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Sealing of investigation boreholes, Phase 4

Final report

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September 2011

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Summary

The report describes the outcome of Phase 4 of the project "Sealing of investigation boreholes", which deals with 1) characterization and planning of borehole sealing, 2) performance and quality assessment, 3) sealing of large diameter holes, and 4) interaction of clay and concrete plugs.

A specific goal was to find ways to characterize plan and seal of boreholes so that their impact on the overall hydraulic performance of the repository rock can predicted and controlled. The work comprised selection of representative "reference holes" at the Laxemar and Forsmark sites for development of a general programme for planning and simulating implementation of borehole plugging campaigns, considering also cost issues. A second aim was to define and quantify the role of seals in the reference holes for finding out how important sealing really is. A third was to test a practical way to seal large diameter boreholes and a fourth to find out how concrete matures and performs in contact with smectite clay.

The study demonstrated, in conclusion, the need for developing techniques for preparing deep boreholes before lasting seals are installed in them, since poor sealing can short-circuit hydraulically important fracture zones intersected by the holes. The practically oriented sealing activities showed that the technique developed for tight sealing of large-diameter boreholes is practical and feasible. The issue of chemical stability was investigated by testing the performance and constitution of a plug consisting of CBI concrete in contact with smectite-rich seals for almost three years. This study showed that none of them underwent substantial degradation in this period of time, but chemical reactions and thereby generated changes in physical behaviour of the plug components had taken place, particularly in the clay. The rate of degradation is, however, not yet known. It was concluded from this study that it is suitable to carry out a corresponding investigation of the plugs in the "twin" hole (KA1621G02) at the –220 m level at Äspö HRL and to develop other concrete brands of more inert type.

A number of not yet solved problems in constructing and installing seals have been identified in the course of the study. They are defined and listed in the report and should be considered in the planning of future work for providing a basis for full-scale implementation.

Sammanfattning

Rapporten beskriver resultatet av Fas 4 av "Sealing of investigation boreholes" som rör 1) karakterisering och planering av borrhålspluggning, 2) kvalitetsbedömning och värdering av borrhålstätning, 3) byggnad respektive installation av pluggar av betong och smektitlera i borrhål med stor diameter, samt 4) byggnad och funktionsvärdering av borrhålstätningar av betong i kontakt med smektitlera.

Ett särskilt syfte var att finna sätt att karakterisera borrhål och planera pluggning av dem så att pluggningens inverkan på den översiktliga hydrauliska funktionen hos förvarsberget kan bestämmas. Arbetet omfattade val av representativa "referensborrhål" för att utveckla ett generellt program för planering och genomförande av borrhålstätningskampanjer, med samtidigt beaktande av kostnader.

Ett annat mål var att definiera och kvantifiera borrhålstätningarnas funktion i de valda "referenshålen" för att bedöma hur angeläget det är täta dem i längre tidsperspektiv. Ett tredje var att pröva ett praktiskt förfarande att täta borrhål med stor diameter och ett fjärde att utvärdera hur betong i kontakt med smektitlera fungerar med hänsyn till möjlig ömsesidig degradering.

Studien visade sammanfattningsvis på behovet av att nyttja beständiga tätningar i djupa borrhål som annars kan kortsluta hydrauliskt aktiva sprickzoner som hålen skär igenom. De praktiskt inriktade undersökningarna visade att tekniken som utvecklats for tätning av grova borrhål är praktisk och funktionell. Undersökning av CBI-betong i kontakt med smektitrik lera har inte visat omfattande degradering av någon av dem under den 3 år långa testperioden men både kemiska reaktioner och därav orsakade förändringar av de fysikaliska egenskaperna hos pluggkomponenterna hade ägt rum, särskilt i leran. Hastigheten hos degraderingen är dock inte känd. En slutsats från denna undersökning är att det är angeläget att genomföra motsvarande undersökning i ”tvillinghålet" (KA1621G02) på –220 metersnivån i Äspölaboratoriet och att utveckla andra betongtyper av mera inert typ.

Ett antal ännu inte lösta problem när det gäller byggande och installation av tätningar identifierades under loppet av studien. De är definierade och listade och bör beaktas i planeringen av fortsatt arbete med att utarbeta en grund för fullskalig tillämpning.

Contents

1 Introduction

1.1 Scope of study

The objective of Phase 4 of the borehole sealing project was to work out principles for sealing of typical long boreholes extending from the surface and from the repository level respectively, so that they do not form effective transport paths for radionuclides migrating from the repository to the biosphere. The study comprised the following sub-projects:

1. Characterization and planning of borehole sealing.
2. Performance and quality assessment.
3. Sealing of large diameter holes.
4. Interaction of clay and concrete plugs.

The specific goal of "Subproject 1" was to characterize and plan plugging of boreholes for evaluation of the overall hydraulic performance of the repository rock comprising investigation holes. The work comprised selection of representative "reference holes" for development of a general programme for planning, materialising and evaluating the effect of borehole plugging, considering also cost issues.

The aim of "Subproject 2" was to define and quantify the role of seals, interchangeably called plugs in the study, in boreholes selected in "Subproject 1", considering above all the need for sealing. This called for numerical groundwater flow modelling applied to the hydrogeological models of the Forsmark and Laxemar sites and consideration of the quality of constructed seals.

All the modelling work is presented in a separate report, SKB R-11-17 (Bockgård 2011). Borehole characterization will be required in practice for determining possible geometrical restraints respecting the dimensions and sealing potential of clay plug segments. The borehole diameter controls this potential and also the rate of maturation of contacting clay and concrete, witch determine the procedure of installing them. Suitable principles of installations have been identified but futher development of techniques for adequate construction were found to be required, especially for very long boreholes. Preliminary cost estimates were included in this study.

"Subproject 3" focused on sealing of large-diameter holes and included actual construction of plugs in two 300 mm boreholes used in a separate SKB study, on the hydraulic performance of fracture zones at about 400 m depth in the Äspö HRL. The finally selected sealing technique Will be presented in a separate report "Sealing of 300 mm boreholes KXTT3 and KXTT4 at Äspö HRL, SKB R-11-19 (Pusch and Ramqvist 2011a).

"Subproject 4" dealt with an issue of fundamental importance for repository performance, i.e. the chemical interaction of smectite clay and concrete. It has been in focus in a number of earlier studies and will determine the possibility to use CBI concrete in contact with clay in deep boreholes. A comprehensive laboratory study including X-ray diffraction (XRD), X-ray fluorescence (XRF) and electron microscopy study (SEM and TEM) on the sample material was performed including also dual beam (combined ion and electron) microscopy. Samples for geotechnical and chemical analyses were stored at 5°C in the laboratory before being tested at SWECO's lab and at the geological laboratory of Greifswald University in January/February 2010.

The present document shows the outcome of the four subprojects focussing on the issues considered in "Subprojects 1 and 2", with special emphasis on the impact of poorly performing seals and on particle tracking in the integrated system of boreholes. It also describes the experience from Subprojects 3 and 4 in sufficient detail to realise the comprehension and practical importance of the respective issues. The scientific treatment of the matters in "Subproject 4" is far to extensive to be included even in condensed form in the present summary report, and the reader is therefore referred to the forthcoming special report "Interaction of clay and concrete plugs – Plugging of 5 m deep hole KA1621G01 at Äspö", SKB- R-11-18 (Pusch and Ramqvist 2011b).

1.2 Fundamental principle of sealing deep boreholes

The basic principle selected for borehole sealing is to tightly seal those parts of long boreholes where the rock has few fractures and a low hydraulic conductivity, and to fill the parts that intersect permeable fracture zones with physically stable material that does not need to be very tight. The latter zones are those with a potential to undergo tectonically induced strain and plugs placed in them may be exposed to repeated large strain that would anyhow affect the sealing potential. This fundamental principle was selected for the entire Phase 4 but detailed plugging techniques were not specified in the work performed in Subprojects 1 and 2.

For Subproject 3, compacted blocks of smectite clay (CEBO-gel), were moved into the inclined 300 mm diameter holes for occupying parts with little water inflow and separated by concrete cast in the holes. The technique for clay plugging is termed the Couronne principle (Pusch and Ramqvist 2006a).

For Subproject 4, which was initiated in 2006, the clay plugs brought in contact with CBI concrete cast on top of them were of Basic type, i.e. consisting of a perforated copper tube containing tightly fitting highly compacted smectite blocks (MX-80).

2 Subproject 1 – characterization and planning of borehole sealing

2.1 Work plan

The work included the following activities:

- to identify several candidate boreholes for selecting a few reference holes among them for determining how they may interfere with a repository and how they can be sealed,
- to make a first simple estimate of the overall function of plugs separating permeable fracture zones. This would indicate how important plugs really are for sealing off boreholes,
- to estimate the flow rate of water from a selected imaginary repository through selected boreholes passing through the repository to the nearest large fracture zone,
- to estimate if partial or complete loss of the sealing potential of borehole plugs plays a practically important role. This would make it possible to determine if the plugs need to be of high quality or, if sufficiently effective, be simple and cheap.

The latter two were preliminarily considered in Subproject 1 but became main issues in Subproject 2.

2.2 Selection of candidate holes

The selection of reference holes was based on the following premises:

- at least three deep holes for each of the Forsmark and Laxemar sites should be identified for detailed study of the function of seals. The holes must be well characterized with respect to the nature and location of intersected fracture zones and of the borehole constitution (diameter variation, straightness, inflow/outflow of water),
- one subhorizontal hole of 50 to 100 m length extending from the Äspö HRL should be selected for later investigation of how sealing can be made where very high hydraulic gradients prevail. The hole must be characterized in the same way as the long ones,
- the holes should represent typical conditions of the respective site,
- one or two of the selected deep candidate holes at each site should be appointed "reference" holes and used in the project.

Examination of maps and sections showing the location of major fracture zones led to the conclusion that of the 43 boreholes made with depths up to 1,200 m length [1] those specified in Table 2-1 should be taken as candidate holes in the project. The argument for this is that the length should exceed 500 m – except for a subhorizontal borehole – and that several major fracture zones should be intersected by each of the deep holes.

Table 2-1. Candidate holes in the borehole sealing project. The holes were core-drilled.

Site	Borehole	Length, m
Forsmark	KFM07A	1,000
Forsmark	KFM09A	800
Forsmark	KFM09B	620
Laxemar	KLX04	1,000
Laxemar	KLX06	1,000
Laxemar	KLX10	1,000
Äspö	KA3386A01	80

[1] Most of the holes are 300–400 m deep.

Boreholes reaching deep down into the repository rock can serve as migration paths for possibly released radionuclides to the biosphere. This may involve major fracture zones that are intersected by the holes, and mutual hydraulic interaction of these zones. They are exemplified in Figures 2-1 and 2-2 and listed in Table 2-2 for the Forsmark and Laxemar sites. Fracture data are from Sicada database, October 2009.

Table 2-2. Major fracture zones intersected by the boreholes (here denominated first-order zones) as well as zones (here called second-order zones) penetrated by the first-order zones 1 = Single Hole Interpretation. 2 = Rock Visualization System. 3 = metres borehole length (mbl). OF = Open Fractures, SF = Sealed Fractures, RU = Rock Unit.

Borehole	First-order zones, (geological model names, borehole part and fracture character)	Second-order zones (RVS-model name)
Forsmark	**Length of intersected borehole section in metres borehole length**	
KFM07A	DZ1, ZFM1203, ZFMNNW0404, 90–154 mbl, OF/SF	ZFMENE0159A, ZFMNNE2309, ZFMWNW2225, ZFMA2, ZFMENE2320, ZFMENE2325A–B
KFM07A	DZ2, 165–173 mbl, OF/SF	Not associated with a deterministically modelled zone of length >1 km.
KFM07A	DZ3, ZFMENE0159A, 351–355 mbl, SF/OF	ZFMNW1200, ZFMNNW0100
KFM07A	DZ4, ZFMENE1208B, ZFMENE1208A, ZFMNNW0100, 665–815 m, SF/OF	ZFMNW1200, ZFMENE0159A, ZFMENE2320, ZFMENE2325A–B
KFM09A	DZ1, ZFMENE1208A, 9–30 mbl, SF/OF	ZFMNW1200, ZFMNNW0100
KFM09A	DZ2, ZFMENE1208B, 69–95 mbl, SF	ZFMNW1200, ZFMNNW0100
KFM09A	DZ3, ZFMENE0159A, ZFMNNW0100, 179–232 m, SF/OF	ZFMNW1200, ZFMENE2320, ZFMENE2325A–B, ZFMENE1208A–B
KFM09A	Vuggy rock, 416–424 mbl	RU6
KFM09A	DZ (identified at extended SHI), 530.5–531 mbl	Not associated with an RVS name
KFM09A	DZ4, ZFMNW1200, 570–591 mbl, OF/SF	ZFMENE1208A–B, ZFMENE0159A, ZFMNNW0100
KFM09A	DZ5 ZFMNW1200, 602–615 mbl, SF	ZFMENE1208A–B, ZFMENE0159A, ZFMNNW0100
KFM09B	DZ1, ZFMENE1208A, ZFMENE1208B, ZFMENE0159A, 3–103 mbl, SF/OF	ZFMNW1200, ZFMNNW0100
KFM09B	DZ (identified at extended SHI), 222.8–223.2 mbl	Not associated with an RVS name.
KFM09B	DZ2, 242–266 mbl, SF/OF	Not associated with a deterministically modelled zone of length >1 km.
KFM09B	DZ3, ZFMENE2320, 284–322 m, SF/OF + vuggy rock	ZFM1203, ZFMNNW0404, ZFMNNW0100
KFM09B	DZ4, ZFMENE2325A, 399–420 mbl, SF/OF	ZFM1203, ZFMNNW0404, ZFMNNW0100
KFM09B	DZ5, ZFMENE2325B, 428–437 mbl, SF/OF + vuggy rock	ZFMENE2325A, ZFM1203, ZFMNNW0404, ZFMNNW0100

Borehole	First-order zones, (geological model names, borehole part and fracture character)	Second-order zones (RVS-model name)
Laxemar	**Length of intersected borehole section in metres borehole length**	
KLX04	DZ3, ZSMEW946A, 5 m, OF	ZSMEW007A, ZSMNE944A, ZSMNE942A, ZSMNE107A, ZSMNW042A, ZSMNS059A, ZSMNS046A
KLX04	DZ4, ZSMEW007A, 2 m, OF	ZSMEW946A, ZSMNS059A, ZSMNE944A, ZSMNE942A, ZSMNS046A, ZSMEW002A, ZSMNE005A, ZSMNS945A, ZSMNW929A
KLX04	DZ5, ZSMEW007A, 10 m, OF	ZSMEW946A, ZSMNS059A, ZSMNE944A, ZSMNE942A, ZSMNS046A, ZSMEW002A, ZSMNE005A , ZSMNS945A, ZSMNW929A
KLX04	DZ11, ZSMEW007A, 1 m, OF	ZSMEW946A, ZSMNS059A, ZSMNE944A, ZSMNE942A, ZSMNS046A, ZSMEW002A, ZSMNE005A , ZSMNS945A, ZSMNW929A
KLX04	DZ6, ZSMNW928, 100 m, OF	ZSMEW002A, ZSMNW052A, ZSMNW047A, ZSMNS046A, ZSMNE040A, ZSMEW007A, ZSMNE107A, ZSMNE006A, ZSM005A
KLX06	DZ1, ZSMNW052A, 60 m, OF	ZSMEW002A, ZSMNS046A, ZSMNW047A, ZSMNW928
KLX06	DZ2, ZSMEW002A, 135 m, OF	ZSMEW007A, ZSMNS001E, ZSMNW119A, ZSMNE011A, ZSMNS001D, ZSMEW120A, ZSMNW052A, ZSMNS046A, ZSMNW047A, ZSMNW928, ZSMEW013A, ZSMNE040A, ZSMEW014A, ZSMNW931A, ZSMNE006A
KLX10	DZ1, ZSMNE942A, 12 m, OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ2, ZSMNE942A, 10 m, OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ3; ZSMNE942A, 2 m, OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ4, ZSMNE942A, 19 m,OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ5, ZSMNE942A, 8 m, OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ6, ZSMNE942A, 18 m, OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ7, ZSMNE942A, 30 m, OF	ZSMEW946A, ZSMEW007A, ZSMNS046A, ZSMNS945A, ZSMNS947A, ZSMNW042A
KLX10	DZ9, ZSMEW946A, 0 m, OF	ZSMEW007A, ZSMNE944A, ZSMNE942A, ZSMNE107A, ZSMNW042A, ZSMNS059A, ZSMNS046A

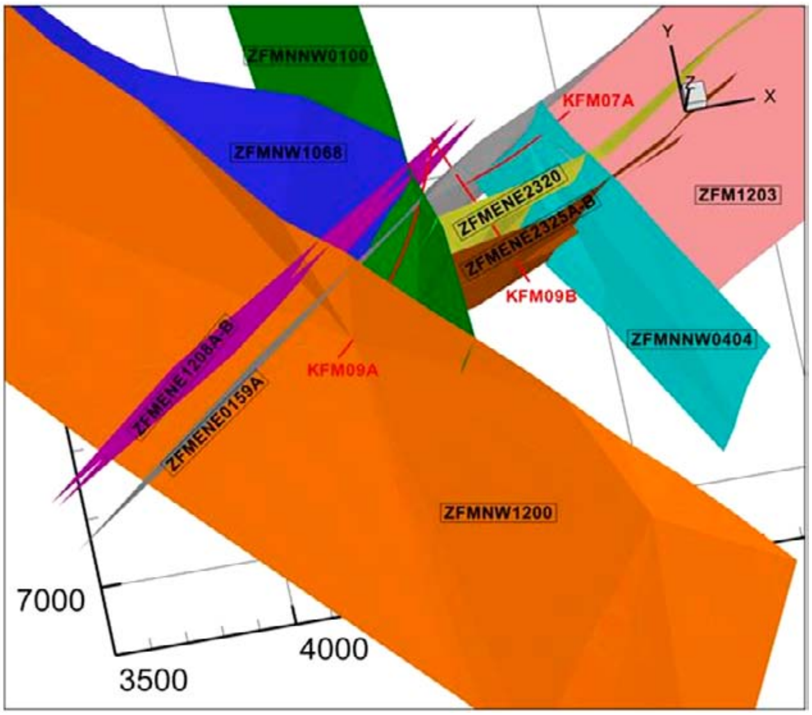

***Figure 2-1.** Parallel perspective view of Forsmark with the three boreholes KFM07A, KFM09A and KFM09B. KFM07A intersects two major zones, ZFMNNW0404 and ZFM1203 as well as the steeply dipping zone ZFMENE0159A and, towards the borehole bottom, the three steep zones ZFMENE1208A, ZFMENE1208B and ZFMNNW0100. KFM09A intersects the small steep components of ZFMENE1208A–B, the very steep ZFMENE0159A and ZFMNNW0100, and the relatively flat-lying ZFMNW1200. They can all be shortcircuited by the borehole if it leaks. KFM09B intersects 4 rather steep zones ZFMENE1208A–B, ZFMENE0159A, ZFMENE2320, and ZFMENE2325A–B. The latter four zones can be short-circuited by this borehole.*

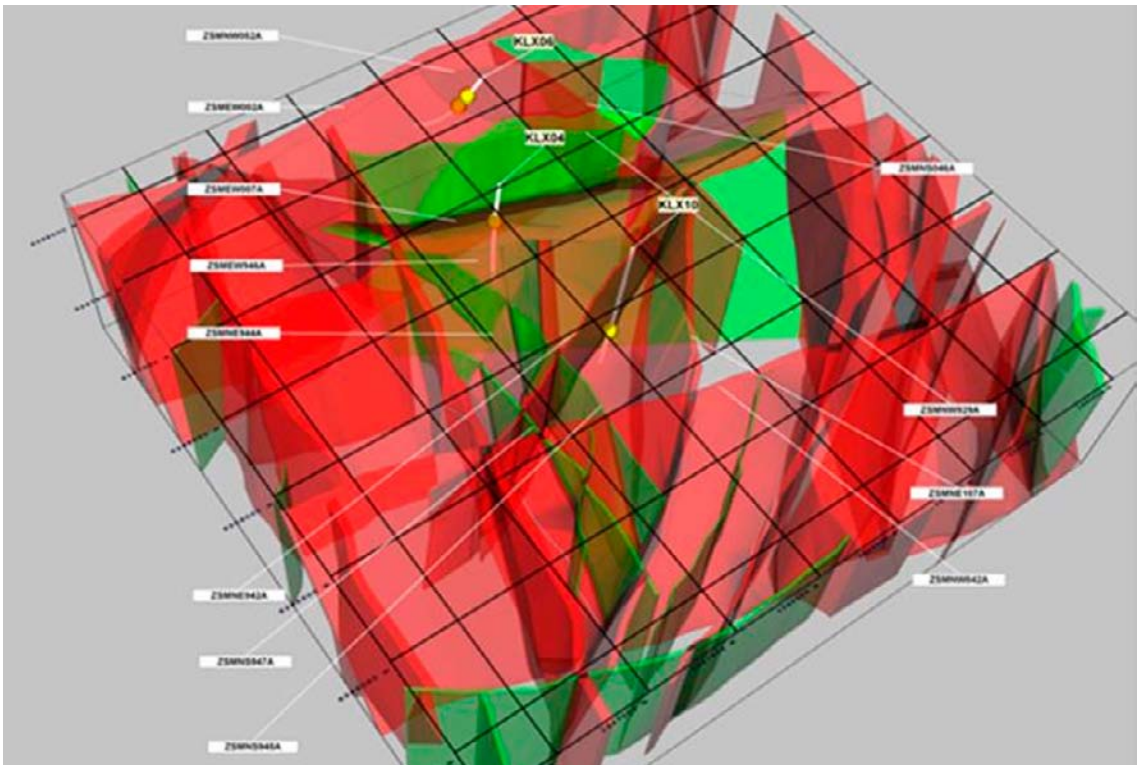

***Figure 2-2.** Perspective view of Laxemar with the three boreholes KLX04, KLX06 and KXL10. The boreholes intersect a number of steeply oriented fracture zones: 19 zones by KLX04, 4 zones by KLX06, and 10 zones by KLX10. The spheres indicate the upper ends of the holes.*

2.3 Borehole plugging techniques and materials

2.3.1 Clay plug types

The principle chosen for the entire Borehole sealing project is to seal the holes tightly with clay plugs where the surrounding rock is poor in fractures and tight and to fill them with physically and chemically stable material, "silica concrete" plugs, where they intersect water-bearing fracture zones. The two types are installed interchangeably, which requires that the respective plug must mature sufficiently much to be able to carry the subsequently placed overlying plug component without yielding before installation can proceed. A basic criterion is that each plug must harden in about 1 day. The tight plug design considered is represented by the examples shown in Figure 2-3. The concrete cast where the holes intersect water-bearing zones is of the type described in the subsequent subchapter. Sealing of the uppermost parts of the boreholes is not included in this report (Pusch and Ramqvist 2007).

2.3.2 Concrete – stabilization

Concrete is used for two purposes in deep or long boreholes: 1) stabilization of intersected fracture zones by reaming, casting of concrete, and re-boring, 2) construction of plugs by casting of cement-stabilized fine-aggregate silty sand. The recipe of the concrete for stabilization purposes is given in Table 2-3. The granulometrical composition of the quartz aggregate will make it perform as a mechanically stable filter for minimizing migration an loss of clay particles.

Table 2-3. Concrete for stabilizing boreholes (CBI[2]) (Pusch and Ramqvist 2007).

Components	Amount (kg/m^3 concrete)	Manufacturer
2.4 White cement	2.5 514.26	2.6 Aalborg Portland
2.7 Silica Fume	2.8 342.84	2.9 Elkem
2.10 Fine ground, α-quartz M300	2.11 133.2	2.12 Sibelco
2.13 Fine ground, α-quartz M500	2.14 107.5	2.15 Sibelco
2.16 Superplasticizer Glenium 51	2.17 8 (dry content)	Degussa
2.18 Fine quartz sand, < 250 µm	2.19 325.4	Askania
2.20 Coarse quartz sand < 500 µm	2.21 488.1	Askania
2.22 Glass fibers, 6 mm	2.23 53.6	2.24 Saint Gobain
2.25 Water	2.26 244.27	2.27 Local

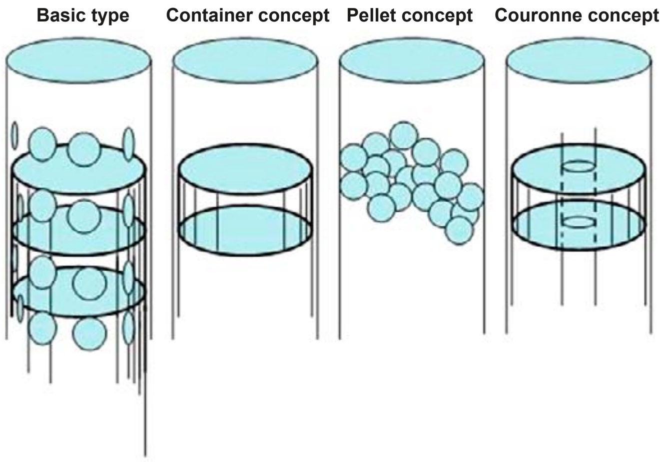

__Figure 2-3.__ Clay plug concepts. Left: "Basic" type with dense clay blocks confined in perforated copper tubes. Second left: "Container" plug with blocks in a cylinder attached to drilling rods and released in the desired position. Third left: Dense, clay pellets poured into the hole. Right: "Couronne" plug with rings of dense clay around jointed copper rods (Pusch and Ramqvist 2006a).

[2] Cement- och Betonginstitutet, Stockholm, Sweden.

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 precede deeper down in the hole after one day. pH is lower than 11 in the porewater of the concrete.

2.3.3 Concrete – casting of plugs

For casting of concrete plugs the recipe in Table 2-4 is would be suitable. The cement content is only about 4% of the solid mass meanings that possible dissolution and loss of this component will not have any practically important impact on the porosity and compressibility. Fuller-type gradation of the ballast material, consisting of quartz grains, preserves the structure of the concrete since the void size distribution minimizes penetration and migration of clay particles through it. The material has fluid consistency and hardens to give a compressive strength of at least 1 MPa in 24 hours, which is estimated to be sufficient for supporting clay plugs placed on it. The content of superplasticizer is so small that its contribution to the formation of organic colloids that can be radionuclide-bearing has been judged negligible in applying the concept to the deep borehole KR-24 at Olkiluoto (Pusch and Ramqvist 2006b).

Table 2-5 shows that the rate of strength growth is high. The criterion of 1 MPa cube (compressive) strength after 1 day is fulfilled.

2.3.4 Borehole geometry

The borehole geometry is of great practical importance for the following reasons:

- the hole length determines the clay plug type: "Basic" type plugs are suitable for less than 500 m and the not yet tested "Container" type for more than 500 m. The "Couronne" type can be considered for holes shorter than about 100 m. The pellet concept is not adequate for the presently considered borehole lengths exceeding a few tens of meters,
- small curvature of the holes means that long plug units may get stuck or require axial force to pushing for bringing them in,
- the borehole diameter determines the dimensions and density of the clay plugs. Thus, 56 mm diameter gives lower density than for 76 mm, which is in turn lower than for 90 or 100 mm hole diameters. The plug diameter is determined by the narrowest part of the hole,
- rough wall surfaces imply that there is a risk that tubes for placing "Basic" and "Container"-type clay plugs and for casting concrete may get stuck if the lower edge hits the wall.

Table 2-6 gives the length, intended diameter and minimum radius of the candidate holes. As shown later in the report, detailed examination of geometrical data may show local bends that may cause problems in preparing and installing clay plug segments.

Length

All the Forsmark and Laxemar holes are suitable as reference holes since the length exceeds 500 m. Short holes extending from a drift, taken to be of those in the Äspö underground laboratory can be plugged by the "Basic" or the simpler "Couronne" method; it will be appointed reference hole because of the expected high hydraulic gradient. Conclusion: *Since long holes were of primary interest in the study the order of priority was:* KFM07A = KLX04 = KLX06, KLX10, KFM09A, KFM09B.

Curvature

Measurement of the borehole shape and orientation has formed the basis for evaluation of the curvature of the holes. Taking the length of clay plug units of "Basic" type as 12 m, the critical deviation from an assumed straight axis would be about 4 mm over this length, corresponding to a radius of curvature of about 4,000 m (see further discussion in Section 2.4). This is valid for most of the examined holes but any sharper bend would imply that the tube can come in contact with the borehole walls at its ends. The impact of the curvature on the design of boreholes is hence such that very careful characterization of the shape of the borehole is required. Conclusion: *All the holes are ranked equal in this respect.*

Table 2-4. Concrete recipe for plugging of boreholes (Pusch and Ramqvist 2007).

Components	Kg/m^3 of concrete
White cement (Aalborg Portland)	60
Water	150
Silica Fume (Elkem)	60
Finely ground α quartz (Sibelco)	200
Finely ground cristobalite (Sibelco)	150
Superplasticizer (Glenium 51 Modern Betong)	4.38 (dry weight)
Aggregate (ballast), (Underås Jehanders grus)	1,679

Table 2-5. Rate of strength growth of bore hole concrete (Pusch and Ramqvist 2007).

Curing time in days	5°C Cube strength in MPa	20°C Cube strength in MPa
2	1.9	4.5
3	4	6.6
7	7.5	10.6
28	14	40
72	32.9	55.2
91	35.4	57.4

Table 2-6. Length, intended diameter, and average radius of the candidate holes.

Site	Borehole	Length, m	Nominal diameter, mm	Av. radius of curvature, m
Forsmark	KFM07A	1,000	77	>4,000
Forsmark	KFM09A	800	77	>4,000
Forsmark	KFM09B	620	77	>4,000
Laxemar	KLX04	1,000	77	>4,000
Laxemar	KLX06	1,000	77	>4,000
Laxemar	KLX10	1,000	77	>4,000
Äspö	KA3386	80	77	>4,000

Variation in diameter [3]

Caliper measurements have been part of the standardized geophysical borehole loggings performed in all boreholes that were drilled in the Laxemar and Forsmark site investigation campaigns. Two caliper techniques have been applied, i.e. one-arm mechanical calliper and acoustic televiewer, and measurements have been calibrated by use of drill bit data (Nilsson and Nissen 2007). Caliper raw data as well as calibrated data from a core drilled borehole at Forsmark, KFM04A, are displayed in Figure 2-4. Caliper mean data were used for calibration of acoustic televiewer measurements. The diameter of "76 mm holes" appears to vary between approximately 77.0 and 77,5 mm over the larger part, rising to 78–79 mm over about ¼ of the total length and locally even to 80 mm. It is clear that diameter variations have a substantial impact on the ultimate density of the clay plugs and that the accuracy in caliper measurement therefore needs to be determined. Table 2-7 gives the estimated accuracy for cored Forsmark holes. One concludes from Figure 2-4 and Table 2-7 that there may be considerable deviations from the intended diameter and smoothness of the boreholes.

Prior to installation of borehole plugs, measurements of the actual variations in diameter and topography of the borehole walls needs to be made with highest possible accuracy for defining practical measures of the diameter and density of clay plugs. Conclusion: *Regarding the three candidate holes KFM07A, KFM09A and KFM09B, Table 2-7 confirms that they should be accepted as reference holes from this point of view.*

[3] The data emerge from the Sicada data base. The matter is further discussed in Section 3.5.

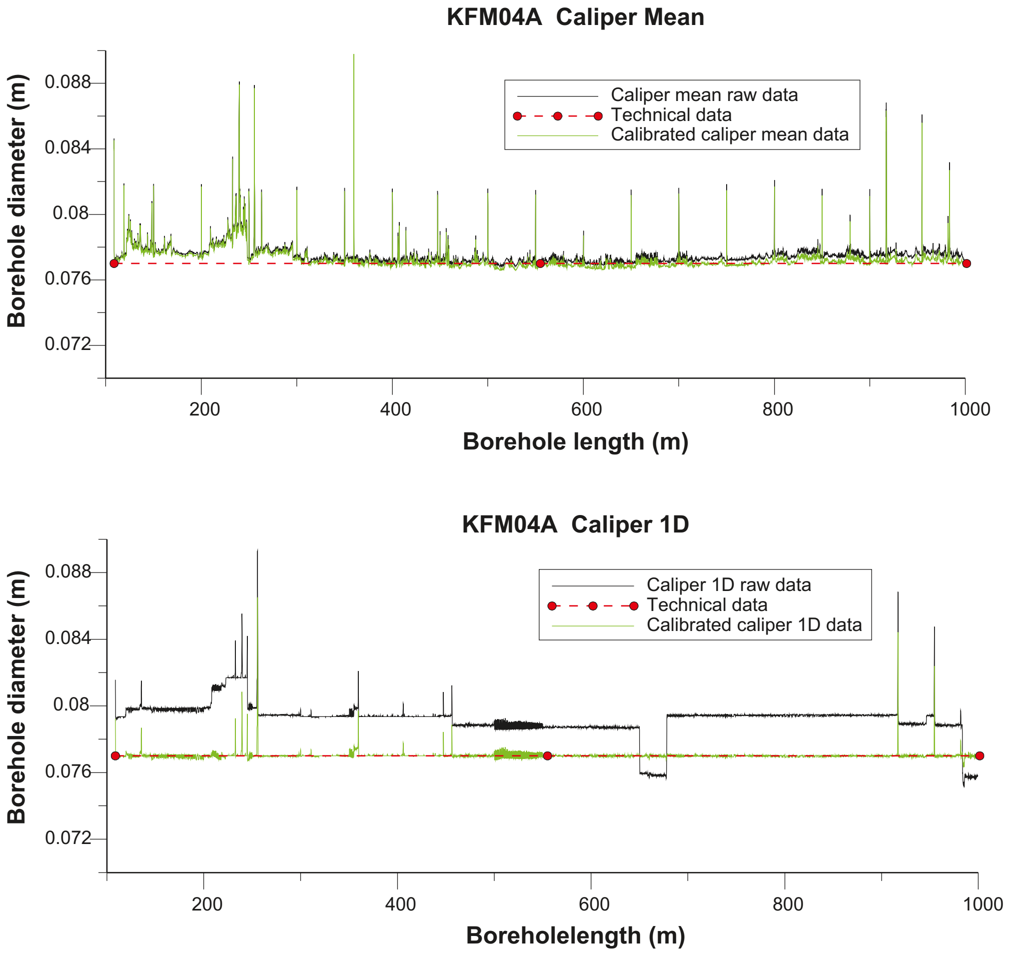

Figure 2-4. *Example of calibrated caliper measurements in a 1,000 m long, steep borehole. The upper diagram illustrates results from one arm mechanical caliper measurements, whereas the lower diagram illustrates diameter data from acoustic televiewer (Nilsson and Nissen 2007). Thin "spikes" in the diagrams represent single fractures or reference grooves milled into the borehole wall to serve as a means for length calibration.*

Table 2-7. Estimated accuracy of caliper data for Forsmark holes (Nilsson and Nissen 2007).

Borehole	Caliper mean accuracy (mm)	Borehole	Caliper mean accuracy (mm)
KFM01A	0.06	KFM07A	0.42
KFM01B	0.20	KFM07B	0.11
KFM01C	0.10	KFM08A	0.50
KFM01D	0.07	KFM08B	0.10
KFM02A	0.43	KFM08C	0.31
KFM02B	–	KFM08D	0.52
KFM03A	0.28	KFM09A	0.10
KFM03B	0.16	KFM09B	0.31
KFM04A	0.27	KFM10A	0.21
KFM05A	0.20	KFM11A	4.00
KFM06A	0.15	KFM12A	0.02
KFM06C	0.15	**Average**	**0.39**
		Median	**0.20**

2.4 Impact of borehole anomalies on the function of clay plugs

2.4.1 General

The borehole geometry controls the possibility of placing plugs and the tightness of placed plugs. The placeability is determined by the straightness and smoothness of the holes. The presence of obstacles in them. The tightness of clay plugs is determined by the difference in diameters of the hole and the plug since they control the density of the clay.

2.4.2 Placeability

If clay plug segments are too long it may be difficult or impossible to install them as indicated in Figure 2-5, which shows a "Basic" type clay plug segment squeezed or stuck in a curved borehole. The maximum length of the segments allowed for avoiding such difficulties is naturally a function of the radius of the borehole. The risk of rock fall immediately before or in the course of the plug installation must also be realized. It implies that detailed plans must have been worked out for removing failing plug units by redrilling at any stage of the plug installation project. Also for the concrete plugging activities preparation for redrilling and rinsing of the holes must have been made in case of inadequate quality of the plug construction. Such activities can cause significant delay and cost.

Taking the length of clay tubes of "Basic" type as 12 m, the critical deviation from an assumed straight axis would be about 4 mm over this length, corresponding to a radius of borehole curvature of about 4,000 m. This is on the same order of magnitude as the actual bend of most of the examined holes but any local sharper curve would imply that the tube could come in contact with the borehole walls at its ends. The sensitivity of the curvature hence calls for very careful characterization of the shape of the boreholes.

The need for testing the hole by moving a dummy up and down is obvious. For the KR-24 hole at Olkiluoto such testing showed that the safe length of a plug segment was only 6 m (Pusch and Ramqvist 2006b). The pretesting required for for selecting suitable segment lengths is obvious from the upper diagram in Figure 2-6 that illustrates rather small radii below 300 m depth for the Forsmark hole. This is in contrast with the Laxemar hole KLX10 that has an average radius of curvature of significantly more than 4,000 m over the larger part of its length.

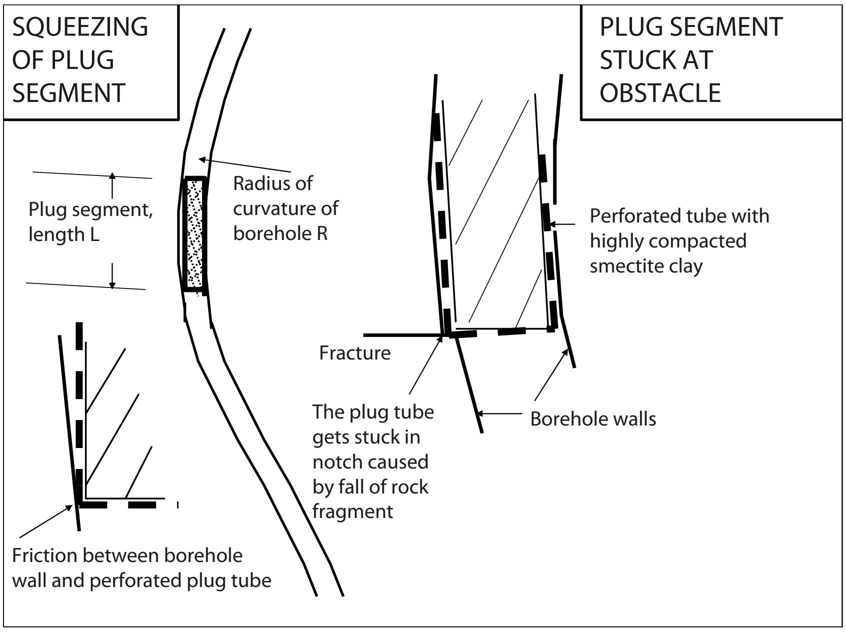

Figure 2-5. *The length of borehole plug must be limited for avoiding problems at placement.*

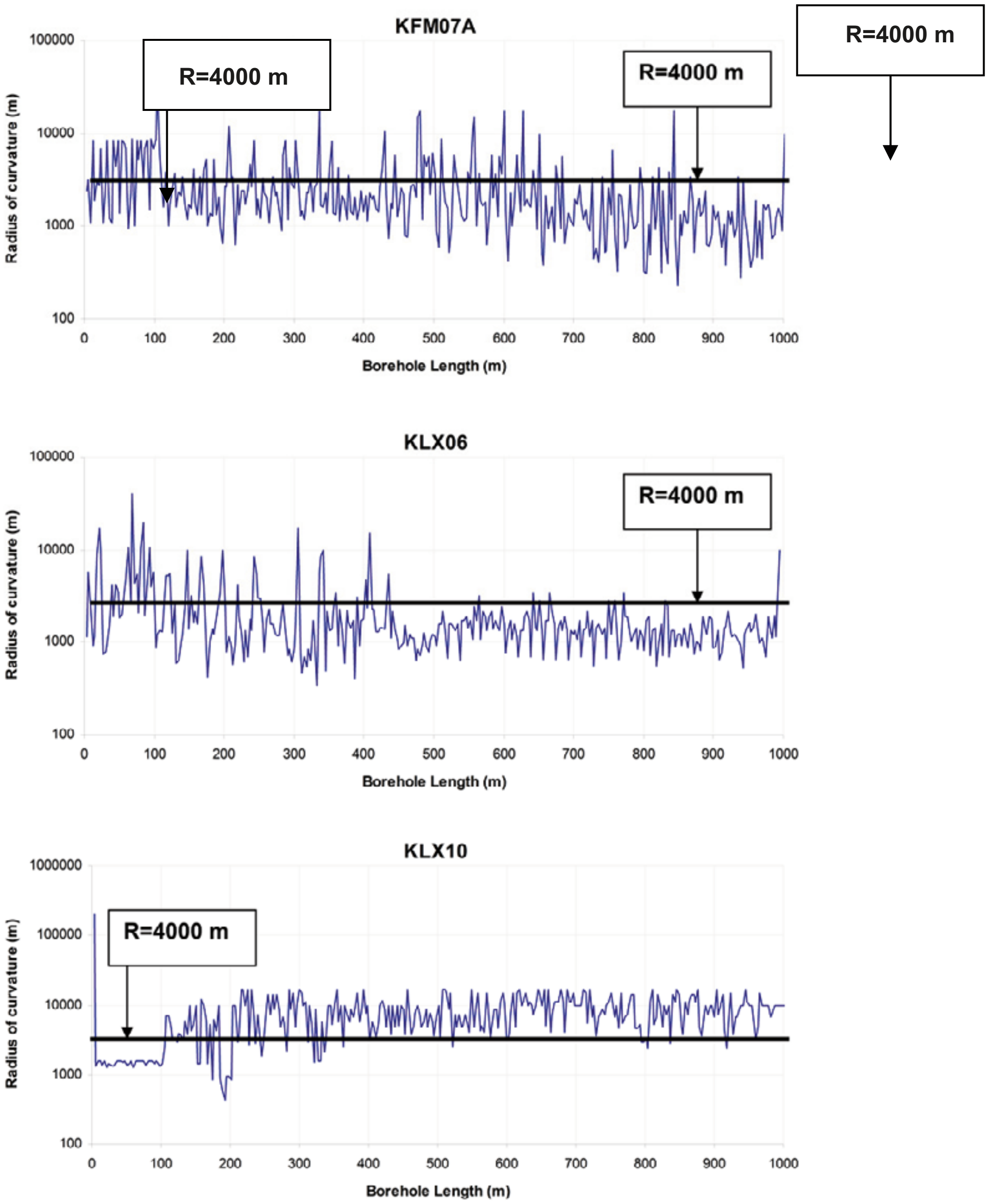

Figure 2-6. *Examples of rather small radii of curvature (upper two diagrams) and rather large radii (lowest) (Nilsson and Nissen 2007).*

2.4.3 Performance of clay plugs

Controlling factors

The tightness of clay plugs in boreholes is a function of the density of the clay. For "Basic" type plugs (Figure 2-7) it is determined by the density of the central core confined in a perforated copper tube and of the clay formed around it by expansion of the core through the perforation. With time more clay moves out and consolidates the first formed soft clay by which the entire clay component tends to become uniform.

The electrolyte content of the groundwater affects the hydraulic conductivity of the clay by determining the void size and the fraction of sorbed water.

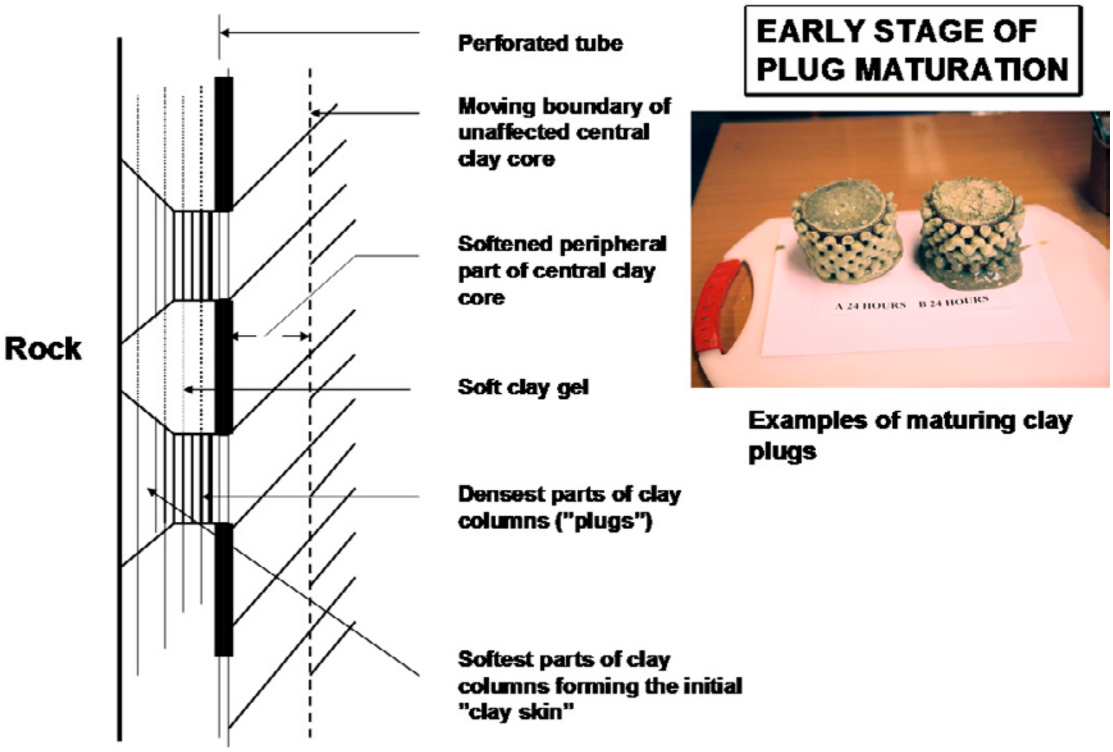

Figure 2-7. Schematic view and photos of the earliest stage of a maturing clay plug.

Impact of density on the hydraulic conductivity of smectite-rich clay plugs

Comprehensive laboratory studies have led to the relationship between the hydraulic conductivity and density of smectite-rich clay shown in Figure 2-8. The plottings were derived from oedometer tests applying hydraulic gradients of 20–60 m/m that are commonly used in soil mechanical laboratory investigations (Pusch and Yong 2006). Significantly higher gradients cause underestimation of the conductivity while significantly lower gradients give in fact lower values than implied by the diagrams as indicated by ongoing studies (Pusch 2008).

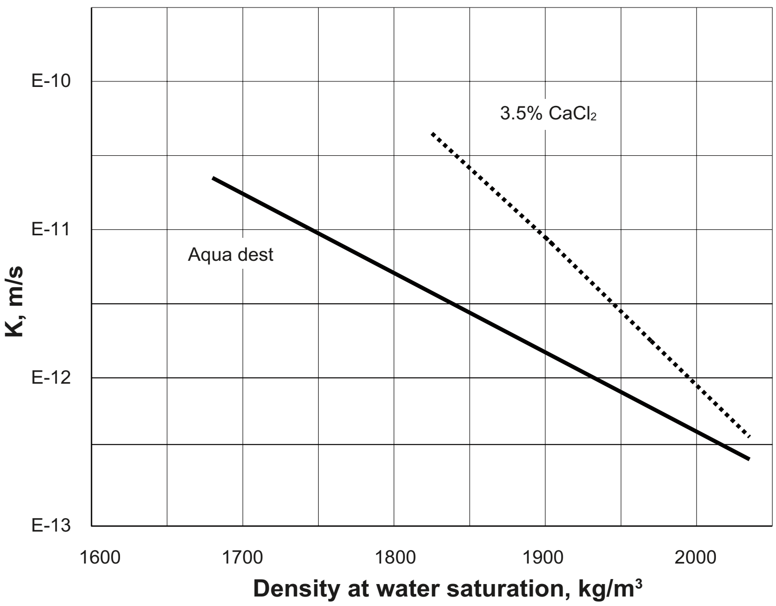

Figure 2-8. Appoximate relationship between density and hydraulic conductivity of smectite-rich clay. (Pusch and Yong 2006)

One finds from Figure 2-8 that for a density at saturation with Ca-rich groundwater of 2,000 kg/m^3 the average hydraulic conductivity is about E–12 m/s while it increases to about 3E–11 m/s for a density at water saturation of 1,850 kg/m^3 and to E–10 m/s for a density of 1,800 kg/m^3. Estimating the average hydraulic conductivity of fracture-poor granitic rock to be in the interval 5E–11 to 6E–10 m/s at about 400 m depth (Pusch 2008), the clay plug should have an ultimate density of at least 1,850 kg/m^3 for being less permeable than the rock. Since the bulk conductivity of the rock at 400 to 1,000 m depth is estimated here to be in the range of 5E–12 to E–11 m/s the required density of water-saturated clay would have to be about 1,950 kg/m^3 according to the diagram in Figure 2-8. The diagram in Figure 2-9 shows that this would require the initial dry density of the dense clay core in the perforated tube to be about 1,770 kg/m^3 for a borehole with 80 mm diameter and a tube diameter and wall thickness of 76.1 and 2 mm, respectively. In practice, the minimum dry density has to be higher, because the clay ultimately formed around the tube may be somewhat less dense than the core by internal friction in the expansion phase and by erosion in the placement phase when water flows along the plug. We will consider both effects here.

Impact of erosion on the density of the matured clay plug

The density of the clay is affected by erosion in the course of the installation in the hole and it is estimated that a loss of solid clay substance of about 5% will take place in boreholes with lengths of 1,000 m if the placement does not take more than 3 hours (Pusch and Ramqvist 2006a). This means that the lowest part of a 1,000 m long 76.1 mm plug with 1,770 kg/m^3 initial dry density placed in an 80 mm borehole would ultimately get a net average density of only slightly more than 1,920 kg/m^3 Figure 2-10 illustrates the impact of erosion on the average plug density at different borehole diameters and one finds that for 7.5% erosion, which would give some margin, the diameter of the hole can be up to 82.5 mm without reducing the density to less than 1,920 kg/m^3. For 15% erosion, this plug density would not be reached for borehole diameters larger than 80.0 mm.

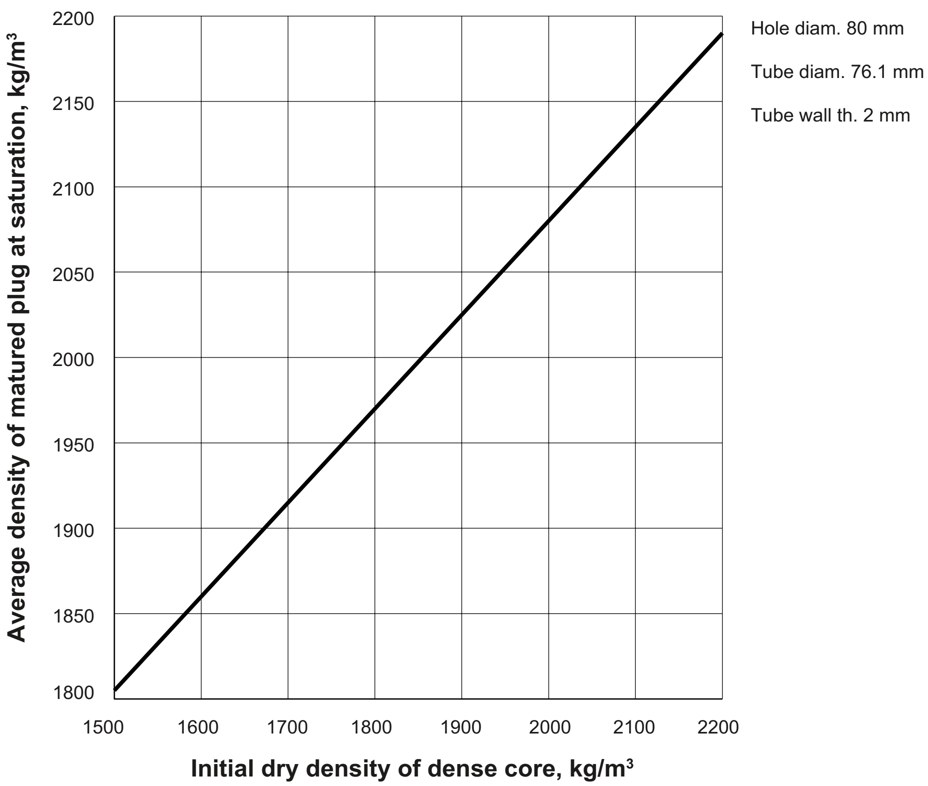

Figure 2-9. *Relation between initial dry density of the dense core in the tube and the theoretical average density at water saturation of the entire clay plug.*

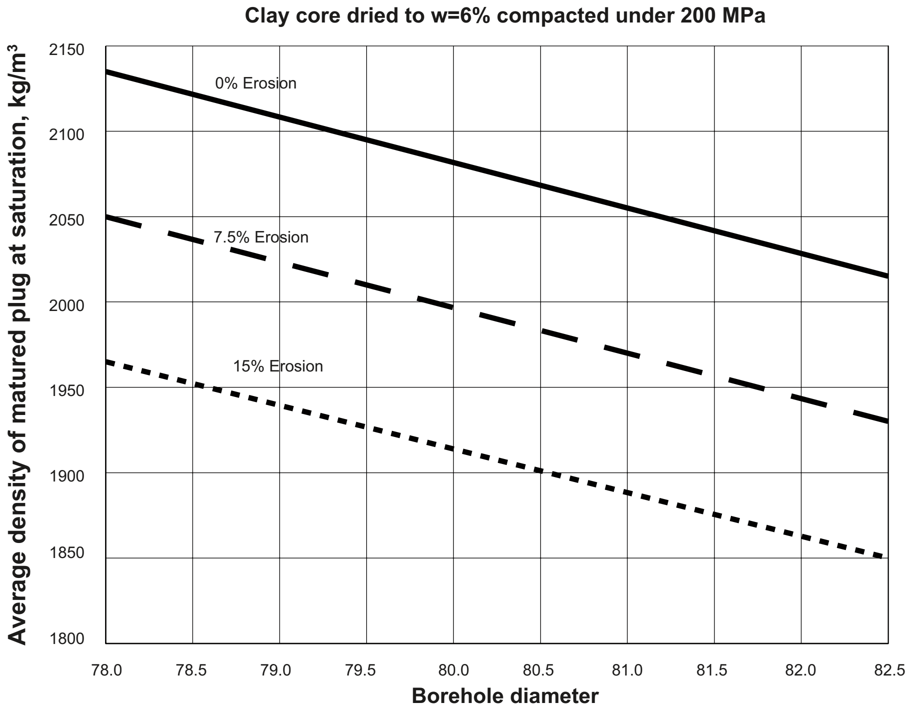

Figure 2-10. *Theoretically derived relation between borehole diameter and ultimate density at water saturation of "Basic" type clay plugs for three erosion scenarios (SKB IPR-06-28).*

Impact of heterogeneity of the matured clay plug on the hydraulic performance

The expansion of clay through the perforation of the tube is delayed by internal friction and metal/clay friction and the ultimate density of the clay "skin" between the rock and the copper tube may not fully reach the density of the central part of the matured clay core. This suggests that the initial dry density should preferably be somewhat higher than 1,700 kg/m^3. We will consider the matter in greater detail here.

Differences in density between the peripheral and central parts of clay plugs can be estimated on theoretical grounds, but the value of such calculstions is questionable since there are uncertainties concerning parameter values respecting internal friction and creep rates. Experimental data provide practically useful information on the strength of the clay skin formed between the perforated tube and the rock that can suffice for the time being. Such tests involved determination of the "adhesive" strength by axial loading of plugs in 80 mm diameter holes at different times after placement. They showed that nearly complete swelling and homogenisation were obtained in 10–20 days for saturation of the clay with strongly brackish water at Äspö HRL. Measurement of the hydraulic conductivity of the clay paste between tube and rock showed that it was lower than E–12 m/s for saturation and percolation with fresh water and twice this value for Äspö water. The density of the clay paste between tube and rock was estimated at slightly more than 1,900 kg/m^3 after about 3 weeks. These tests gave data that were in principal agreement with those derived from earlier field tests of the same type performed in SKB´s earlier underground laboratory (Pusch 2008).

Comparison of boreholes with intended 56, 76, 80 and 100 mm diameter

The larger the borehole diameter, the smaller is the drop in density of a fully matured "Basic" type clay plugs. For equally large gap between tube and rock and thickness of the tube wall. , the difference in theoretical ultimate density of such plugs in boreholes with 56, 76, 80 and 100 mm diameter is illustrated in Table 2-8. One finds that density and tightness of the clay plugs increase significantly with increased borehole diameter. This matter is of great practical importance and one concludes that reaming holes with 76–80 mm diameter to 100 mm would greatly improve the quality of the clay plugs.

Table 2-8. Theoretical ultimate density of plugs in boreholes with different diameters assuming that the initial dry density is 2,000 kg/m^3 and that the gap between tube and rock and the thickness of the tube wall are 2 mm.

Borehole diameter, mm	Initial dry density, kg/m^3	Final dry density, kg/m^3	Final density at saturation, kg/m^3	Final density at saturation if the borehole is 3 mm wider, kg/m^3
56	2,000	1,683	2,060	1,942
76	2,000	1,760	2,110	1,995
80	2,000	1,785	2,124	2,037
100	2,000	1,830	2,150	2,083

The importance of the borehole diameter for the function of clay emphasis the need for accurate measurement of this geomeltical parameter. In practice it involves use of mechanical calipers or acoustic televiewers. SKB's criterion (c.f. activity plans for core drilling) is that the accuracy shall be better than ±0.5 mm and tests have shown that it is ±0.55 mm for the mechanical device, and ±0.39 mm for the acoustic one. The anomalies recorded are not readily explained and further investigation is needed.

A survey of recorded Sicada (Sept. 2008) data from 76 mm boreholes is illustrated by the diagrams in Figures 2-11 and 2-12, which indicate that a variation in borehole diameter by 1 mm has to be expected in addition to much larger, local diameter changes (several millimetres). While variations up to 1 mm will not have any important impact on the tightness of clay plugs, the larger ones would imply significant drops in plug density but no assessement of diameter variations. It is recommended, however that the location of clay and concrete plugs be decided on the basis of careful diameter mesurements. It is probable that many of the large diameter changes are related to fracture zones.

Long-term function

The performance of clay plugs in a long-term perspective depends on the impact of groundwater erosion and chemical processes. The applied principle of locating clay plugs in fracture-poor parts of the boreholes minimizes the risk of erosion by adflowing or percolating water. Degrading chemical processes are 1) conversion of the smectite minerals to nonexpanding illite and chlorite, 2) exchange of the initially sorbed sodium to calcium or copper and 3) dissolution by interaction with contacting concrete. The moderate temperature, i.e. less than 50°C down to 500 m depth and less than 90°C at 1,000 m depth, is not expected to cause significant illitization/chloritization (Pusch and Yong 2006).

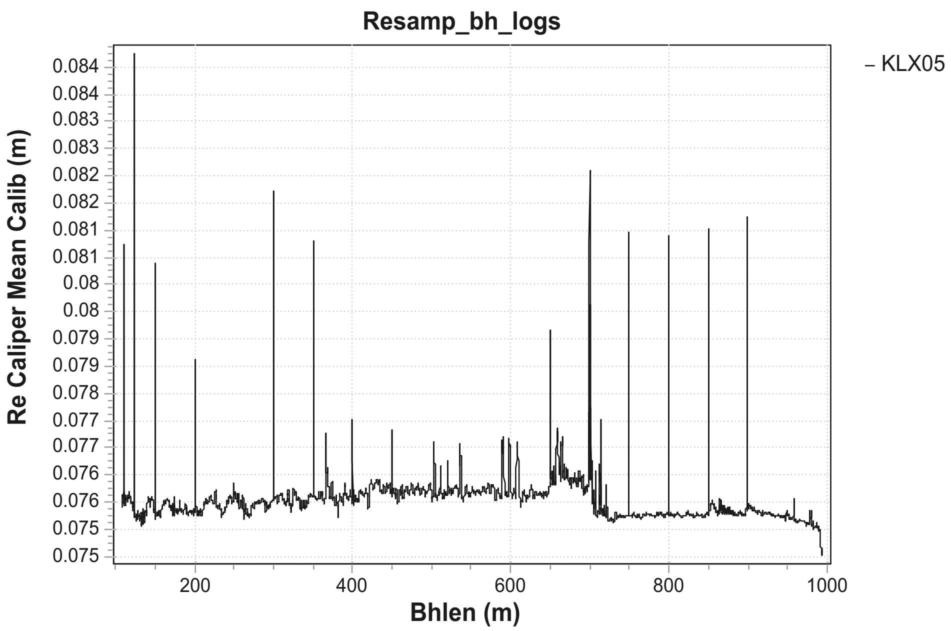

Figure 2-11. Example of diameter variation in Borehole KLX05.

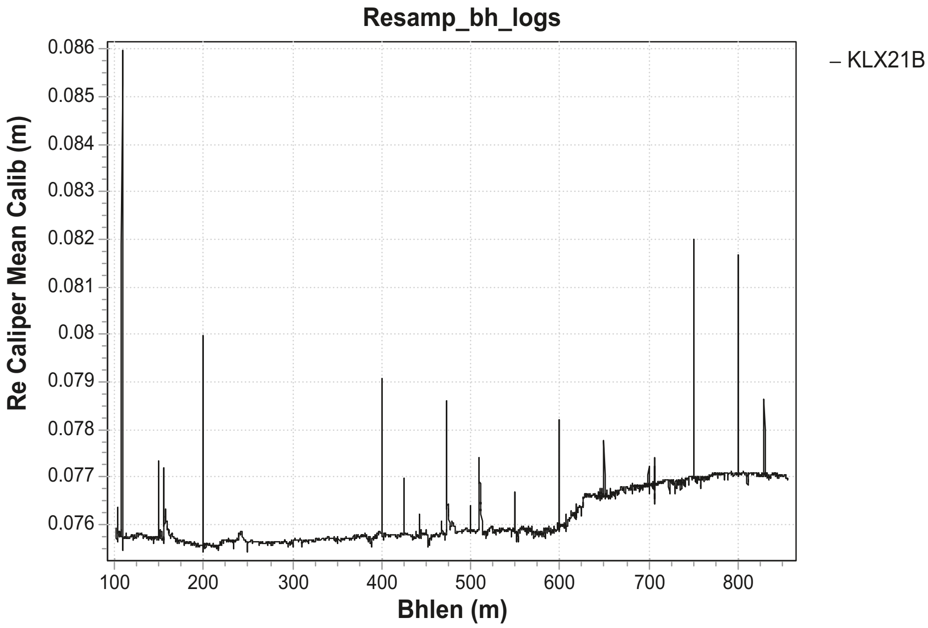

Figure 2-12. *Example of diameter variation in Borehole KLX21B.*

Cation exchange will not lead to a significant increase in conductivity if the density of the water-saturated clay is 1,900 kg/m^3 or higher (Pusch and Yong 2006). The most important risk is dissolution caused by contacting concrete but the reaction products, amorphous silicious material and illite, are expected to be low-pervious although not as tight as the original clay.

2.4.4 Performance of concrete plugs

Construction of concrete "linings" and plugs at depth in boreholes is not a straight-forward matter and there is limited experience from such work. Problems may arise from slow-hardening concrete and erosion and piping by differences in piezometric conditions in the holes, and it remains to demonstrate that construction can actually be made at required rate and with acceptable quality. The performance of concrete plugs is determined by their homogeneity and density, which requires testing by use of not yet developed techniques.

The properties of importance are:

- compressive strength as a function of time after casting,
- erodability as a function of time after casting,
- dissolution of the cement component,
- hydraulic conductivity.

The compressive strength one day after casting should be at least 1 MPa, which is reached under realistic rock temperature conditions as shown earlier in the report. The CBI concrete for casting concrete is known to undergo further increase in compressive strength to 30 MPa after a few weeks (Pusch and Ramqvist 2007). Total loss of the cement component should not cause any significant drop in bearing capacity or increase in compressibility, if the granulometry of the aggregate component of the CBI concrete for plugs follows the Fuller law (Pusch and Yong 2006). Erosion and mixing with water may take place in the casting process and great care has to be taken for avoiding mishaps, which suggests use of a proposed but not yet tested technique, i.e. the "container method" (Pusch and Ramqvist 2006b). Dissolution of the cement reduces the coherence and mechanical strength of the concrete but the required function, i.e. to serve as mechanical support of the clay plugs, will be preserved provided that the remaining grain system is homogeneous and without larger voids. The hydraulic conductivity of the concrete must not be very low but it is valuable if it is not much higher than that of the clay plugs, since the risk of piping in these plugs is thereby minimized. Laboratory-determined conductivity values are usually in the range of E–13 to E–11 m/s depending on the age and homogeneity of the concrete (SKB–SWECO–Westinghouse Atom Joint Venture 2002).

2.5 Selection of reference holes

2.5.1 Principles of assessment

The decision was made that only one or two of the candidate holes at each site should be selected as "reference" holes for closer study. For getting an appropriate basis for selecting it/them, the following activities were performed:

- assessment of the representativeness of the boreholes ("typical", i.e. few fracture zones, and "extreme", i.e. frequent fracture zones),
- assessment of the importance of hydraulic short-circuiting of fracture zones.
- assessment of the importance of possible anomalies with respect to the hydraulic function, the major parameter being the frequency of intersected zones and the existence or creation of differences in piezometric pressure that can cause piping and destruction of plugs in the construction phase (i.e. large distance between hydraulically active fracture zones),
- assessment of possible difficulties in performing stabilization and plugging (water inflow, unstable rock).

2.5.2 Assessment of the importance as to the hydraulic function

A high frequency of fracture zones means that the number of clay and concrete plugs will be high, which makes plugging tedious but not necessarily more difficult. A high frequency may indicate that the identified zones belong to the same large fracture zone and that effective sealing of the individual ones is not very important. This would speak in favour of using concrete in a large part of the hole even where some tighter parts are present and reserving clay plugging for longer, continuous, parts of of tight rock. This firts mentioned case is represented by KLX04 (17 zones in 1,000 m), and, to a somewhat less extent, by KLX10 (10 zones in 1,000 m). KLX06, which is also 1,000 m long, intersects only 4 zones and is therefore a representative of the second case.

As to the Forsmark holes, KFM09A and KFM09B are similar to KLX10 (all three have an average spacing of zones of about 100 m), while the 1,000 m long KFM07A is intersected by only 4 zones and KLX06 by two. KFM09B is only 620 m long and is therefore left out from the screening.

Respecting the frequency of fracture zones it is believed that KFM07A at Forsmark and KLX06 at Laxemar should be appointed reference holes.

2.5.3 Assessment of difficulties in performing stabilization and plugging

As indicated earlier in the report, a small spacing of intersected fracture zones will require longer time for plugging since each placement of concrete and clay plug requires at least one day for maturation. Technically, however, the plug construction at smaller spacing of zones and plugs is not more difficult. It is estimated that placement of a few clay plugs in tight rock containing few fracture zones may imply higher hydraulic gradients and greater difficulties with risk of piping of both clay and concrete plugs in the construction phase.

Respecting possible practical difficulties in borehole sealing it is estimated that KFM07A at Forsmark and KLX06 at Laxemar should be appointed reference holes.

2.5.4 "Typical" and "atypical" holes

As indicated in Section 2.3 the six candidate holes at Forsmark and Laxemar represent two distinct groups, one with few fracture zones and the other with a higher number of zones. Although investigation of construction and performance of borehole seals under different conditions can be of interest, it is proposed that comparison of similar holes and conditions at the two sites would offer more interesting and valuable results.

Respecting selection of hole types it is proposed that KFM07A at Forsmark and KLX06 at Laxemar be appointed reference holes.

2.5.5 Importance of hydraulic short-circuiting of fracture zones

General

As stated in Section 2.3 it is estimated that the risk of short-circuiting hydraulically active fracture zones with differential water pressures is significant and that they can cause hydraulic gradients along the holes, especially where the boreholes intersect a few zones of this type. This speaks in favour of selecting holes that intersect a few, discrete fracture zones for making the study conservative. It would be of particular value if these zones are hydraulically very active by being connected to other major zones, which is the case for KFM07A (8 interacting zones according to Table 2-2).

Respecting selection of holes that represent the highest risk of hydraulic short-circuiting of fracture zones it was decided to appoint KFM07A at Forsmark and KLX06 at Laxemar as reference holes.

2.5.6 Plug positions

Taking KFM07A at Forsmark and KLX06 at Laxemar as reference holes, suitable plug types and positions are specified in Tables 2-9 and 2-10. The principle followed is to construct clay plugs in tight rock and concrete where fracture zones are intersected. However, for practical reasons some generalization has been made, mostly implying that concrete is placed where the spacing of fracture zones is very small.

The relatively large number of different plugs (6 concrete plugs and 5 clay plugs over 545 m borehole length, mbl[4]), can possibly be reduced at least for the required calculation of the hydraulic performance of the rock mass with penetrated long holes. Thus, the plan can be altered to replace the whole series of clay and concrete plugs from 0 to 545 m borehole length by concrete, or alternatively, to place clay from 210 to 415 m, following the proposed plug sequence in Table 2-10 below 415 m borehole length. Even simpler concepts may be considered depending on the constructing time and possible difficulties met in practice.

WellCad-plots, transmissivity diagrams and BIPs images for the Forsmark and Laxemar holes are not included in this report for space reasons.

Table 2-9. Generalized table of proposed approximate plug positions in borehole KFM07A.

Borehole length, m below ToC*	Plug type	Fractures zones
0–210	Concrete	DZ1, DZ2
210–260	Clay	
260–290	Concrete	Fracture-rich
290–325	Clay	
325–345	Concrete	Fracture-rich
345–415	Clay	
415–435	Concrete	DZ3
435–495	Clay	
495–505	Concrete	Fracture-rich
505–535	Clay	
535–545	Concrete	Fractures
545–790	Clay	
790–1,000	Concrete	DZ4

* ToC means "top of casing"

[4] mbl means "meters borehole length".

Table 2-10. Proposed plug positions in borehole KLX06.

Borehole length, m ToC	Plug type	Fracture zones
0–100	Concrete	DZ3
100–110	Clay	
110–190	Concrete	DZ4
190–210	Clay	
210–280	Concrete	DZ1
280–290	Clay	
290–395	Concrete	DZ2
395–410	Clay	(Tight part of DZ2)
410–450	Concrete	DZ2
450–500	Clay	
500–530	Concrete	Fracture-rich
530–560	Clay	
560–580	Concrete	Fracture-rich
580–635	Clay	
635–670	Concrete	Fracture-rich
670–735	Clay	
735–750	Concrete	Fracture-rich
750–830	Clay	
830–845	Concrete	Fracture-rich
845–910	Clay	
910–1,000	Concrete	Fracture-rich

2.6 The subhorizontal hole KA3386A01 at Äspö

Plugging of hole KA3386A01 at Äspö would provide an example of how a relatively short sub-horizontal borehole with a high hydraulic gradient operating axially along it can be sealed. The general principle for locating plugs should be followed, i.e. construction of concrete plugs where fracture zones are intersected and placement of clay plugs in the parts where the rock is poor in fractures. For this hole the existence of a high hydraulic gradient is a major problem, and the work should be focused on selecting a practical procedure for sealing the hole.

The location and interaction with hydraulically significant fracture zones is illustrated by Figure 2-13.

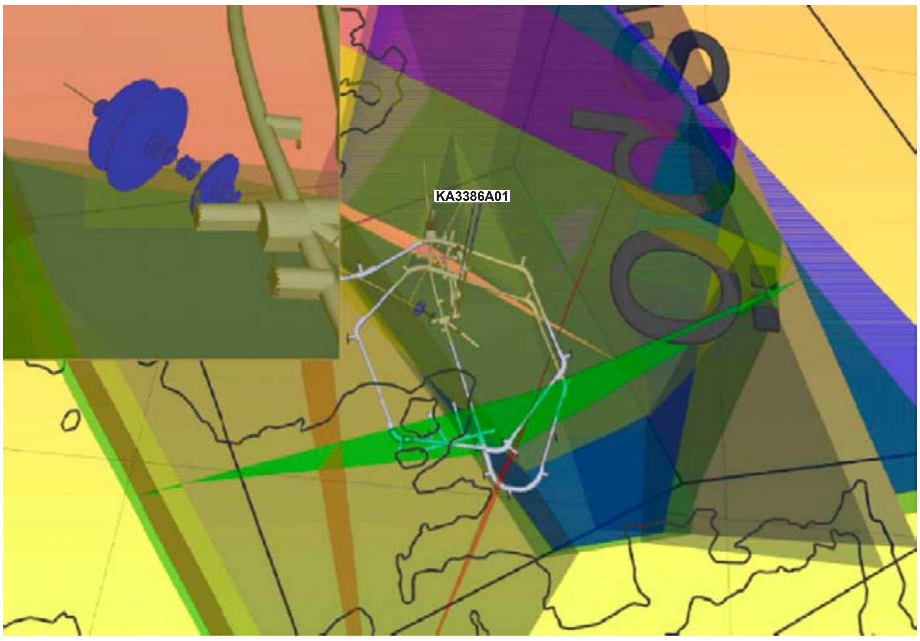

Figure 2-13. Detailed view of the Äspö structure model, the Äspö tunnel and borehole KA3386A01. It demonstrates that the borehole does not penetrate any of the major fracture zones (Bockgård 2011).

An overview of the current interpretation of the occurrence and geometry of large scale deformation zones at the island of Äspö, the so called Äspö structure model, is illustrated in Figure 2-13. The increased fracture frequency within the borehole interval 32–45 m borehole length (Figure 2-14) is associated with a transient change of rock type, from diorite to fine grained granite and an increase in transmissivity (Figure 2-15). Such features are illustrated by the core photo in Figure 2-16.

Figure 2-14. Borehole KA3386A01. WellCad-plot showing rock type and fracture distribution.

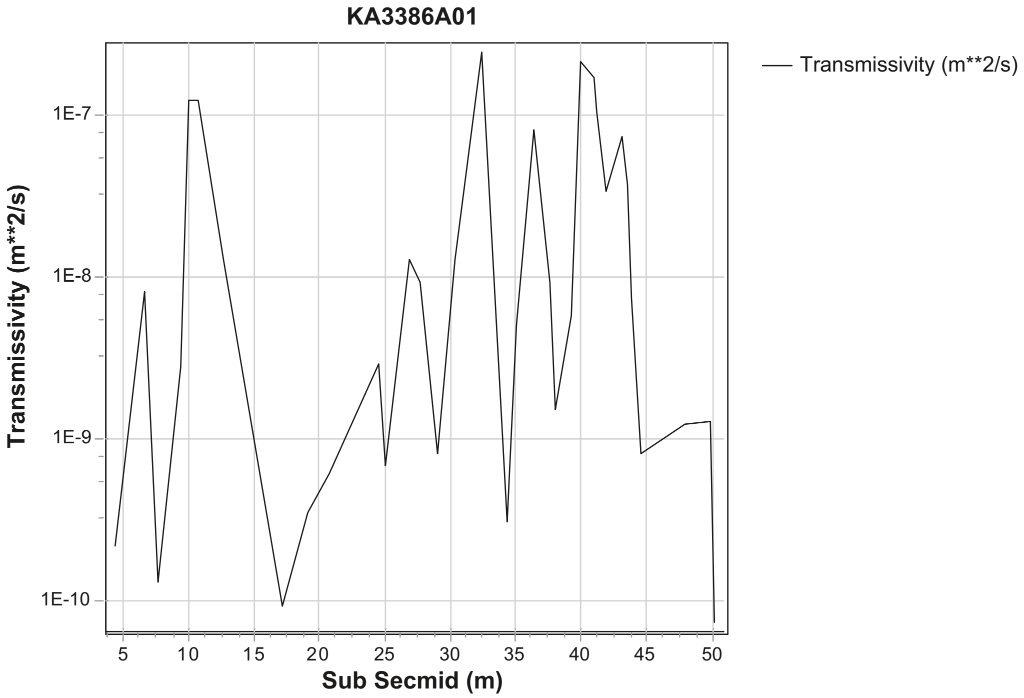

__Figure 2-15.__ Borehole KA3386A01 – hydraulic transmissivity along the borehole.

__Figure 2-16.__ Borehole KA3386A01. Small fracture zones or fracture assemblies can be seen at 8.70 and 9.50 m borehole length.

The location of plugs of clay and concrete is proposed to be as indicated in Table 2-11, which is primarily based on core examination. A simpler concept would well be worth considering in a real sealing campaign.

Table 2-11. Borehole KA3386A01.

Borehole length, m (ToC)	Plug type
0–10	Concrete
10–16	Clay
16–30	Concrete
30–34	Clay
34–44	Concrete
44–64	Clay

3 Subproject 2 – performance and quality assessment

3.1 Importance of borehole seals for the overall hydraulic performance of a rock mass

3.1.1 General strategy

A first and most important issue in planning borehole sealing is to find out how the seals should be located for optimum performance with respect to groundwater flow. A second issue is to optimize the plugging to make it operative over at least 100,000 years and as well as cost effective. The three boreholes KFM07A, KFM09A and KFM09B at Forsmark (Figure 3-1) have been used in a study of the function of degraded seals of quartz silty sand stabilized with cement, and smectite clay, termed bentonite in the report. The hydraulic conductivity of the concrete was taken as E–6 m/s and E–8 m/s of the clay, which are both orders of magnitude higher than of intact concrete and clay (cf. Subsection 2.4.3).

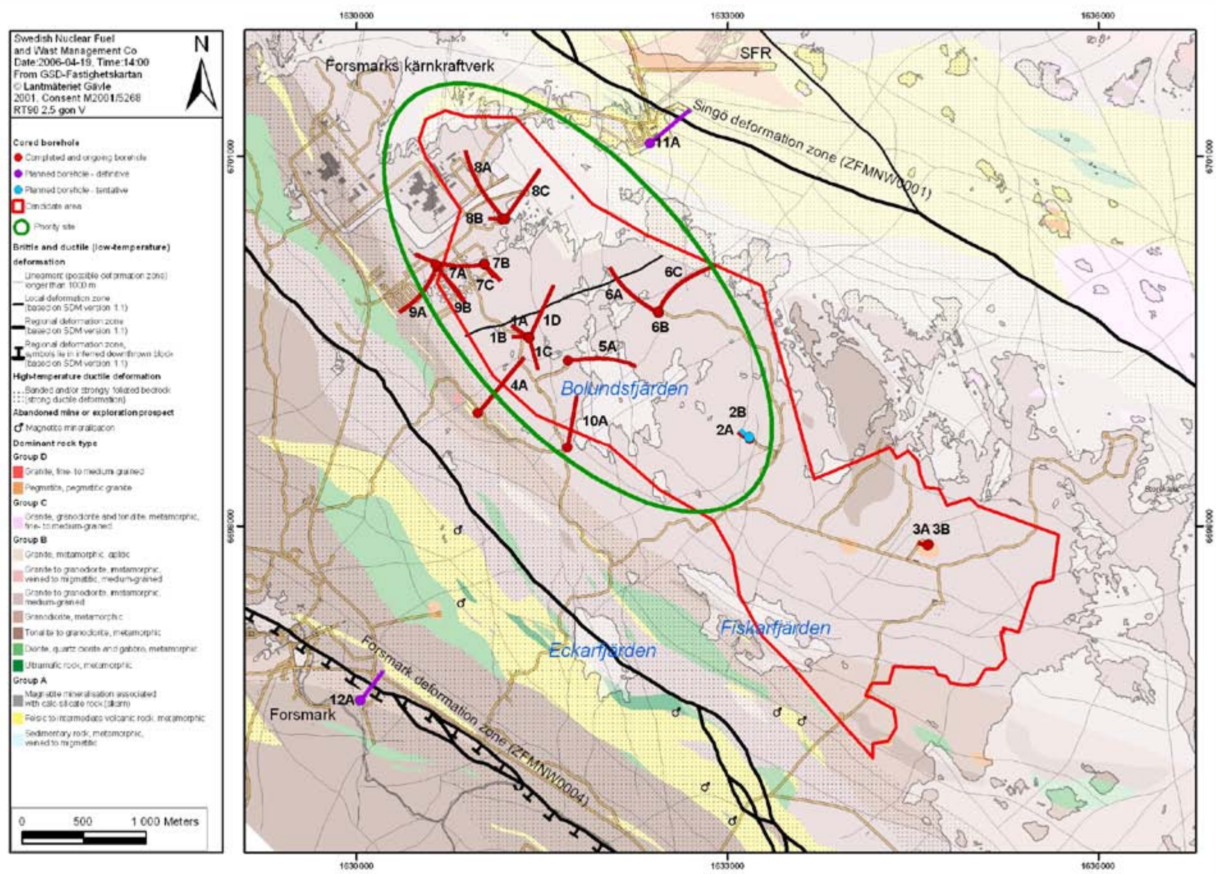

Figure 3-1. Map of the Forsmark area with all core drillings marked (SKB).

3.2 The risk of short circuiting of deep boreholes

3.2.1 Main principle of study

The basis of the calculations, which were made by Golder Associates AB in a study reported separately ("Hydraulic effects of unsealed boreholes. Numerical groundwater flow modelling of the Forsmark and Laxemar sites", SKB R-11-17 (Bockgård 2011)) was fracture (deformation) zones and DFN properties from the site descriptive model. Detailed models were created for the nearfield of the boreholes containing fractures larger than 5 m within 20 m distance from the holes, and fractures larger than 0.5 m within 10 m distance from them. The assumptions respecting the presence of long-extending fractures strongly affect the interaction of fractures in the nearfield. Thus, for example if fractures with sizes above 10 m are not represented in the Forsmark model, the nearfield of the holes has no interconnected fracture network.

Borehole KFM07A was considered first and the flow through a defined rock volume sized 1,300 mx 800 mx 300 m calculated. Comparison was made of the cases 1) no boreholes, 2) open boreholes, and 3) sealed (degraded) plugs. The result was that the flow through the rock volume was 0.86 l/min when there were no boreholes and when the borehole was sealed according to Table 2-9. However, for the case with open boreholes, representing also totally vanished seals, the inflow into the rock volume was 1.01 l/min and the outflow 0.64 l/min, yielding a net outflow through the boreholes of 0.37 l/min. This illustrates the necessity of sealing the deep borehole. Since the macroscopic rock structure is similar in other parts of the Forsmark site, it is concluded that all the deep boreholes at this site must be sealed. The conditions at Laxemar are different. Here, the higher frequency of hydraulically interacting fracture zones would make the need for effective sealing less obvious, but the limited information on the rock structure still calls for sealing of all deep boreholes for avoiding hydraulic short-circuiting that can have the form in Figure 3-2.

Another important difference between the Forsmark and the Laxemar sites is that for present-day conditions the flow of deep groundwater is predominantly directed upwards at the Forsmark site, whereas at the Laxemar site the flow is directed downwards. This means that open boreholes will act as conduits for deep groundwater to the surface at the Forsmark site, but the flow in the boreholes will be directed downwards at Laxemar. The hydraulic boundary conditions will change by time, which has to be taken into consideration for the assessment of the long-term performance.

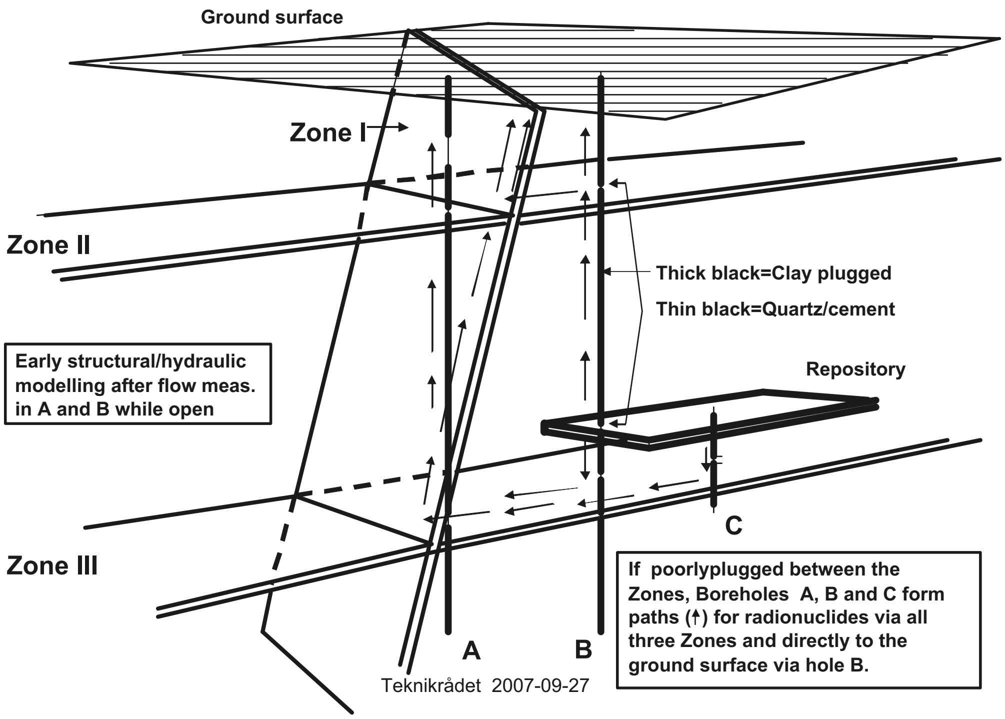

Figure 3-2. Short-circuiting of fracture zones by open or inadequately sealed or leaching boreholes.

3.3 Particle tracking in rock intersected by boreholes with differently performing seals

The advective travel time of solutes, which include radionuclides, from repository depth to the ground surface were calculated using the DFN groundwater flow model. This study is reported separately in the previously mentioned report "Hydraulic effetcs of unsealed boreholes. Groundwater flow modelling of the Forsmark and Laxemar sites", showed that the transport is rapid in highly transmissive horizontal fracture zones (sheet joints) that are known to be present in the upper 200 m of the bedrock at Forsmark. For the case of open boreholes they turn out to have a strong impact on the solute transport as demonstrated by the distribution of advective transport time and path lengths. This is in contrast with the case of well and poorly performing and even nearly totally degraded seals in the holes. Thus, according to the investigators the study has shown that there will be no difference in particle transport potential between rock with no boreholes and rock with more or less sealed boreholes.

3.4 Installation of borehole plugs

3.4.1 Issues

The study included consideration of important issues in the planning, preparation and performance of plug construction and installation. The following major ones were identified and need to be taken into account:

- Characterization of boreholes respecting straightness, diameter variations, constitution of stabilized parts, hydraulic gradients.
- Equipment for installation of plugs.
- Construction and installation of plugs.
- Current checking of materials, equipment and installed plugs (accuracy of location in boreholes, determination of bearing capacity of cast concrete by coring, recording of installation data).

3.4.2 Characterization

The need for detailed characterization of the boreholes is obvious from the subsections that describe the impact that diameter variation and radius of curvature have on the density and sealing potential as well on the placeability of clay plugs. From the point of hydraulic performance of the rock the possible existence of overpressures along the boreholes is of great importance, since they can cause channel flow in freshly cast concrete and in the "skin" of clay plugs. Hence, piezometric measurements must be made over sufficiently short intervals in the holes.

3.4.3 Equipment

Heavy-duty equipment is required for hoisting and submerging plug units and holding up to a kilometre long drill strings. Conventional drill rigs for deep drilling will do, but they must be adaptated to the special conditions met in the work with respect to reserve capacity and precision in positioning equipment for reaming and concrete casting and installation of clay plug segments. Improvement of standard equipment will be required and detailed manuals worked out for the staff that must be experienced and well trained.

3.4.4 Construction of plugs

The first and most important activity after checking the condition of the borehole to be plugged is to stabilize those parts that intersect water-bearing, potentially unstable fracture zones. This includes reaming and casting of concrete for subsequent re-boring to provide a lined part of the hole. This procedure has not yet been made in deep boreholes and hence has to be applied, tested and developed further if required. Casting of concrete plugs is a routine matter in oil- and gas drilling, leading to extensive experience but with very little publicly available detailed information on techniques and results. The only comprehensive experience from sealing of deep boreholes has been gained from

POSIVA's campaign of plugging the steep, about 500 m deep borehole KR-24 at Olkiluoto (cf. Pusch and Ramqvist 2006b). It took place in the lowest 30 m part of the hole and was performed by use of the techniques described in Subchapter 2.3. The most important conclusions from the work were:

- Stabilization of the hole where it was intersected by fracture zones had not been successful and there were risks of unsuccessful completion of the work. Technique for performing safe stabilization has to be developed.
- Casting of concrete at depth was partly unsuccessful, but the reason for this is not known.
- The decided levels of the plugs were not reached with accuracy.
- Hydraulic gradients may have caused disturbance of the concrete cast and axial displacements of the contents in the hole.
- Placement of two clay plug segments of 5 m length was successful.
- Weather conditions, especially low temperature, rain fall and strong winds, play a practically important role both for concrete casting and handling of clay plugs.
- The planned extraction of concrete and clay plugs at somewhat more than 520 m depth was abandoned.

It was obvious from the KR-24 sealing project that several of the concrete-related techniques are not yet sufficiently well developed for safe application. In particular, borehole stabilization and casting of concrete plugs for getting them in the desired positions requires development, while no problems occurred at the installation of clay plugs of "Basic" type in this moderately deep hole. The impact of erosion etc when sealing deeper holes needs to be considered and steps taken to minimize difficulties.

3.4.5 Quality assurance

Quality measures have to be taken with respect to the following issues:

- Selection of plug positions for sufficiently effective cut-off of water flow along the holes must be found. This requires hydrological analysis in the way indicated in the present project and accurate evaluation for taking adequate decision.
- Stability of the boreholes in the sealing phase must be guaranteed. This requires stabilization of intersected fracture zones by reaming, casting of concrete and subsequent re-boring. These activities have not been altogether successful in the attempts made so far to seal deep boreholes,
- Sufficient density and homogeneity of concrete and clay plugs require that the materials used and the homogeneity obtained fulfil the specifications that will be provided.
- Long-term performance has to be assured. This is concluded to meet no difficulties as concerns clay plugs of "Basic" type in moderately deep boreholes (500 m) but reduction in density of the clay in deeper holes by erosion at the installation may make it vulnerable to chemical impact of concrete.
- Measurement of the bearing capacity of concrete plugs have to be made by loading, using drill strings or special tools, for making sure that clay plugs can be placed over them without risk of yielding of the concrete.
- Measurement of the positions of placed concrete and clay plugs must be made and compared with the detailed plugging plan. Deviations from the plan require reconsideration of the integral performance of the plug series in the hole. Reboring for removal of it and installation of a new one may be necessary depending on the evaluation of the performance of the inadequate series.

3.5 Simulated plugging of a typical deep hole

3.5.1 Activities

We will consider a typical deep hole with an assumed length of 900 m length, and containing 10 clay plugs and 10 concrete plugs, assuming presently available construction capacity.

The following construction and installation steps are taken, requiring the specified time for each of them:

- Replacement of water in the hole by flushing with tap water through a drill string. Time: 16 man-hours.
- Casting of a 5 m concrete plug in the lowest part of the hole followed by core sampling after 2 days. Total time: 48 man-hours.
- Casting of additional concrete in 5 m parts with checking of the consistency and levels by recording and evaluating machine parameters for each part. Time required per 10 m plug length: 32 man-hours.
- Determination of the bearing capacity of the uppermost concrete by coring and testing on site. Time required: 48 man-hours.
- Cleaning of borehole and replacement of water by flushing tap water through a drill string. Time required: 16 man-hours.
- Installation of 6 m clay plug segments at selected locations in the borehole. Time including handling and jointing of plug segments per 12 m plug length: 16 man-hours[5].
- Casting of concrete plug above the uppermost clay plug. Minimum length 10 m with determination of the quality by coring and testing after 2 days. Time required: 48 man-hours.
- Sealing of the upper end of the borehole by not yet determined technique.

3.5.2 Cost issues

Estimated cost of materials and manufacturing, excluding the sealing of the uppermost part of the hole, are: 1) perforated copper tubes and components SEK 2,000/metre length. 2) Clay components SEK 4,000/m assuming manual manufacturing. For the assumed 900 m long hole containing 10 clay seals and ten made of concrete is thus approximately 4 MSEK. The cost for the copper tubes is based on the assumption of 76.1 mm outer diameter, which is a standard diameter, requiring that the borehole diameter is increased to 80 mm by reaming.

The total estimated cost for field work representing approximately 2,000 man hours à 700 MSEK is 1.4 MSEK.

3.6 Risk analysis

In practice, a borehole sealing project involves a number of risks of which the major ones are the following:

- The selection of plug positions may be inadequate for preventing or limiting radionuclide migration from the repository to the biosphere and correction of the plug planning associated with complementary hydrological analyses may be needed.
- The performed sealing may be inadequate for the purpose of preventing or limiting radionuclide migration from the repository, and reboring and installation of new sets of plugs may be required. This may be found necessary in the course of ongoing field work or afterwards as a consequence of post-analysis of materials, installation depths etc. Typical risks in the installation phase are:
  - the replacement of initial groundwater by tap water with low electrolyte content may have failed and requires repetition of the water exchange,
  - drop of tools or drill strings and fall of rock fragments from the walls requires fishing or even reboring,
  - quality checking of the sealing materials, like incorrect mixing of concrete components and deviations of the diameter of clay plugs from the design may have been overlooked,
  - checking of the positions of installed plugs may indicate substantial deviations from the design or be found to have taken place by displacements after placement driven by water pressure, expansion or compression.
- Future reconsideration of the quality and performance of the sealing systems may turn out to judge them inadequate. One must therefore be prepared to take steps to improve the tightness of the systems, which will have the form of reboring and reinstallation of sealing systems.

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[5] The required time is expected to decrease with reduced borehole length.

4 Subproject 3 – sealing of large diameter holes[6]

4.1 Scope

Two boreholes with 15–20 m length and 300 mm diameter shall be plugged so that no axial water flow can take place. The holes extend from a niche excavated from the large ramp in the Äspö HRL at Section 2950 and oriented largely WNW/ENE as indicated in Figure 4-1, which illustrates that the holes intersect a number of identified fractures grouped as shown in the perspective. The boreholes have been used for tracer experiments as part of the TRUE-1 project (Winberg et al. 2000).

The distribution of the inflow of water is illustrated in Figure 4-2, which is also an indication of the rock structure. One concludes that the inflow is relatively uniform except for peaks at about 3, 10, 13 and 20 m distance from the upper ends of the holes. Two "dry" intervals can be assumed, one at 10–12 m distance from the upper ends of both holes, and one above 2 m depth.

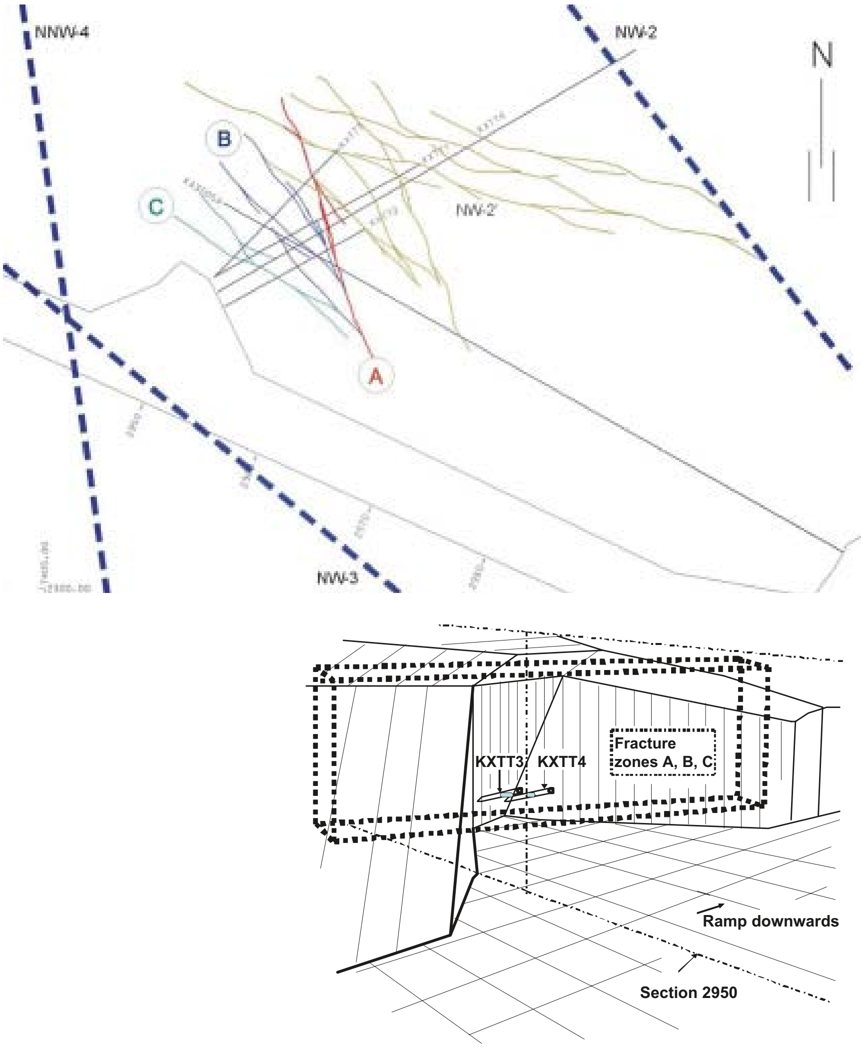

Figure 4-1. *Upper: Horizontal section at Z = –400 showing structural model based on identified conductive geological structures in the TRUE-1 volume (Winberg et al. 2000). Lower: Perspective view.*

[6] Subproject 3 is fully reported in a separate SKB report "Sealing of 300 mm boreholes KXTT3 and KXTT4 at Äspö HRL. Report of Subproject 3 of Borehole sealing project" (Pusch and Ramqvist 2006a).

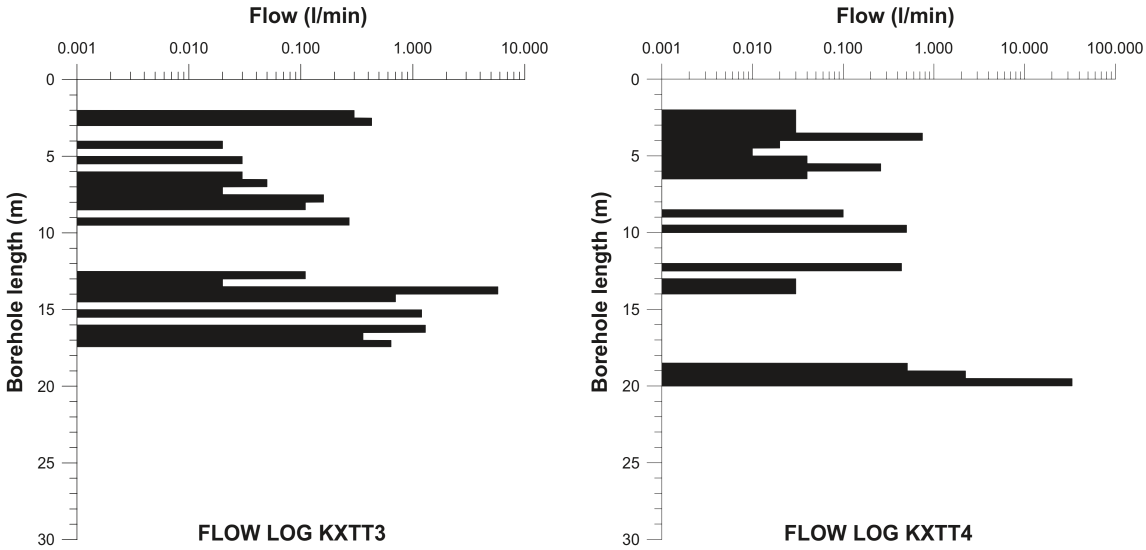

Figure 4-2. Measured inflows in the two boreholes KXTT3 and KXTT4 (Winberg et al. 2000).

The finally selected and applied way of plugging the two 300 mm boreholes is illustrated in Figure 4-3. It follows the general principle of plugging boreholes, i.e. to fill them with physically stable material, concrete, where the holes intersect water-bearing fracture zones, and install dense clay blocks where the rock is poor in fractures. The ultimate density would be at least 1,900 kg/m^3. Concrete cannot provide the required tightness, but sufficiently dense smectite-rich clay will serve acceptably. The water pressure can be about 3 MPa, which will exert an axial force of about 20 t (200 kN). This made it necessary to seal the upper ends of the holes with durable concrete anchored to the rock by a reamed recess.

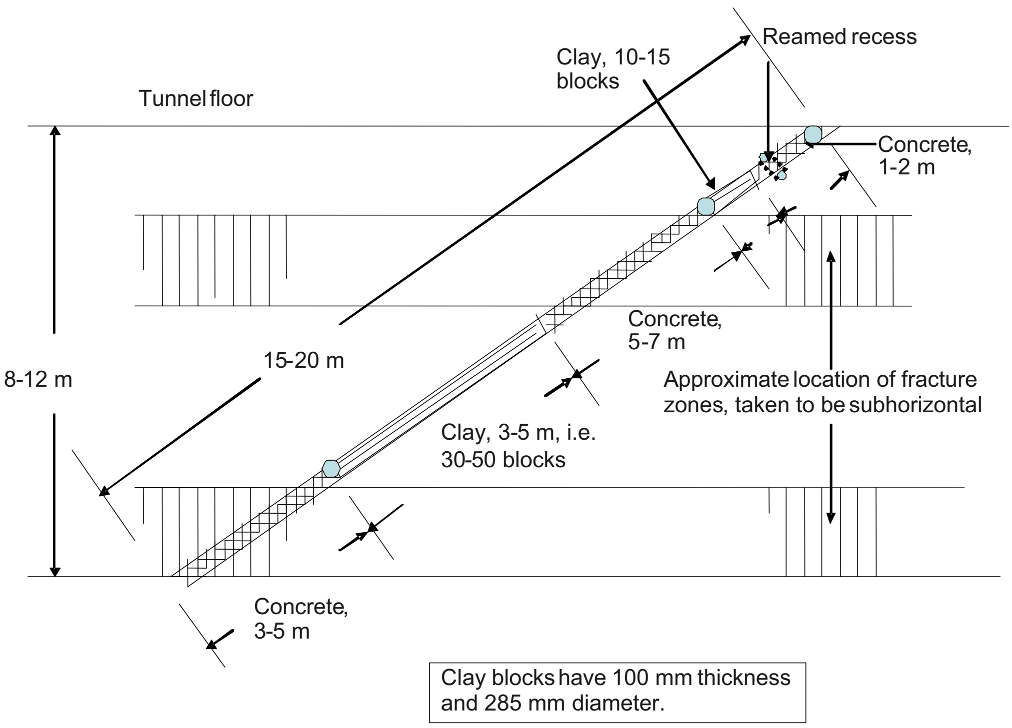

Figure 4-3. The selected sealing principle using on-site cast CBI concrete and prefabricated clay plugs of "Basic" type.

4.2 Materials

4.2.1 Concrete

The concrete recipe used in preceding full-scale boreholes sealing projects in Finland ("KR-24" at Olkiluoto) and in construction of concrete plugs in 200 mm boreholes at Äspö is shown in Table 4-1. Results from CBI's testing and from the last mentioned field experiment had indicated that the uniaxial compressive strength would be about 1 MPa after one day of curing and at least 10 MPa after one month (Pusch and Ramqvist 2006a).

4.2.2 Clay

Blocks were prepared by compaction of two types smectite-rich clay material (CEBOgel and G001-L) in a steel form. The form which had a slightly conical shape was manufactured by Livinstone AB (SKB order 17474 November 2007) that also made the compaction using a compressive force of up to 250 t (2.5 MN, pressure = 22 MPa), cf. Figure 4-4. Major block data are compiled in Table 4-2.

Table 4-1. Concrete (low strength) recipe for plugging of boreholes (Pusch and Ramqvist 2007).

Components	Kg/m^3 of concrete
White cement (Aalborg Portland)	60
Water	150
Silica Fume (Elkem)	60
Finely ground α quartz (Sibelco)	200
Finely ground cristobalite (Sibelco)	150
Superplasticizer (Glenium 51 Modern Betong)	4.38 (dry weight)
Aggregate (ballast), (Underås Jehanders grus)	1,679

Table 4-2. Material specification of granular materials and blocks, which were prepared by uniaxial compression under 22 MPa pressure.

Material	Water content, %	Density, kg/m^3 of compacted blocks	Dry density, kg/m^3 in expanded form in the holes	Density at saturation, kg/m^3 in expanded form in the holes
Compacted block of CEBO-gel	20.2	2,060	1,615	2,017

Figure 4-4. *Compaction of blocks. CEBOGEL bentonite block with 285 mm diameter and 100 mm height. Density 2,060 kg/m^3.*

4.3 Construction of plugs

4.3.1 Concrete

The low-viscous concrete was poured through the central tube that was equipped with a copper flange serving as upper form. It was vibrated for complete filling of the holes. A sufficient degree of hardening had taken place after 1 day, allowing insertion of the clay blocks.

4.3.2 Clay

Figure 4-5 illustrates the installation of the 285 mm diameter blocks stacked around the central copper tube used for drainage and for subsequent concrete casting. It was finally filled with dense CEBO-gel pellets to a dry density of about 1,100 kg/m^3 (1,700 kg/m^3 at water saturation).

The finally matured clay plugs will have a density of around 2,017 kg/m^3 (dry density about 1,615 kg/m^3) and a hydraulic conductivity of less than E–12 m/s, which is estimated to be at least one order of magnitude lower than the estimated bulk conductivity of the surrounding rock mass. This provides excellent sealing of the holes deeper than about 1–2 m below the tunnel floor. Groundwater flowing in the rock around the clay plugs can cause some slight erosion of the clay where it is in contact with water-bearing fractures, but this effect is deemed negligible because of the small number of such fractures and the low hydraulic gradiens and also considering the coagulating effect that the Äspö brackish water has on possibly escaping smectite particles.

4.3.3 Overall conclusions

The following conclusions were drawn:

- The sealing operation was successful and the system of clay and concrete components is coherent.
- The sealing operation serves as an example of how boreholes of any direction and with 300 mm or smaller dimensions can be plugged even where the water inflow is strong.
- The performance of the plugs is expected to be very good although two mechanisms may have a degrading effect in a long-term perspective:
  - groundwater flowing in the rock around the clay plugs can cause slight erosion of the clay where it is in contact with water-bearing fractures, but this effect is deemed negligible mainly because of the small number of such fractures in the positions chosen for the clay plugs,
  - chemical interaction between clay and concrete may lead to degradation of both. This matter is presently being investigated by analysis of contacting clay and concrete in boreholes on the 220 m level at Äspö. These materials are of the same type as those used in the 300 mm holes.

Figure 4-5. *Placement of clay blocks. Block column with copper plate fixed to the throughgoing central tube.*

5 Subproject 4 – interaction of clay and concrete plugs

5.1 Scope

The proposed concept of sealing deep boreholes in repository rock implies that the parts of a bore-hole 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. Concrete can 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 processes are and how far from the contact of the two components that they reach. This was the purpose of the experiments with 5 m deep holes, which were bored from the floor of a room with its floor at 220 m depth. The design principle is shown in Figure 5-1.

The photo in Figure 5-2 illustrates the low frequency of intersected fractures, implying slow inflow of water to the hole. Following earlier estimates on the rate of maturation of clay plugs it was still estimated that complete water saturation would be reached in months rather than years.

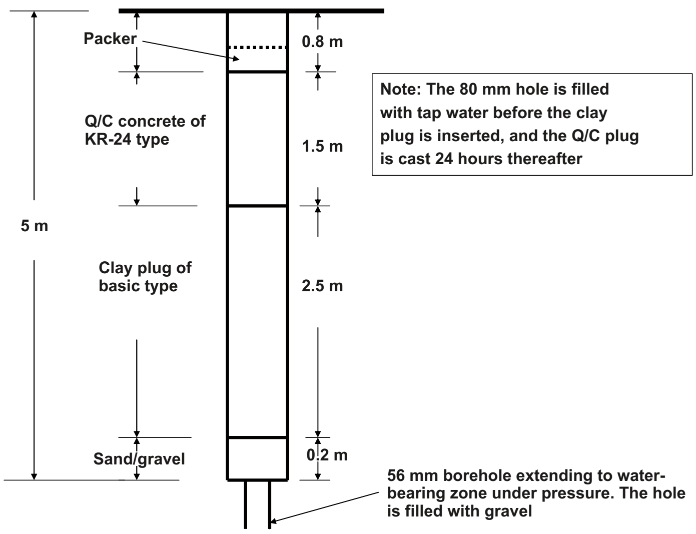

Figure 5-1. *Schematic view of the two 5 m boreholes (actual depths 6.00 and 5.90 m) with 80 mm diameter for testing of the interaction of quartz/cement and clay. The upper part of the hole was filled with CBI concrete over a clay plug of "Basic" type resting on sand gravel.*

Figure 5-2. *Hole KA 1621 G02. The core from the 80 mm-diameter hole representing the uppermost 3 metres of the hole has at least 5 water-bearing fractures.*

5.2 Materials

5.2.1 Concrete

The concrete plug was made of CBI concrete (Table 5-1) and was cast directly on the clay plug 8 hours after placing the clay plug for letting it mature sufficiently much to prevent the fluent concrete to enter the gap between the copper tube and the rock and displace the clay "skin" formed around the clay plug.

Table 5-1. Concrete recipe for plugging of boreholes (Pusch and Ramqvist 2007).

Components	Kg/m^3 of concrete
White cement (Aalborg Portland)	60
Water	150
Silica Fume (Elkem)	60
Finely ground α quartz (Sibelco)	200
Finely ground cristobalite (Sibelco)	150
Superplasticizer (Glenium 51 Modern Betong)	4.38 (dry weight)
Aggregate (ballast), (Underås Jehanders grus)	1,679

5.3 Clay plugs

The MX-80 clay plug in the 80 mm diameter hole was of "Basic" type with the following data:

- Outer and inner diameters of the copper tube with 50% degree of perforation were 76.1 and 72.1 mm, respectively. The length was 2.5 m.
- The clay blocks, which were trimmed to fit tightly in the tubes, had 6% water content and a density of 2,150 kg/m^3, corresponding to a dry density of 2,028 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 was 2,078 kg/m^3.

5.4 Construction

As for full-scale application of the borehole sealing method, the hole was filled with low-electrolyte water before installation of the plugs. With time, electrolytes will 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 than where the salt concentration is low. The access to water for maturation is the most important factor. It is controlled by the rock structure and water pressure, which was estimated at 500–1,000 kPa..

5.5 Expected plug evolution

5.5.1 Concrete plugs

The water pressure is relatively low in the rock and saturation and maturation of the plug components were expected to be slower than in rock with unlimited access to water. Still, it was estimated that all major chemical processes would have proceeded far enough to be identified by chemical analyses after one year, which was the initially planned testing time.

Earlier investigations have indicated that ordinary Portland cement gives very high pH, which is known to degrade smectite clay that is in contact with it. Thus, theoretical considerations 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 (Pusch and Yong 2006). Interstratified smectite/illite (S/I) with up to 20% illite was found when the solution contained much K^+. Uptake of Mg^{2+} in the montmorillonite crystal lattice resulted in conversion to the smectite species saponite. It is well known that Portland cement has porewater with very high pH.

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 was planned to be tested by microstructural analysis, and determination of the uniaxial compressive strength and hydraulic conductivity of the cement at different distances from the clay contact.
- The dense cement paste fissures. This was planned to be tested by microstructural analysis.

5.5.2 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 in a few hours. The initially low density of this skin causes early chemical interaction with cement water and dissolved elements and migration of cement porewater to the clay. Ca would migrate from the cement to the clay causing ion exchange and change in the microstructure of the clay by coagulating softer parts. This was documented by microstructural analysis and determination of the hydraulic conductivity and swelling pressure of clay samples at different distances from the clay/concrete contact.

5.6 Example of interaction of concrete and clay

5.6.1 Objective

The purpose of the project was to investigate if and how smectitic clay plugs interact chemically with contacting concrete of CBI-type. The plugs had been in the holes for 3.1 years when they were extracted from the rock. A second hole of the same type can be investigated later (see Figure 5-1).

5.6.2 Extraction of plugs

The plugged borehole was recovered in late November 2009 from the rock by slot-drilling to give a rock column of about 6 m length, which was sectioned by sawing (Figure 5-3).

Figure 5-3. *The rock column containing the plugged borehole KA 1621 G02. Upper: Slot drilling. Lower: Wire sawing to produce 100 mm thick discs.*

A total number of 10 discs were prepared so that possible physical, chemical and mineralogical changes could be investigated at different distances from the clay/concrete contact (Figure 5-4). Disc 7 contained this contact and was subject to detailed analysis. Figure 5-5 illustrates the appearance of the sectioned clay plug.

5.6.3 Description of samples

The plug materials in the discs are described in Table 5-2.

Samples of concrete ("cores") with 27–28 mm diameter and 40 mm length were bored from Disc 8 for determination of the hydraulic conductivity and unixial compressive strength, the remaining material being investigated with respect to the content of major chemical elements. A "core" with 29.5 mm diameter was trimmed from Disc 7B and divided for determining the hydraulic conductivity and unixial compressive strength of the concrete that reached 0–10 mm from the contacting clay and from 10–20 mm, respectively. The remaining part of the concrete was used for chemical and mineralogical characterization. Clay was trimmed from Disc 4 for determination of the hydraulic conductivity and swelling pressure.

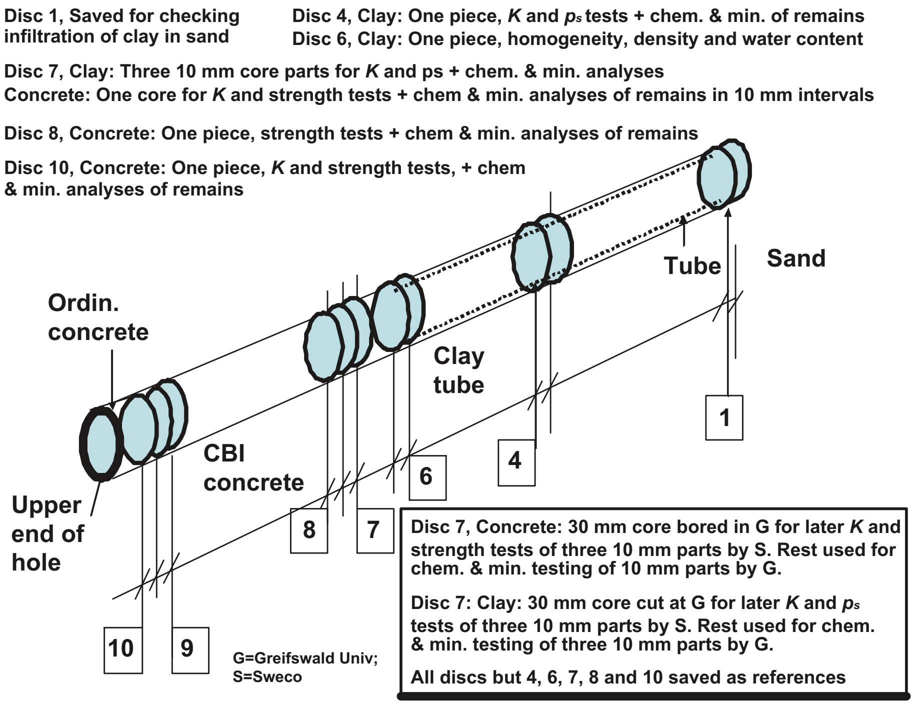

Figure 5-4. *Schematic view of the plugs in the hole. Disc 1 served as reference. Discs 2.3 and 5 were saved for information. The other ones were analyzed.*

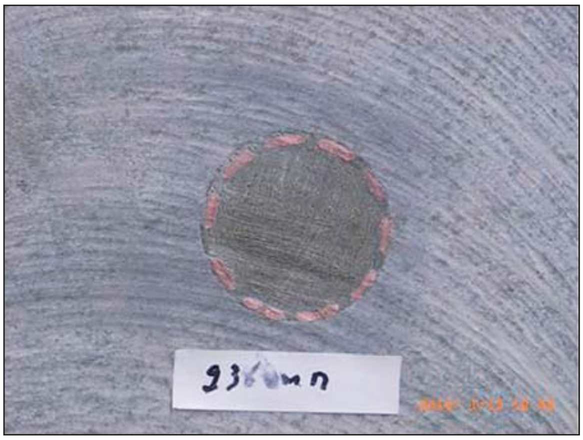

Figure 5-5. *The sectioned clay plug with the perforated copper tube embedded in dense clay.*

Table 5-2. Plug materials in the discs. Discs 2,3 and 5 were not investigated,

Disc no	Distance from clay/concrete contact, mm	Material
1	About 2000	Saved
4	About 1000	4L=100 mm clay
6	50–150	6L=100 mm clay
7	50	7L=50 mm clay, 7B=50 mm CBI concrete
8	50–150	8B=CBI concrete
9	150–250	Saved
10	250–350	10=ordinary concrete, not investigated

5.6.4 Results from the laboratory testing of physical properties[7]

The work is complete and the outcome summarized in this subchapter.

Disc 4. About 1,000 mm from the clay/concrete contact

The central part of the clay "core" had an average water content of 26.6% and a density of 1,980 kg/m^3 (dry density 1,555 kg/m^3). The density was slightly lower than predicted, which can be explained by a slightly larger borehole diameter than 80 mm or by gaps between the clay blocks in the copper tube at the plug preparation. The hydraulic conductivity was found to be 2.5E–11 m/s and the swelling pressure 3.05 MPa at saturation and percolation with distilled water. The conductivity was hence considerably higher than expected (cf. Figure 2-8), which indicates that the expected impact of Ca-uptake from the concrete implying widening of voids, was preserved at the saturation and percolation with electrolyte-free water. The swelling pressure agrees well with the diagram in Figure 5-6 showing typical data from oedometer testing of smectite-rich clays. It should be noticed that Na and Ca saturation give nearly the same pressure at densities equal to and exceeding about 1,950 kg/m^3.

Disc 6. 50–150 mm from the clay/concrete contact

Figure 5-7 shows the clay plug extracted from the rock, verifying that the "skin" completely covered the tube. The average water content of the "skin" was 38.8% and the density 1,800 kg/m^3 (dry density 1,270 kg/m^3). The central part of the clay "core" had an average water content of 37.0% and a density of 1,850 kg/m^3 (dry density 1,350 kg/m^3). The density was significantly lower than predicted because one or a few unconfined 72.1 mm diameter clay blocks had been placed on top of the copper tube and swelled out to a larger volume than if they had been in the tube.

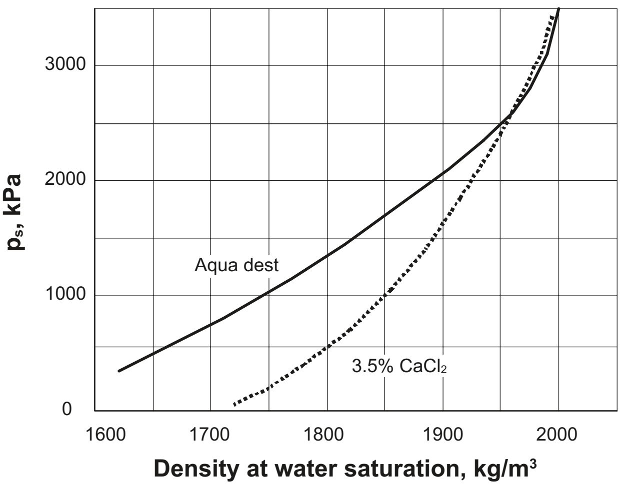

Figure 5-6. *Approximate relationship between density at water saturation and swelling pressure of smectite-rich clay (Pusch and Yong 2006).*

[7] The laboratory work and evaluation of data is performed by the Geological Dept. at Greifswald University. All rawdata is stored in SKB database, Sicada.

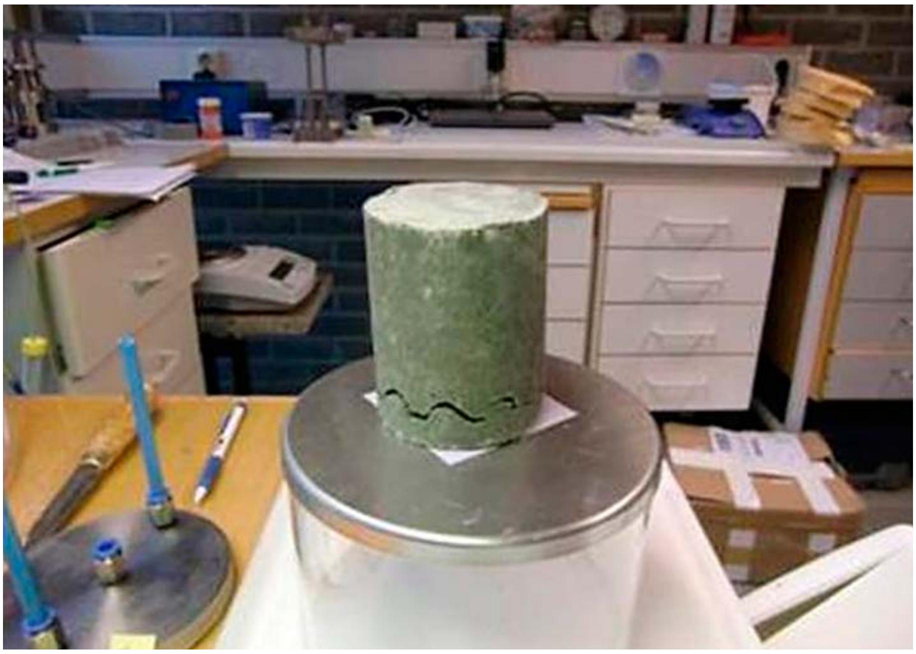

***Figure 5-7.** The clay plug (turned upside down) released from Disc 6. The wavy fracture was caused at the dissembling and occurred at the contact of a tube-confined part and one where only clay blocks had been placed in the hole.*

Disc 7B. 0–60 mm from the clay/concrete contact

The 100 mm thick disc consisted of 50 mm concrete and 50 mm clay. The concrete was divided into 3 pieces, a 10 mm thick disc from the clay contact (7B-0-10), a 10 mm thick disc 10–20 mm from the clay contact (7B-10-20), and a 40 mm long plug 20–60 mm from the previous one (7B-20-60).

Disc 7L. 0–30 mm from the clay/concrete contact

Three clay columns with 30 mm diameter and 10 mm height were trimmed from the clay sample contacting concrete for determining the hydraulic conductivity, swelling pressure, and compressive strength. They were termed 7L-0-10, 7L-10-20 and 7L-20-30. Material from the remaining clay plug at the same distances from the clay contact was analysed according to the program.

Table 5-3. Data from tests of 7B samples.

Sample	Density, kg/m^3	Hydraulic conductivity, m/s	Compressive strength, MPa
7B-0-10	2,253	3.9E–11	31.7
7B-10-20	2,183	3.9E–11	24.5
7B-20-60	2,180	2.3E–11	21.1

Table 5-4. Data from tests of 7L samples.

Sample	Density, kg/m^3	Hydraulic* conductivity, m/s	Swelling pressure*, kPa
7L-0-10	1,721	1.0E–11	960
7L-10-20	1,880	2.1E–11	775
7L-20-30	1,910	1.3E–11	770

* Saturated and percolated with distilled water.

Disc 8. 50–150 mm from the clay/concrete contact

This disc contained concrete and was investigated with respect to the compressive strength. The plug was extruded from the rock frame by axial loading, which gave the adhesive strength of the concrete, 80 kPa. This low shear strength suggests that the organic plasticizer can have accumulated at the clay/rock interface and served as lubrication. The plug was then exposed to uniaxial compression at a loading rate of about 100 kg per second leading to failure by axial splitting at 8,000 kg, corresponding to a compressive strength of 15.9 MPa. This value is appreciably lower than of the concrete in Disc 7, which indicates that the concrete was heterogeneous. This indicates that the technique for concrete casting in boreholes, especially at large depths, must be improved. The best candidate method is to use the container principle that has, however, not yet been fully tested.

5.6.5 Results from testing of chemical and mineralogical properties[8]

Focus has been on the contacting concrete and clay in Disc 7 and the main information is as follows:

- Calcium had migrated from the concrete into the entire clay in Disc 7.
- In the interval 0 to 10 mm from the concrete the clay had dominant 2 interlamellar hydrate layers as indicated by the 001 reflections, and 1 hydrate layer at larger distance from the concrete.
- The concrete was depleted of calcium, and electron microscopy showed that the cement phases have undergone significant dissolution. Elemental mapping showed a decrease of calcium on a micron scale away from the interface.
- Gypsum was found in all parts of the clay in Disc 7.

The microstructural investigations indicated the presence of numerous uniformly spaced voids of a few micrometer size in the clay in contact with the concrete (Figure 5-8). This is assumed to be caused by the contraction of initially expanded clay stacks in the Na clay when Ca invaded it. This would yield an increase in hydraulic conductivity.

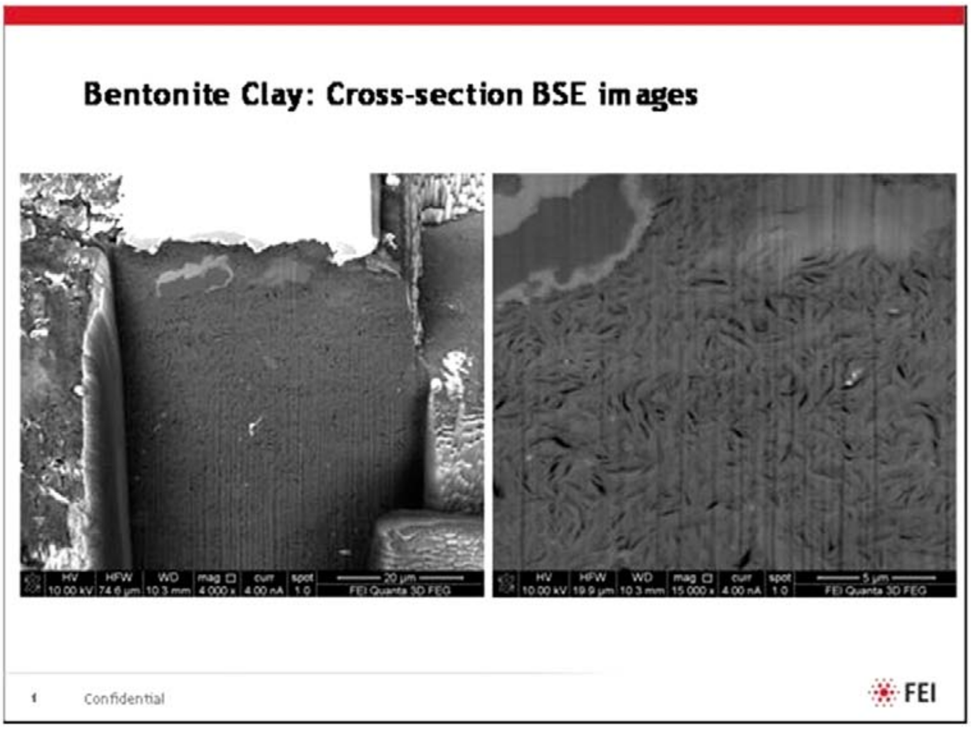

Figure 5-8. *Example of the appearance of the microstructural organization of clay at 0–10 mm distance from the concrete in Disc 7 (Laurence Warr, Greifswald University).*

[8] The laboratory work and evaluation of data is performed by the Geological Dept. at Greifswald University.

5.6.6 Tentative conclusion from the laboratory studies

Physical data

The analyses indicate that the physical properties of the concrete and clay had not undergone any dramatic change in the 3.1 years that the plugs stayed in the borehole, but that practically important alteration had taken place. The fact that the compressive strength of the concrete distant from the clay (Disc 8) was lower than of the concrete adjacent to the clay (15.9 MPa and 21.7–31.7 MPa, respectively) indicates that the clay did not have any significant degrading impact on the concrete.

For the clay one finds no significant differences in hydraulic conductivity when comparing the sample distant from the clay/concrete contact (Disc 4) and the one in contact with concrete (Disc 7) despite the significantly higher density (1,980 kg/m^3) of the firstmentioned. For the latter low-density clay the swelling pressure and conductivity are in fair agreement with data for clay saturated with distilled water, while for the denser sample extending 20–30 mm from the concrete in Disc 7 the data fit better with those for clay saturated with 3.5% $CaCl_2$ solution (Figure 5-6).

Chemical and mineralogical data

A major finding was that all the clay had undergone cation exchange from the original dominating cation sodium to calcium. Near the concrete the density was lowest and here 2 interlamellar hydrate layers were hosted.

The concrete was depleted of calcium near the clay, and the cement phases have undergone significant dissolution. Gypsum was found in the clay and concrete in the contact region of clay and concrete.

6 Conclusions and discussion

6.1 Main results from the sub-projects

The subprojects comprised study of:

No. 1 Selection of reference holes.

No. 2 Positioning of seals.

No. 3 Sealing of large-diameter boreholes (300 mm).

No.4 Clay/concrete interaction in boreholes.

The main results from each of them were as follows:

Sub-project 1

The work in Sub-project 1 comprised selection of reference holes for predicting suitable location of concrete and clay plugs and determination of the importance of sustainable clay plugs for hydraulic separation of major intersected fracture zones. The roles of a number of practically important conditions and properties of the boreholes have been interpreted and assessed, like geometrical features respecting straightness and variations in diameter of the holes, and the existence of axial hydraulic gradients. The firstmentioned determine the length of plug segments that can be installed without risk and the latter the quality of the concrete and clay plugs with respect to the risk of destruction by piping and erosion in the construction phase. A number of issues for improving the practicality in installation and the quality of the plugs have been identified; and further specific development of plugging materials and techniques for installation have been suggested.

It is concluded that practically useful methods for sealing of boreholes are available and can be recommended in practice. For this purpose it is required that sufficient information respecting the location of intersecting fracture zones can be obtained and that the basis for selecting sealing methods, i.e. need for stabilization, access to geometrical borehole data and hydrological conditions, can be obtained. This can be made by core and borehole examination as well as by hydrological measurements.

Sub-project 2

The work in Sub-project 2 has focused on identification of suitable plug positions in the selected representative boreholes with respect to the hydraulic performance of identified practically important fracture zones that intersect them. The importance of the sealing efficiency has been investigated by calculating the difference in piezometric pressure in a typical borehole left open and sealed by plugs of different quality. This work certified that long-lasting plugs installed in suitable positions are required for avoiding short-circuiting of the rock mass between the repository and the ground surface.

This sub-section also describes detailed design and construction principles and a general procedure for assessment of QC/QA of the integrated system of seals, including also estimation of cost. These activities indicated the strong need of preparing the holes so that they are ready for sealing, requiring cleaning, dummy testing, and stabilization, and that the feasibility of some of these activities have not yet been demonstrated.

The main outcome of this study is that long-lasting plugs installed in suitable positions is required for effective sealing and control of the groundwater flow in a rock mass intersected by long boreholes. The need for long-lasting plugs in hydrologically important positions has been realized and design and manufacturing and techniques for placing suitable seals have been identified. There is an obvious difference in rocks with different contents of fracture zones, as exemplified by a comparison of the Forsmark and Laxemar sites. It is also clear that all holes are individual and require characterization for selecting suitable positions and nature of seals.

Sub-project 3

Plugging of the two 300 mm holes comprised preparation and placement of large-diameter clay plugs according to the "Couronne" concept, and casting of concrete seals under high water inflow conditions. The major problem, identified and described in the report, was the impact of inflowing water. It was drained off in the sealing phase and the high water pressure built up after sealing had to be sustained by the constructed seal. An obvious difficulty identified in the project was that handling and placement of heavy object like compacted clay blocks require special equipment and competence.

The successful completion of this study gave excellent proof of the feasibility of the proposed techniques for borehole sealing. The overall conclusion was that the design and construction as well as operation of clay seals placed and operating under severe conditions in large-diameter boreholes are practical and feasible.

Sub-project 4

An important issue is how concrete and clay seals interact in boreholes and a special study was made for investigating physical and chemical processes in a borehole containing contacting clay and concrete. The experiment had a duration of slightly more than 3 years and involved detailed mineralogical and geotechnical investigations of the two components.

The retrieval of a rock column containing a 5 m long concrete/clay plug gave access to clay and concrete at varying distances from their contact. Investigations in co-operation with international expertise showed that CBI concrete in contact with smectite-rich seals had not led to substantial degradation of either of them in the 3 year testing time. However, chemical reactions and changes in physical properties of the plug components had taken place, particularly in the clay. It was concluded from this study that it is suitable to carry out the corresponding investigation of the plugs in the "twin" (KA 1621 G01) hole at the 220 m level and to develop other concrete brands of more inert type.

7 Remaining problems and proposed solutions

7.1 General

Assessment of the function of seals and need for improvement was made considering the following issues:

- Clay seals – material and placement.
- Concrete – material and placement.
- Test facilities.
- Stabilization and reboring.
- Longevity.
- Sealing of the uppermost part of deep holes.
- Removal and replacement of seals.
- Techniques for grouting sections of boreholes.

7.2 Clay seals

The presently favoured method intended for inserting clay plugs is the "Basic type" method, implying use of perforated copper tubes will fitting highly compacted smectite clay. It works well to a limited length of the holes (about 500 m). However, development of a type that can be used in at least 1,000 m long deep holes is strongly desired for placing clay plugs and concrete. The "Container" method (Figure 7-1) is believed to be suitable for bringing the clay plug units down to the desired depth with minimum disturbance by erosion. A prototype version has been used for concrete sealing of the deep hole KR-24 at Olkiluoto, but it has to be developed and used for certifying that it can be used in at large depth for placement of clay and concrete. The type of clay used in the various subprojects may not be ideal and further experiments are needed for finding an optimal clay material.

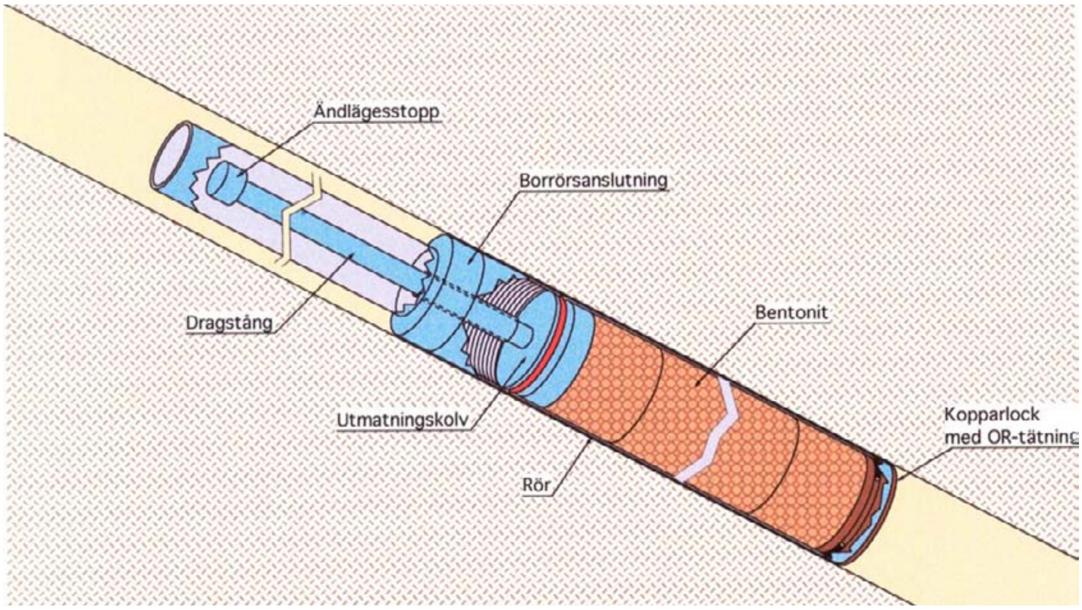

Figure 7-1. *The "Container" plug equipment placed in a steel tube that is brought into the hole. The brownish clay (or concrete) is contained between a piston ("utmatningskolv") by which it can be extruded to the desired position. At the outer end of the tube there is tight lid of copper ("kopparlock med OR-tätning") that moves down with the clay and stays in the hole.*

Smectite clay muds are necessary components in oil- and gas drilling for stabilizing deep boreholes and transporting debris from the drilling head up to the rig. They should be considered also in working out a practical procedure for installing clay plugs for delaying their expansion and for reducing erosion of clay plugs of "Basic" type during installation. An alternative method for delaying hydration of such plugs would be to coat them with a suitable mineral composition as verified by pilot tests. It is recommended to continue this R&D work.

7.2.1 Concrete

Two issues are in focus: the stability of concrete seals in boreholes, and use of concrete without organic plasticizers for preparing them:

- With time, cement in the concrete will be dissolved and lost but the remaining silicious aggregate mass is expected to remain as a coherent body separating clay plugs. Proper granular composition of the mass will provide the required physical behaviour and minimize invasion of clay particles from contacting clay plugs. However, both functions must be proven by adequate laboratory and bench-scale tests, as well as by suitably performed field experiments (cf. Section 1.2).
- An important issue is to use concrete without organic superplasticizer, as is also required for any concrete construction in HLW and LLW repositories. Preliminary investigations indicate that ordinary superplasticizers can be replaced by commercially available minerals without significant loss of compressive strength but further systematic work for development of a suitable concrete recipe is required.

7.3 Test facilities

Full-scale application of presently available techniques and improved versions of them is needed. Some of the deep Laxemar holes are suitable for testing techniques, especially methods for stabilizing boreholes, and for staff training. An earlier proposal of drilling an 800 m long hole parallel to the straight ramp of the Äspö URL for getting access to it from existing niches in the ramp at any desired time is hereby revived since it would make it possible to follow the evolution of installed plugs of presently considered types and of further developed ones over a longer period of time.

The not yet fully tested techniques for sealing of the upper 50–100 m of deep boreholes (Pusch and Ramqvist 2006a) can suitably be made by use of existing or new holes at Äspö with this length.

7.4 Stabilization and re-boring

There is still no proven technique for safe and effective stabilization of boreholes for minimizing inflow of water in the sealing campaign. Experiments in short holes have indicated the applicability of proposed techniques, which include reaming followed by casting concrete and re-boring, leaving an annular concrete tube that supports the rock. However, long holes are expected to give problems as demonstrated by the partly unsuccessful stabilization of the deep hole KR-24 at Olkiluoto.

Development and testing of methods for stabilization of long boreholes, boring and sealing of a 700–800 m long hole bored parallel to the straight part of the Äspö ramp would be valuable since stabilized parts can be tested and sampled for examination at desired time. This possibility is offered by access to the hole from existing niches. It would also give opportunities to test and assess methods for borehole characterization, stabilization, and cleaning, which are all prerequisites for successful sealing.

7.5 Longevity

The successive time-dependent change in physical properties caused by chemical and mineralogical processes is not well known for clay plugs and almost unknown for concrete. Its importance is indicated in the report on Subproject 4 in the present document and calls for more detailed and comprehensive investigation and development of conceptual and theoretical degradation models. The ultimate state of contacting clay and concrete, implying complete degradation and loss of coherence of the plugs, must be defined and the function of the clay/concrete system assessed with respect to time after sealing. A matter of possible importance for the longevity of plugs with metal components is the impact of electrical potentials in the rock. The relevance of considering them is illustrated by the comprehensive corrosion of metallic gauges in deep boreholes at Forsmark as reported in SKB's current investigation of earth potentials.

7.6 Sealing of the uppermost part of deep holes

Sealing of the uppermost part of deep holes has been proposed to be made by use of copper, concrete, or trimmed rock blocks and the two first mentioned have been tested for demonstrating the constructability. Since the rock may be glacial-eroded by up to some 50 m depth, it will be required to demonstrate that plugs of these types can be constructed below this depth. Because seals of trimmed rock components would be intact for hundreds of thousands of years, they should be considered and prototypes prepared and installed in suitable large-diameter holes for evaluation of constructability and function.

7.7 Removal and replacement of plugs

Unsuccessfully constructed plugs may have to be removed and new or other seals installed. Drilling for removal would not be difficult but it is required that obstacles and debris can be removed and that the drill follows the hole without deviating or significantly changing its dimensions. Techniques for guaranteeing this have to be worked out and tested. Reaming to a larger diameter will have to be considered for reaching sufficient quality of the new plugs. All this can be tested in a borehole drilled parallel to the ramp as proposed in Sub-chapter 7.2.

7.8 Technique for grouting sections of boreholes

Borehole plugs of clay and concrete are sensitive to through-flow early after installation. Such flow can result from local hydraulic gradients caused by axial piezometric differences over smaller or longer parts of the boreholes and generate piping and erosion that can lead to a permanently increased hydraulic conductivity of the clay and concrete seals. It is therefore important to tighten intersected fracture zones by grouting them. The grout must penetrate into the zones sufficiently much to stabilize the fractured rock to several centimetres distance from the borehole and minimize inflow into the holes in the plugging campaign but not thereafter. It is therefore acceptable if the sealing component of the grout, which is suitably of cement type, undergoes successive dissolution and gets lost with time but the granular composition of the remaining aggregate component must be such that it prevents penetration of clay particles from nearby clay plugs in any time perspective. The grout should be of low-pH type for minimizing chemical interaction with the clay plugs and chemical alteration of fracture minerals like feldspars.

The required technique for such grouting and suitable grout materials are not at hand today and they are urgently needed for making it possible to permanently seal deep boreholes and boreholes extending from a repository.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Bockgård N, 2011. Hydraulic effects of unsealed boreholes. Numerical groundwater flow modelling of the Forsmark and Laxemar site. SKB R-11-17, Svensk Kärnbränslehantering AB.

Nilsson G, Nissen J, 2007. Forsmark site investigation. Revision of borehole deviation measurements in Forsmark. SKB P-07-28, Svensk Kärnbränslehantering AB.

Pusch R, 2008. Geological storage of highly radioactive waste: current concepts and plans for radioactive waste disposal. Berlin: Springer.

Pusch R, Ramqvist G, 2006a. Äspö Hard Rock Laboratory. Cleaning and sealing of borehole. Report of Sub-project 1 on design and modelling of the performance of borehole plugs. SKB IPR-06-28, Svensk Kärnbränslehantering AB.

Pusch R, Ramqvist G, 2006b. 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. SKB IPR-06-30, Svensk Kärnbränslehantering AB.

Pusch R, Ramqvist G, 2007. Borehole projects– Final report of Phase 3. SKB R-07-58, Svensk Kärnbränslehantering AB.

Pusch R, Ramqvist G, 2011a. Sealing of 300 mm boreholes KXTT3 and KXTT4 at Äspö HRL. Report of Subproject 3 of Borehole sealing project. SKB R-11-19, Svensk Kärnbränslehantering AB.

Pusch R, Ramqvist G, 2011b. Interaction of clay and concrete plugs – Plugging of 5 m deep hole KA1621G01 at Äspö. Final report. SKB R-11-18, Svensk Kärnbränslehantering AB.

Pusch R, Yong R N, 2006. Microstructure of smectite clays and engineering performance. London: Taylor & Francis.

Winberg A, Andersson P, Hermanson J, Byegård J, Cvetkovic V, Birgersson L, 2000. Äspö Hard Rock Laboratory. Final report of the first stage of the tracer retention understanding experiments. SKB TR-00-07, Svensk Kärnbränslehantering AB.