process in order to get close to the desired level. The work could start immediately. Aggregates can be flushed off from the hole (if needed) in the future when the access tunnel is ready and the sampling of the copper/bentonite plug has been completed. If the aggregates are hard, they can be core drilled.

Decision-making, step by step

1. The decision was to fill the bottom (30 m) of the hole with aggregates (0-8 mm).
2. Then install a 5 m long quartz cement plug on top of that.
3. Then install 4 copper tubes with bentonite blocks, each with a length of 2.5 m, on top of that.
4. And then another quartz cement plug of approximately 5 m ends the test installation.

Christer pointed out that this introduces a risk for the application 2008, as the outcome of the performance is difficult to predict with so many unknown parameters involed, and a negative outcome certainly would affect the repository programme in Sweden in the future.

The installation, in case it is successful, may only serve as a benchmark, and be of value as an example of an outcome when things go wrong, or possibly be an example for defining a "worst case scenario".

Posiva will take full responsibility for the installation phase, if anything happens during lowering into the hole, they will try to pushed don to the bottom, and fill the hole with cement.

Contacts

Antti Mustonen and Gunnar Ramqvist are the contact persons during this weekend and they will send SMS and e-mail on the status of the bore hole KR24. On Sunday the latest there need to be a decision about the continuation with the quartz cement plug.