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Borehole project – Final report of Phase 3

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Abstract

The report describes borehole plugging techniques for use in deep boreholes extending from the ground surface, and construction and placement of plugs in holes of different lengths and orientations bored from the repository rooms. The principle employed is the one proposed in earlier phases of the project, i.e. to tightly seal those parts of boreholes where the rock has few fractures and a low hydraulic conductivity, and filling of those parts that intersect water-bearing fracture zones with physically stable material that does not need to be low-permeable. Four methods for tight plugging have been identified and tested and a technique has been found for filling boreholes that are intersected by fracture zones. The upper end of boreholes extending from the ground surface needs a "mechanical" seal for which copper metal and concrete work well. The experience from plugging of a 550 m deep borehole at Olkiluoto (OL-KR24) has been compiled and plans worked out for sampling and testing of contacting clay and concrete in this hole and in short holes in the Äspö URL.

Summary

The principle of borehole sealing employed in the work is the one proposed in earlier phases of the project, i.e. to tightly seal those parts of boreholes where the rock has few fractures and a low hydraulic conductivity, and filling of those parts that intersect water-bearing fracture zones with physically stable material that does not need to be low-permeable. The presently reported work concerns Phase 3 of the borehole sealing project based on the presumption that preparation of the plugging operations in the form of hydraulic, mineralogical and structural characterization, as well as stabilization and clearing of the holes have been completed before plugging starts. The document summarizes the basic principles involved in borehole sealing using four specific techniques for plugging boreholes of different length. These techniques are briefly described in the main text for explaining their major features and general conditions for practical application. The first is focused on design of plugs and prediction of their performance, as well as on manufacturing. The second describes construction and testing of clay plugs in 5 m long holes in rock at 450 m depth and in 5 m tubes in the laboratory. The third describes the plugging operations in the 550 m deep borehole OL-KR24 at Olkiluoto. The fourth deals with the "mechanical" seals that are required for physical securing of the upper end of holes extending from the ground surface.

The report is focused on description of four clay plugging techniques, termed the "Basic", "Container", "Couronne", and "Pellet" concepts. The "Basic" type has been introduced and applied a couple of decades ago but systematic analysis of its performance has not been made earlier. The advantages of this method are that the core of highly compacted smectite-rich clay is confined in a perforated copper tube that minimizes erosion of the clay in the placement phase and gives the clay plug a very well defined position. A disadvantage is that the perforation retards the maturation, i.e. the migration of clay to fill the space between the rock and tube. The second method implies that a closed tube with clay is placed in the desired position and opened to let the clay core mature without hindrance after lifting off the opened container. This method has a great development potential for use in very deep holes. The third method simply involves stacking of annular discs of clay on a central rod and moving the package in position. Like the two first mentioned it can be used in holes of any direction but the length of the hole is limited. The fourth method involves filling of very dense clay pellets in steep holes. Its simplicity is favourable but the density of the finally matured clay is low.

The report also describes how the upper end of boreholes extending from the ground surface can be equipped with a "mechanical" seal for which copper metal and concrete work well as shown by demonstration tests on the ground surface and load tests at 450 m depth in the Äspö URL.

Sammanfattning

Principen för borrhålspluggning är densamma som föreslagits i projektets tidigare faser, dvs placering av effektiva avtätningar där berget har få sprickor och låg hydraulisk konduktivitet, samt fyllning av de delar av hålen som genomskärs av vattenförande sprickzoner med fysikaliskt stabilt material som inte behöver vara tätt. Det utförda arbetet avser Fas 3 av borrhålspluggningsprojektet och grundas på förutsättningen att beredning av pluggningsoperationen i form av hydraulisk, mineralogisk och strukturell karakterisering samt stabilisering och rensning genomförts innan pluggningen börjar. Rapporten summerar huvudprinciperna för borrhålspluggning och beskriver kortfattat i huvudtexten fyra specifika tekniker för pluggning av hål av olika längd. Den första fokuserar på design och prediktion av funktionen, samt tillverkningen. Den andra beskriver applicering och testning av lerpluggar i 5 m långa borrhål på 450 m djup och i 5 m långa rör i laboratoriet. Den tredje beskriver pluggningen av det 550 m djupa hålet OL-KR24 i Olkiluoto. Den fjärde behandlar ”mekaniska” lås som erfordras för fysisk säkring av överänden hos hål som utgår från markytan.

Rapporten rör främst beskrivningen av fyra lerpluggningsmetoder benämnda Basic”-, ”Container”-, ”Couronne”-, samt ”Pellet”-koncepten. ”Basic”-typen introducerades och tillämpades för flera decennier sedan men systematisk analys av verkningssättet har inte gjorts tidigare. Fördelarna med denna metod är att kärnan av högkompakterad smektitrik lera är innesluten i ett perforerat kopparrör som reducerar erosionen av lera i appliceringsfasen och ger lerpluggen ett väldefinierat läge. En nackdel är att perforeringen fördröjer mognaden, dvs utvandringen av lermaterial som leder till utfyllnad av utrymmet mellan hålvägg och rör. Den andra metoden innebär att leran innehålls i en sluten tub som öppnas i önskat läge och lämnar lerkärnan att mogna utan fördröjning efter det att tuben lyfts bort. Denna metod har en stor utvecklingspotential för användning i mycket djupa hål. Den tredje metoden innebär helt enkelt att ringformade lerskivor (”Couronnestenar”) staplas på en central metallstång som förs in i hålet till önskat läge. Den fjärde metoden innebär fyllning av lerpelletar med hög densitet i brantstående hål. Dess enkelhet är en fördel men densiteten hos den slutligen mognade pluggen blir låg.

Rapporten beskriver också hur överänden hos borrhål som utgår från markytan kan förses med ett ”mekaniskt” lås för vilket kopparmetall och betong fungerar väl enligt demonstrationsförsök och belastningsförsök på 450 m-nivån i Äspös underjordslaboratorium.

Contents

1 Introduction

The Borehole Plugging Project has developed from the initial state described in the report "Borehole sealing, preparative steps, design and function of plugs – basic concept", December 2004 /1/. The overall aim of the project, which comprises three phases, is to develop and test techniques for plugging boreholes of different length in repository rock. Placement of plugs requires stabilization and clearing of the holes, which have been investigated in Phase 1 but which require further consideration in future R&D. SKB and Posiva cooperate in this project respecting performance and financing. It is planned to comprise four phases of which the presently reported work concerns phase 3. It has been presumed that preparation in the form of hydraulic, petrologic and structural characterization, as well as stabilization and clearing of the holes have been completed before plugging starts.

The present document summarizes the basic principles employed in borehole sealing and four specific techniques for plugging boreholes of different length. These techniques are briefly described in the main text for explaining their major features and general conditions for practical application.

Sub-project 1

- Design of plug types.
- Prediction of the performance of clay and concrete plugs.
- Description of manufacturing and construction of clay and concrete plugs.

Sub-project 2

- Construction of clay plugs in 5 m long holes in rock at 450 m depth and in 5 m tubes in the laboratory.
- Prediction and testing of maturation of plugs in 5 m long holes in rock and in 5 m tubes in the laboratory.

Sub-project 3

- Construction of clay and concrete plugs in POSIVA's about 550 m deep hole OL-KR24 at Olkiluoto.
- Prediction of maturation of clay plugs in OL-KR24.
- Construction of plugs with clay and concrete components in 5 m boreholes at 220 m depth at Äspö for chemical and mineralogical investigations.

Sub-project 4

- Design of concrete and metal plugs in large-diameter holes for serving as "mechanical locks" of the upper ends of deep holes or elsewhere.
- Demonstration in shallow holes of technique for preparing recesses for anchoring metal and concrete plugs by reaming.
- Construction of concrete plugs in 200 mm diameter holes at 450 m depth.
- Testing of the resistance to axial displacement of concrete plugs at 450 m depth.

2 Basic principles employed in borehole sealing

2.1 General

The principle of borehole sealing that was defined early in the project is proposed to construct tight sealing of the parts of boreholes where the rock has few fractures and a low hydraulic conductivity, and filling of those parts that intersect water-bearing fracture zones with physically stable material that does not need to be very low-permeable but that must be chemically compatible with the tight seals. These consist of smectite-rich clay in the form of highly compacted blocks or pellets, while the fillings separating them consists of silica concrete with little cement of low-pH type and aggregates of quartz sand and quartzite. This type of concrete is largely inert with respect to chemical interaction with smectite clay and can be allowed to loose the cement component without jeopardizing its function as fill by using a size distribution of the aggregate grains that prevents the large majority of them to migrate into the rock fractures. This risk is largely eliminated by stabilizing the intersecting fracture zones by casting cement-poor concrete in reamed parts followed by re-boring. Hence, stabilization and subsequent clearing and cleaning of borehole walls are prerequisites for plugging, which comprise segment-wise placement of clay plugs and casting of silica concrete[1].

2.2 Tight seals

The reason why several clay plug types – all described in the subsequent chapters – are being investigated is because the different conditions that are met with in practice call for plugs with different properties and placeability. Thus, while very deep holes require a safe technique that is presently represented by plugs of "Basic" type with the clay confined in a perforated tube, a particularly safe version has been worked out for use in even deeper holes, i.e. the "Container" type with the clay confined in a closed tube that is opened at the desired depth. Shorter holes may preferably be sealed by using simpler types represented by the "Couronne" and "Pellet" types. All the plugs for constructing tight seals have highly compacted smectite-rich clay as most important component but the density and thereby the tightness, expressed as hydraulic conductivity and expandability, depend on the function of the plug constructions, which were investigated in the project.

2.3 Upper end seals

The tight seals of expandable clay must be confined at the upper end of the holes, which can be produced by use of long-lasting silica concrete or metal plugs anchored in recesses made by reaming. Foreseeable climatic changes and tectonic impact are expected to erode the rock to a considerable depth, up to 100 m by two glaciation/deglaciation events, which means that the tight, lower parts must still be intact in the considered 100,000 year perspective. Hence, the plan should be to seal holes extending from the ground surface by materials with at least the same mechanical strength and erosion-resisting potential as the rock down to this depth. This can be made by backfilling the holes with densely compacted moraine and stone fills and suitably placed "mechanical locks" of silica concrete and metal plugs. The latter two plug types were designed and tested in the project.

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[1] The project involved development of special concretes for stabilization of fracture zones and for filling parts of boreholes. These matters are described in detail in the report.

3 Tight seals in ordinary boreholes

3.1 Clay plug concepts

The four clay plugs are illustrated in Figure 3-1 /3/. They are primarily intended to be used in boreholes with diameters ranging from 56 to 100 mm but at least the "Basic" and "Pellet" plugs can be used in much wider holes. This latter type and the "Couronne" plug can hardly be used in very deep holes while the other two may be used in kilometre-deep holes. The density of the matured clay should be on the order of 2,000 kg/m^3, corresponding to a dry density of 1,590 kg/m^3, for fulfilling the criterion that the hydraulic conductivity must be lower than that of the surrounding rock.

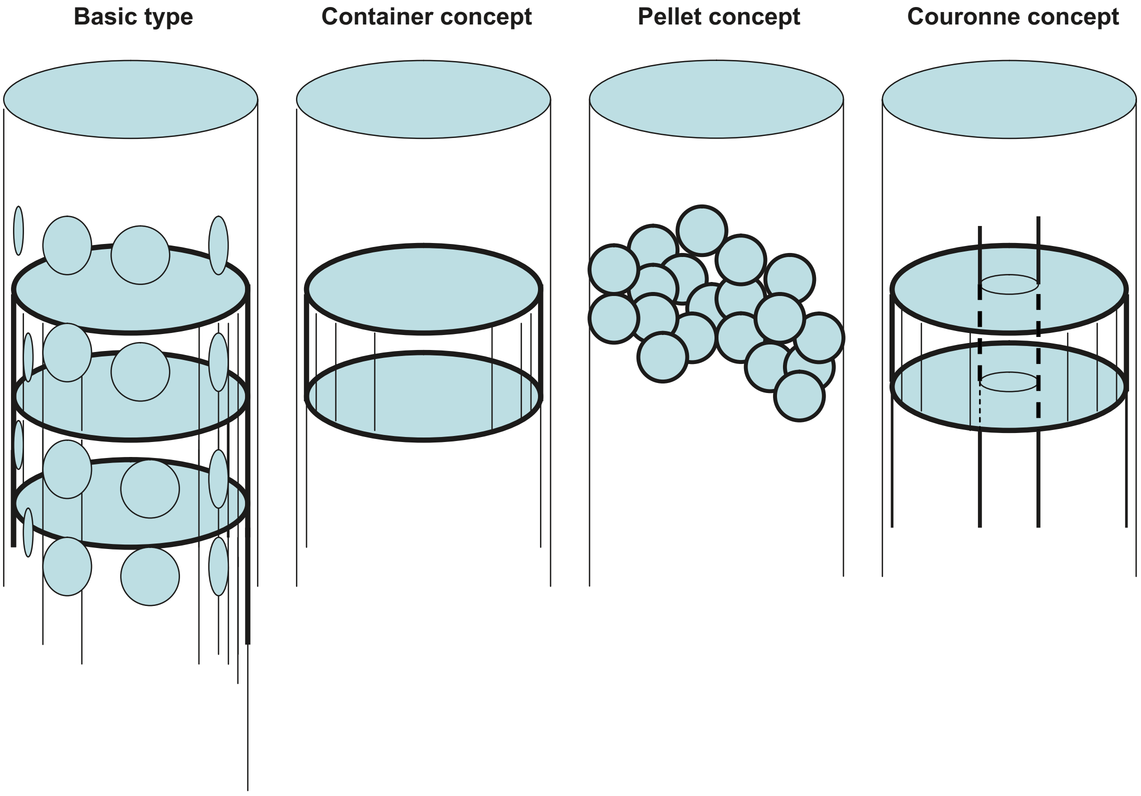


Figure 3-1. *The four alternative clay plug concepts. Left: The "Basic" plug with highly compacted MX-80 clay columns confined in perforated copper tubes. Second left: The "Container" plug with highly compacted MX-80 clay blocks contained in a cylinder attached to drilling rods and released when the tip of the cylinder is in the desired position. Third left: MX-80 pellets poured into the hole without compaction. Right: The "Couronne" plug with annuli of highly compacted MX-80 clay stacked around jointed copper rods that are pushed into the hole.*

3.2 The “Basic” concept

3.2.1 Design

The “*Basic”* plug concept was developed in the early eighties and has been used successfully for plugging short and long holes as demonstrated by field experiments performed in conjunction with the international Stripa Project /2/. It has been used for sealing boreholes from a drill rig at sea for the SFR repository at Forsmark, which demonstrated the feasibility of the method. The plugs consist of perforated copper tubes that contain well fitting blocks of highly compacted smectite-rich clay that migrates through the perforation and ultimately embeds the tube that is left in the hole. The density of the clay formed between the tube and the rock is very soft in the earliest maturation phase but solidifies and encloses the tube with a density that is determined by the geometry and time of maturation. The plug segments can be a few metres long and connected by a screw mechanism, bayonet clutch or by clinching.

In principle, the method is very safe since one has complete control of the position of each individual segment and good opportunities to pull up those that may not be placeable because of unforeseen roughness of the borehole walls or of a too small radius of curvature of the hole.

3.2.2 Materials and dimensions

The perforated tubes with the dense clay blocks placed in them must have sufficient strength to be handled in the placement phase without being deformed or break. This puts a limit to the degree of perforation and to the thickness of the tube walls and a comprehensive study was made in the early phase of the project for finding an optimum geometry with respect also to the rate of maturation of the clay component.

Metal type

Four metals were considered: copper, navy bronze, titanium, and steel, and they were all found to be acceptable but copper was selected because its chemical stability is documented and its impact on smectite clay is negligible. Also, the deformability of copper tubes can adaptate well to the curvature of the holes in the placement phase.

Perforation ratio

The degree of perforation is a determinant of the rate of maturation of the clay component and of the compressive and tensile strength of the tubes. For plugs in deep holes the high water pressure implies that access to water for maturation of the clay is not a limiting factor while geometrical constraints in the form of the size and spacing of the perforation holes control the rate of migration of clay to form a clay gel in the gap between tube and rock. For plugs close to the ground surface or located in those parts of a repository where the water pressure is low in the construction and waste placement phases, the ability of the rock to give off water to the clay determines the maturation rate.

Earlier field experiments with 50% perforation ratio and 10 mm hole diameter and 2 mm tube wall thickness gave acceptable performance with respect to the maturation rate of the clay and to the mechanical performance of the tubes and these measures were found to be at optimum in the study performed by Clay Technology AB in the present project (Sub-project 1) /3/.

3.2.3 Maturation – processes and predictions

Water saturation and homogenization

The rate of maturation of the clay component is very important: if it is very low the state of sealing can be strongly delayed and make the construction of intermediate concrete plugs difficult, while it can cause difficulties by erosion and friction resistance at the placement if it is very high. Considerable efforts have been made to develop a theoretical model of the maturation process but the complexity, provided amongst other things by the geometry of the perforation holes, has caused difficulties. The model is therefore only approximately valid. The most important practical results from the theoretical modelling and supporting laboratory tests were:

- Long-term laboratory tests showed that complete swelling and homogenisation is obtained after 10–20 days. The measured *mean* swelling pressure against the rock was 2.8 MPa for fresh water and 0.6 MPa for salt water. This is in good agreement with the predicted *mean* pressure for fresh water but not for salt water.
- Measurement of the hydraulic conductivity of the clay paste formed between the perforated tube and the confining tube, representing the condition after 20 days of maturation, gave 5E–13 to 9E–13 m/s for fresh water and 2E–12 m/s for salt water. Both are below typical conductivity values for the surrounding rock, i.e. E–11 to E–8 m/s, hence demonstrating the excellent sealing efficiency of the clay plugs.

For unlimited access to water, which is the case for clay plugs located more than a few hundred metres from the ground surface, complete water saturation is reached within less than a month for plugs in holes with up to 80 mm diameter (Figure 3-2). This does not imply that complete homogenization is reached in this time and a practical issue is whether the clay, which has somewhat different density in the center and in the gap between tube and rock after reaching complete water saturation, will ultimately become totally homogeneous or have permanent differences in density. The laboratory studies suggest that they will be permanent /3/.

At shallow depth where the water pressure is low the wetting rate of the clay plugs can be delayed and this case was considered in the study as well. The factors affecting the rate of water saturation are: 1) the hydraulic conductivity of the rock, 2) the location of water-supplying fractures, 3) the water pressure in the fractures, 4) the density and initial degree of water saturation of the clay, and 5) the geometrical conditions with respect to the perforation of the tube and the gap between tube and rock. FEM calculations using a very simple conceptual model showed that the influence of the hydraulic conductivity of the rock is not very important. Thus, for hydraulic conductivities of the rock higher than E–12 m/s the clay plug will be water saturated in less than a month, while for a conductivity of E–13 m/s it will take about 3 months. An alternative way of estimating the rate of saturation, assuming that it is controlled by diffusive migration of water from the rock into the clay, gave a similar wetting rate.

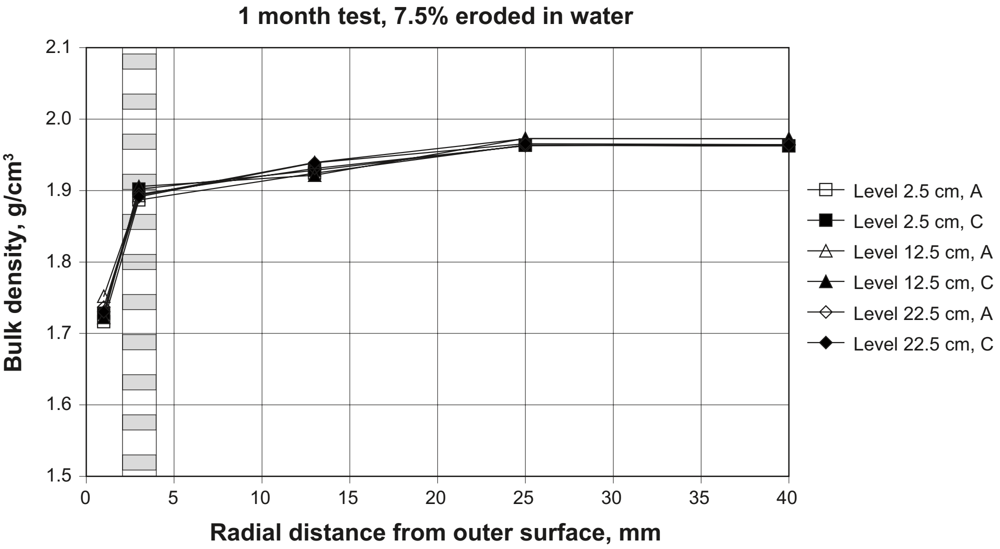


Figure 3-2. *Radial bulk density on three levels and in two directions after 1 month /3/.*

These ways of estimating the maturation rates are not relevant for plugs located in rock with few fractures and low water pressure for which a simple method was developed based on the assumption that water enters the space between the perforated tube and the rock from intersected fractures (Figure 3-3).

According to the model the supply of water for saturation and maturation of the clay ”core” of the “Basic” concept takes place in the initially soft but successively denser clay “skin” that is formed by material moving out through the perforation of the tube. The first phase of this process is characterized by formation of clay columns (“plugs”) growing from the dense clay core through the perforation of the tube and forming an embedment of the tube of different densities (Figure 3-4). After about 24 hours the clay components in the space between the tube and the borehole wall have become relatively homogeneous but it takes weeks and months for them to reach a high degree of homogeneity and a density that approaches that of the successively softening central clay core. From the point of maturation and performance they initially make up a very heterogeneous, soft and permeable “clay skin” that successively becomes denser.

The rate of growth of the clay columns has been investigated in laboratory tests, which have given values of the density of the clay skin in the maturation process.

Stepwise calculation of the evolution of a maturing clay skin in the space between a clay core and the walls of a surrounding hole gave the data in Table 3-1 for the selected example. The driving force is the suction provided by the dense clay core in the tube. The rate of maturation is controlled by the rate of migration of water from the skin, which is established in embryonic form already after 6 hours. For clay plugs confined by a perforated tube the rate of maturation is at least 50% lower.

Application of the model to real boreholes implies that the clay skin is supplied with water from the intersected fractures, and that the density of the clay skin controls its hydraulic conductivity. The water pressure in the fractures determines whether the maturation of the clay skin is delayed or not.

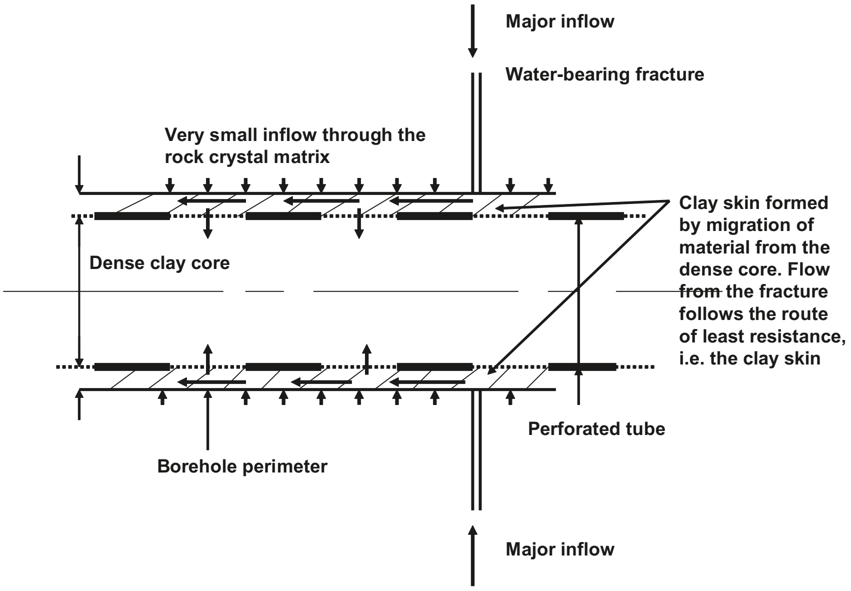


Figure 3-3. *Conceptual model of the inflow path of water from water-bearing fracture. Least resistance to the flow is through the clay “skin” around the perforated tube since it is more permeable than the dense clay core although it becomes denser with time.*

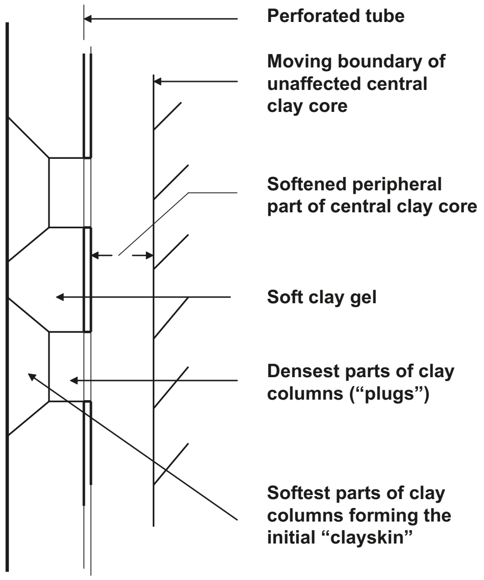


Figure 3-4. *Schematic view of the earliest stage in the maturation of a plug of "Basic" type. The left vertical line is the borehole wall /3/.*

Table 3-1. Expected rate of formation of "clay skin" surrounding a 2.5 m long MX-80 clay core with 72 mm diameter in an 80 mm borehole for the initial dry density 1,700 kg/m^3. Case without perforated tube /3/.

Time, hours	Density of saturated, expanded part, kg/m^3	Amount of sorbed water, liters	Hydraulic conductivity of "skin zone", m/s	Shear strength of "skin zone", kPa
6	1,100	10	E–9	50
12	1,150	15	5E–10	200
24	1,325	33	5E–11	400
48	1,400	40	2E–11	550
96	1,700	70	E–12	700

For maturation without delay the flow must be sufficient to supply the dense clay core with water even at mid-distance between intersected fractures. Thus, the amount of water flowing axially from them in and through the skin must be sufficient to replace water sucked from the skin by the dense core. It was found that this is the case for MX-80 clay plugs located in holes with 1 m spacing of intersected water-bearing fractures with 500 kPa piezometric pressure. For 10 m spacing the water provided by the fractures would be insufficient at this pressure and hence delay maturation, which would also be the case for lower water pressures. One hence finds that the rock structure is of major importance for the maturation rate of the plugs.

Piping resistance

If there are differences in water pressure along a plugged borehole, which will be the case in holes extending from tunnels or shafts where the water pressure will be low until the repository is backfilled, the plugs will be exposed to a pressure gradient that can cause piping before the clay has matured sufficiently. Tests were made in the laboratory of Clay Technology AB for investigating the sensitivity to such degradation, the main results being the following /3/:

- After 8 hours of maturation under 500 kPa uniform water pressure the critical pressure for piping was 700 kPa, after 19.5 hours 900 kPa and after 41.5 hours 1,700 kPa. The successive increase illustrates the maturation rate under prevailing test conditions, i.e. with unlimited access to (tap) water.

- Immediately after the last piping test extrusion of the plug was started. The plug began to be displaced but could not be extruded at the maximum capacity of the hydraulic jack, 7 t (70 kN), possibly because of deformation and locking of the perforated tube in the confining bigger tube.
- The extruded plug had a homogeneous appearance except for some small, local heterogeneities (Figure 3-5).
- Samples of the clay "skin" had a density and water content of 105% at 0.5 m distance from the pressurized end, 94% at 1.25 m distance and 93% at 2 m distance from this end. The clay core inside the tube had a density that was unchanged from the initial state.

Erodability

Placement of clay plugs makes water flow along the plugs, which causes erosion. Tests simulating the impact of water flowing along clay plugs in the installation of a clay plug were made by Clay Technology AB and they showed that 6 to 9% of the solid clay can be lost from a clay plug moved 500 m down in 80 mm borehole. This would reduce the intial dry density to about 1,800 kg/m^3, corresponding to an average density of the fluid-saturated plug of 2,130 kg/m^3. A way of limiting such loss is to use denser clay blocks and additional erosion tests were made with blocks obtained by compacting MX-80 powder that had low water content (6%) under a pressure of 250 MPa. (Figure 3-6). This diagram shows that the dry density can be increased to around 2,100 kg/m^3, and such blocks were therefore used in all the field experiments. The loss of clay recorded in the lab tests simulating placement of clay plugs to 1,000 m depth in 3 hours could be reduced to 4–5%.

As an example referring to very deep holes, the lowest net density of the clay will be found at the lower end of plugs in 1,000 m deep holes, i.e. 1,900 kg/m^3. The corresponding hydraulic conductivity and swelling pressure in salt groundwater are E–12 m/s, and 1.5 MPa, respectively, which are deemed acceptable. Plugs placed down to 500 m depth, corresponding to the repository level, will undergo less erosion and are estimated to have an average density at water saturation of 2,000 kg/m^3.

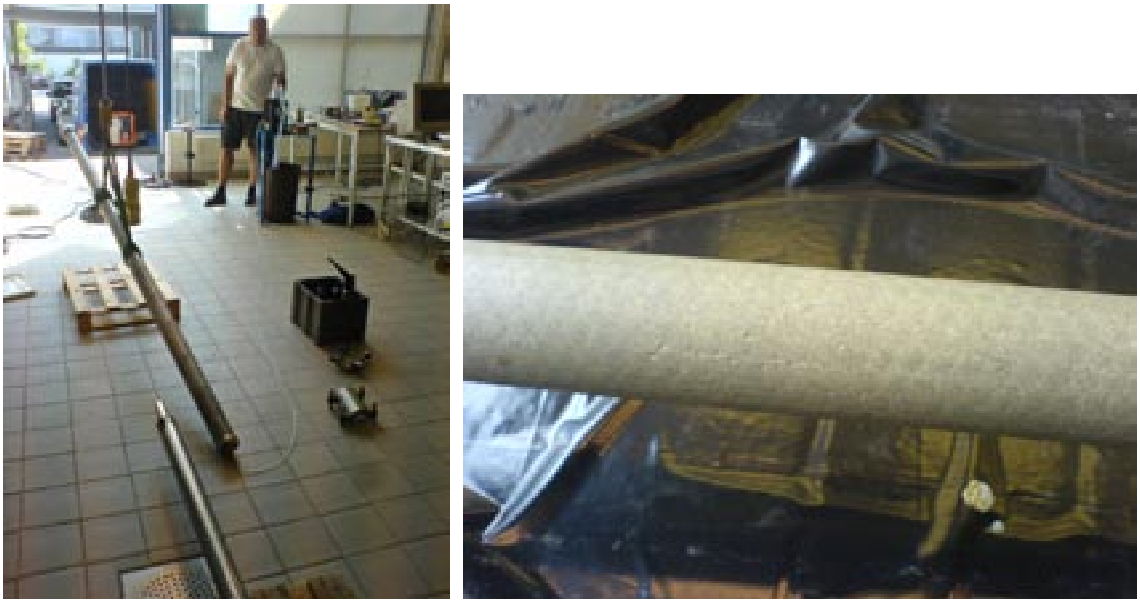


Figure 3-5. *Left: The steel tube with the plug being exposed to a water pressure at the lower end. Right: Appearance of "Basic" plug extruded after 3 weeks of maturation under 500 kPa uniform water pressure /3/.*

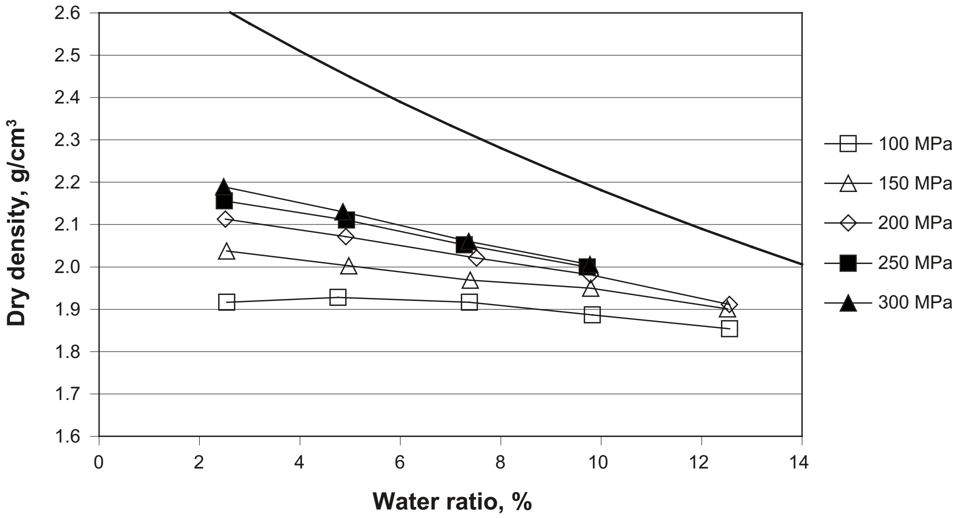


Figure 3-6. *Dry densities obtained by compacting MX-80 clay powder with different water contents by using compaction pressures of 100 to 300 MPa /3/.*

Maturation rate determined in the field

The rate of maturation of the clay plugs is mirrored by the time-dependent growth of the shear resistance when displacing them by applying an axial force. The resistance to displacement is determined by the shear strength of the clay contacting the borehole walls (i.e. the "clay skin"), which was predicted to be 50 kPa after 6 hours, 200 kPa after 12 hours, 325 kPa after 24 hours, 600 kPa after 48 hours and up to 800 kPa after 96 hours depending on the salt content. The salinity is expected to increase from being negligible nearly in the originally filled tap water to strongly brackish after a few days. The axial force that displaces a clay plug is equivalent to the product of the area of the clay/rock contact and the shear strength, which means that the force yielding displacement can be calculated if the borehole diameter, length of the plug, and shear strength of the "clay skin" are known.

The actual rate of maturation was determined by extruding a plug of about 3 m length from an 80 mm diameter and 5 m long borehole at 450 m depth at Äspö URL (Sub-project 2) /4/. The diameter of the hole was 80 mm and the outer and inner diameters of the perforated tube 76.1 and 72.1 mm, and the calculated ultimate density of the plug after complete water saturation 2,078 kg/m^3. The placement of the plug is shown in Figure 3-7. The hole was filled with tap water before the plug was allowed to slip down into the hole (Figure 3-7). A hydraulic jack was placed and secured at the lower end of the 5 m long hole that was connected to another equally long, inclined hole through which the tubing from the jack was led up to the pump on the floor of the room (Figure 3-8). Mechanical strain gauges were installed for measuring the displacement of the released packer resting on the upper end of the clay plug at the loadings.

The plug was loaded from below and the force determined as given in Table 3-2, which also shows the evaluated average shear stress when the plug started to be displaced for the respective load.

The low shear strength in the first few days compared to what had been predicted using lab pilot tests and the models (Table 3-1), confirms that the perforated tube significantly delayed the skin formation and caused microstructural heterogeneity in the first few days. However, it is obvious that the force required to displace a plug of this length is appreciable already after one day and that delay in placing long plugs can cause problems. After four days a 10 m long plug would require a force of about 30 t (300 kN) to move it.

Figure 3-7. *Placement of the plug of "Basic" type.*

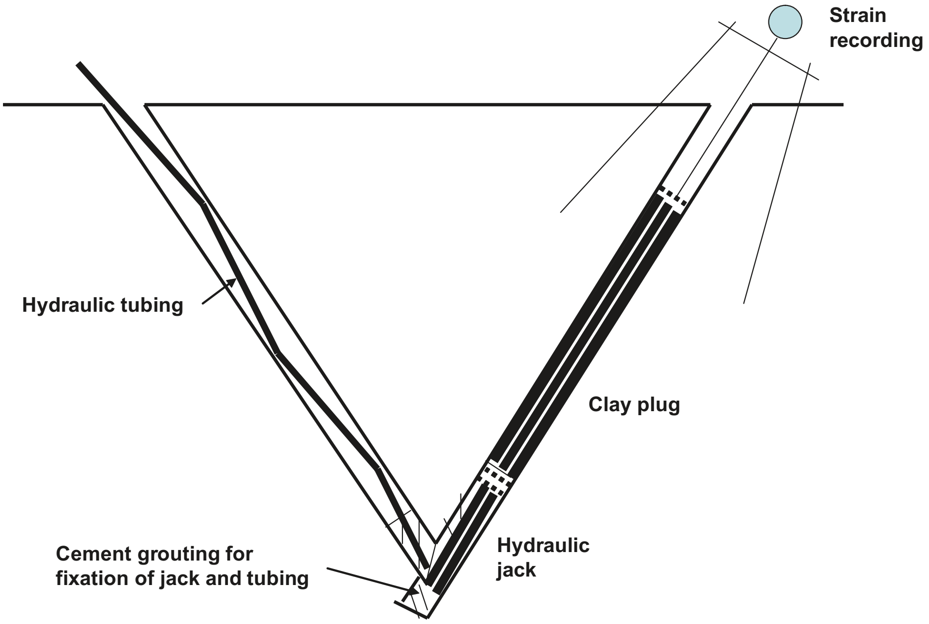


Figure 3-8. *Arrangement for measuring clay/rock adhesion by extruding the plugs in the 5 m long holes and measuring the displacement.*

Table 3-2. Actual force required for displacing the "Basic" plug and the mobilized shear resistance (strength) of the "clay skin".

Time after placement, h	Load required for displacement, t*	Maximum displacement, mm Upper/lower	Average shear stress exerted on the "clay skin", kPa
24	1.16	0.45/1.2	15
48	2.66	0.52/5	35
96	9.96	0.05/–	132
720	3.50	0/> 10	> 133

* Multiplication by 10 gives the force in kN.

Practical function of the clay plug of "Basic" type

The following major conclusions from the various test series were drawn:

- Clay starts to move out from dense plugs of MX-80 clay confined in perforated tubes after 4 hours in low-electrolyte water. A homogenous paste around the tube is not formed until after 8 hours (Figure 3-9).
- The clay paste formed around the perforated tube will cause resistance to insertion of clay plugs in boreholes, which must therefore be made within a limited period of time. In salt water the clay plug must be placed within one hour, while in electrolyte-poor water the corresponding time is 5–10 hours.
- For avoiding very rapid expansion and erosion of the clay gel formed early in the space between tube and rock, the water in the borehole must be poor in electrolytes. In practice, this means that the natural water should be replaced by tap water.
- After a few weeks the clay between the tube and the rock becomes dense and after several months the entire clay mass tends to become relatively homogeneous and sufficiently dense for providing the required tightness. Complete homogeneity may require years or decades and may in fact never be reached.
- The long term tests show that a high degree of swelling and homogenisation is obtained after 10–20 days. The measured mean swelling pressure against the rock for the initial dry density 1,905 kg/m^3 of the clay plug core is 2,800 kPa in fresh water and 600 kPain saline water (Äspö). Measurement of the hydraulic conductivity of the clay paste between tube and rock showed that it was lower than 9E–13 m/s for saturation and percolation with fresh water and 2E–12 m/s for saline water.
- Only clays with Na as major adsorbed cation should be used since Ca-saturated clay does not expand readily in neither fresh nor salt water.
- For very strongly compacted MX-80 powder (compressed under more than 250 MPa) the clay is expected to migrate slower through perforation than ordinarily compacted clay.
- The slow maturation compared to unshielded plug types (Container, Coronne, and Pellet) shows the retarding impact of the perforated tube and hence its erosion-protecting ability in the placement phase.

Figure 3-9. *Growth of soft clay through the perforation of a copper tube confining a dense MX-80 clay core in an 80 mm diameter oedometer. Appearance at removal of the lid 8 hours after start. The larger part of the core is still unaffected by water.*

Some practical rules for the placement were proposed:

- A practical solution for use of copper tubes implies 24 m long segments consisting of jointed 2.5 m long parts. The tensile strength is sufficient, assuming 4-fold safety, and safe attachment to the drill string can be achieved. The thickness of the tube wall should be 2–3 mm and the outer diameter about 6 mm smaller than the diameter of the hole.
- Each 24 m segment is lowered into the desired position, i.e. in the space between two stabilized fracture zones, and left there. Several segments can be placed in series without coupling them together. Their weight guarantees that they will rest on the underlying ones without moving in the axial direction.
- Before a clay plug segment is emplaced a previously cast silica concrete plug must have hardened sufficiently much to be able to carry it. With a suitable concrete recipe this would take about 24 hours.

3.3 The “Container” concept

3.3.1 Design, materials and dimensions

The *Container* concept was proposed by Lars Liiv in the preparation of the borehole plugging project for simplifying and speeding up the placement of clay plugs as well as for protecting them from erosion. The bearing idea is to keep the plug segment confined and isolated from the water in the borehole until it reaches its predetermined position. The container tube of stainless steel is only used in the plug installation phase in which it needs to remain tight and mechanically stable. A prototype version has been manufactured and tested for placing concrete and further development for adaptating it to clay is highly desired. The container will be exposed to a uniform water pressure of 10 MPa in a 1 km deep hole and has to resist this pressure and still be perfectly tight. This determines the thickness of the container wall and the required tightness of all components. Figure 3-10 illustrates the design and function.

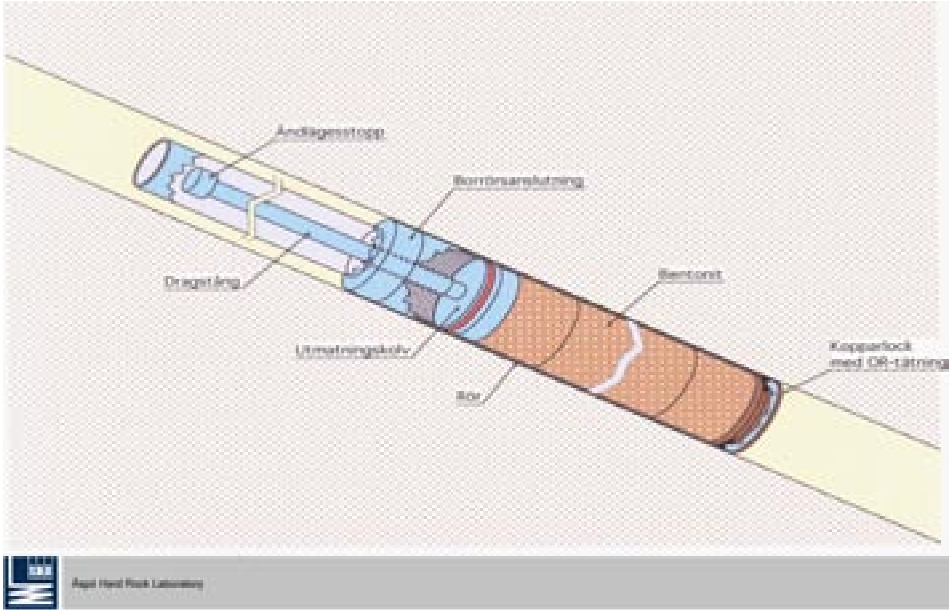


Figure 3-10. *Prototype version of cement/bentonite container. Ändlägestopp = ultimate piston position. Dragstång = push/pulling rod. Borrörsanslutning = drillstring connection. Utmatningskolv = extrusion piston. Rör = tube. Kopparlock med OR-tätning = copper lid with O-ring seal.*

3.3.2 Placement

The container cylinder and accessories were not accessible at the time when the full-size lab and field experiments took place and the highly compacted cylindrical clay blocks therefore had to be placed manually (Figure 3-11). In practice, the water-tight container with the dense clay blocks inside will be brought down to the desired depth where the valve is opened and the clay core moved out from the tube by use of a piston. It will rest on the previously placed clay core or cast concrete and left for hydration from all sides until the next clay core or concrete comes to rest on it, which can take one or a few hours at large depths.

The detailed design and manufacturing of plugs of this type is described in the report on Sub-project 1 /3/. The clay blocks had a water content of 6% 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 diameter of the borehole was 80 mm and the calculated ultimate density of the plugs after complete water saturation was 2,025 kg/m^3.

3.3.3 Maturation – processes and predictions

Water saturation and homogenization

The "Container" concept implies that the dense clay column is instantly exposed to water over its entire surface, which makes it hydrate and expand even quicker than *"Basic"* plugs, hence forming a uniform, shallow, fully water saturated "clay skin" from which the rest of the clay sucks water for hydration. The same conditions for further hydration prevail for all the concepts, i.e. water flows from intersected water-bearing pressurized fractures through the skin for further transport into the dense core by suction. The earliest maturation and hence mobilization of resistance to percolation of the skin occurs close to the fractures but its hydraulic conductivity will continue to be higher than that of the clay core for a long time and it will therefore serve as major water path for wetting and expansion of the dense core until complete saturation and maturation of the entire plug is approached. For all the concepts the joints between the compact clay blocks will let water in quickly but self-sealing is assumed to close them soon. The impact of the water pressure is important in the early maturation phase.

Figure 3-11. *Manual placement of the clay components of the Container Plug. The hole into which the hand-held clay piece is being moved is just below the white label.*

Stepwise calculation of the growth of a maturing clay skin of a long column of compacted clay blocks has been made following the same principle as for the "Basic" case except that the perforation of the tube in this case was omitted (Figure 3-12). It was concluded from these estimates that the criterion of providing sufficient inflow in the skin for unlimited hydration by diffusive water migration into the core MX-80 clay plugs is fulfilled if the spacing of intersecting fractures with 500 kPa piezometric pressure does not exceed about 1 m. The same conditions prevailed approximately for all the 5 m holes in the area. As for the other field-tested plugs these conditions were also approximately valid.

Piping resistance

The same conditions prevail as for "Basic" plugs and the same type of laboratory experiment with the 3 m long "Container" plug has been performed as for the "Basic case". The following steps were taken:

- The tube with 80 mm inner diameter representing a borehole was filled with tap water and the plug inserted in it. Since the tight container was not yet available the blocks that were intended to be placed in it were assembled manually.
- A water pressure of 500 kPa was applied for supplying the plug with water in the maturation process. This pressure was on the same order as at the test site at Äspö where plugs of the same type were tested with respect to the adhesion to the borehole walls (Sub-project 2) /4/.
- After rest for maturation under a uniform water pressure of 500 kPa, a step-wise increased water pressure was applied at one end of the plug-confining tube while the opposite end was pressure-free and connected to a pipe for measuring water flow through the plug. The pressure was increased until through-flow was initiated. When this took place the pressure was immediately reduced to zero after which both ends of the tube were pressurized to 500 kPa for continued maturation of the clay. The critical pressure represents the piping resistance.

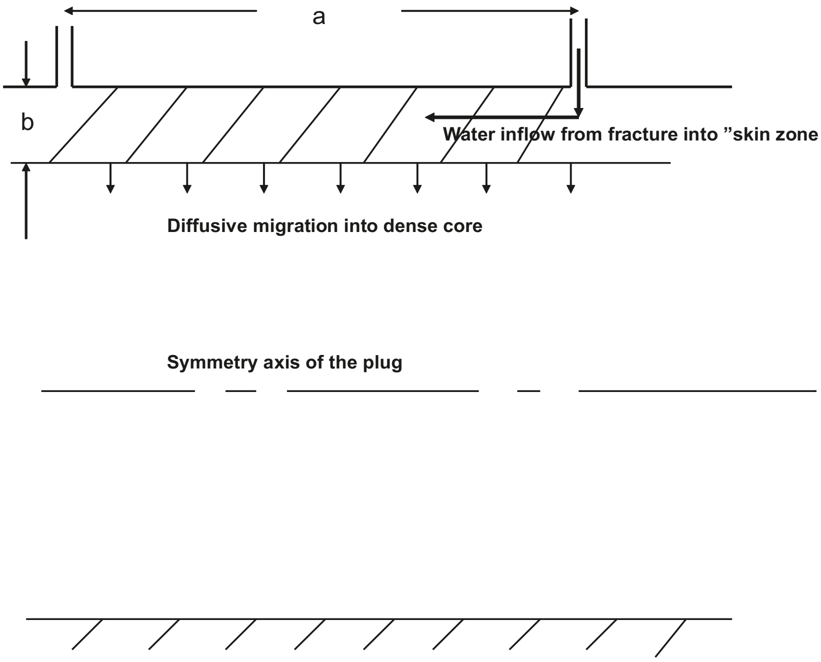


Figure 3-12. *Conditions for saturation of the clay core by sorbing water from the skin zone that is supplied with water from intersecting fractures.*

- After further rest under 500 kPa uniform pressure, a pressure gradient was again established for determining the critical pressure for piping as a function of time. Repeated pressurizing after periods of rest was expected to show the influence of self-sealing on the critical pressure for piping.
- When the piping resistance was finally sufficient to resist the maximum water pressure that could be applied with the available pressure controller (GDS equipment), by which the pressure was controlled and the flow measured, the plug was extruded by use of a hydraulic jack with 60 MPa capacity. This gave the adhesive strength of the plug, i.e. the shear strength of the clay/steel contact that could then be compared to that determined in the field experiment (Sub-project 2) /4/.

The outcome of the tests, which are fully reported in Sub-project 2 /4/, can be summarized as follows:

- After 6 hours of maturation under 500 kPa uniform water pressure the critical pressure for piping was 1,700 kPa.
- After another 18 hours of rest under 500 kPa uniform water pressure the critical pressure for piping was 1,800 kPa. Water did not penetrate the plug and the recorded sudden inflow of pressurized water was concluded to be caused by local displacement of the softest parts of the “skin”. They were successively consolidated and tightened to let no water through.
- The plug could not be extruded for the highest available force of 7 tons, meaning that the adhesion (shear) strength exceeded 115 kPa. Considering the fact that the test arrangement represented 5 m distance between neighbouring fractures and hence a considerable delay in maturation, the deviation from what the model predicts i.e. 550 kPa for a 2.5 m long plug after 2 days, implies that the shear strength may have been far higher than 115 kPa.

Maturation rate determined in the field

The rate of maturation was determined by extruding a plug of about 3 m length from an 80 mm diameter and 5 m long borehole at 450 m depth at Äspö URL (see Sub-project 2). The loading of this plug gave the data in Table 3-5 for the ultimate “sheared” conditions at the testing events.

Table 3-5. Actual force required for displacing the "Container" plug and the mobilized shear resistance of the "clay skin".

Time after placement, h	Force required for displacement, t*	Maximum displacement, mm Upper/lower	Average shear stress exerted on the "clay skin", kPa
24	2.32	3.6/–	31
48	5.98	13.2/–	80
96	11.95	12/–	159
720	> 12	> 10/–	> 160

* Multiplication 10 gives the force in kN.

The very low shear strength, i.e. about 1/12 of the predicted value after 24 hours and about 1/5 after 96 hours (cf Table 3-1), indicates that the consolidation of the initially formed, very soft clay gel was slower than predicted, which can be due to insufficient access to water and quicker rise in electrolyte content than expected. A saline water of Äspö type would cause coagulation and inhomogeneity of the initially formed soft clay gel and cause nearly complete loss of strength (Sub-project 1) /3/. After four days the force required for displacing the plug was about 12 t (120 kN), which was close to the maximum available capacity of the hydraulic jack. As expected, this plug matured significantly quicker than the plug of "Basic" type in the first two days while its shear strength was not much higher after 4 days.

Measurement of the displacement of the lower end of the plug in the field test could not be made with acceptable accuracy.

Practical function of the clay plug of "Container" type

The following major conclusions from the various test series were drawn:

- The quicker maturation of the "Container" than of the "Basic" type is in accordance with the proposed model.
- A beneficial property of the "Container" concept is that the clay component is not exposed to water and hence not to erosion in the placement phase. After releasing it at the desired depth it is momentarily exposed to a high water pressure causing dispersion and formation of an initially soft "skin" that consolidates under the pressure exerted by the expanding dense core. In contrast to the "Basic" concept there is, in principle, no need to replace the original salt water from the hole to be plugged but this is still recommended for avoiding sedimentation of the large aggregates that result from the dispersion since this can cause variations in density of the ultimately matured plug.
- After a couple of days the most shallow part of the clay plug becomes dense and able to resist piping and after several months the entire clay mass will tend to become homogeneous and sufficiently dense for providing the required tightness. Complete homogeneity may require years or decades and it may in fact never be reached.
- Only clays with Na as major adsorbed cation should be used since Ca-saturated expansive clays are expected to be less homogeneous in the fully matured state.

Some practical rules for the placement were proposed:

- The tightness of the container tube is a fundamental requirement since leakage of water into it will make the clay blocks expand and become stuck in the tube.
- Plugs of "Container" type can be made in segments that are 2–5 m long but even longer units can be prepared and placed at depths of 1,000 m or more. In practice, the length is determined by the curvature of the borehole since too long plug segments may imply contact of the ends of the container tube with the borehole walls.

- For reaching a high net density of the plug the fitting between the tube and the clay blocks must be good, which means that the risk of deformation of the tube by being squeezed in the borehole or by hitting irregularities in the borehole wall must be considered. For minimizing the risk the tube must be sufficiently strong, which, in turn, requires a wall thickness that may significantly reduce the net density of the ultimately matured clay plug.
- Before a plug is emplaced, previously cast silica concrete must have hardened sufficiently much to be able to carry it. With a suitable concrete recipe this is a matter of one day.

3.4 The "Couronne" concept

3.4.1 Design, materials and dimensions

The "*Couronne"* concept was proposed a few decades ago and has been used in at least one project /1/. The bearing idea is to use a plug that consists of a central rod around which tightly fitting annular clay blocks are stacked (Figure 3-13). Submerging the plug in a water-filled hole will instantly cause dispersion as in the "Container" case and erosion will be substantial if the plug is brought down in deep holes. Delay caused by jointing plug units to form a continuous train of units will cause intermittently increased dispersion and contribute to make the finally matured plug heterogeneous. One therefore may have to restrict the use of this plugging technique to holes with a depth of less than 100 m. Shorter holes, i.e. with a length of a few tens of metres can be drained so that the plug can be placed under dry conditions. Suitably arranged flanges can make it possible to use this technique for plugging of holes of any direction.

The central rod is left in position after placing the plug and should hence be chemically compatible with the clay, for which copper is proposed to be most suitable. Detailed design with respect to geometrical features and strength of the metal rod must be made for the individual cases, the most important matter being to reach the required ultimate density of the clay.

The detailed design and manufacturing of plugs of this type is described in the report on Sub-project 1 /2/. In the present tests the MX-80 clay blocks had a water content of 6% and a density of 2,150 kg/m^3, corresponding to a dry density of 2,028 kg/m^3 (cf Figure 3-6). The void ratio and initial degree of saturation were *e* = 0.37 (porosity 0.27) and 45%, respectively. The diameter of the borehole was 76 mm and the calculated ultimate density of the plugs after complete water saturation 2,015 kg/m^3. The central rod had a diameter of 8 mm. The inner diameter of the blocks was 10 mm.

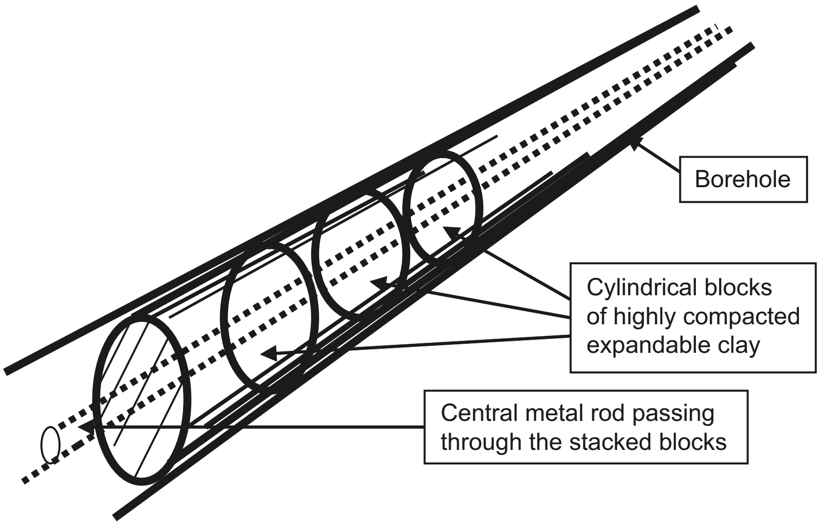


Figure 3-13. *The "Couronne" plug.*

3.4.2 Placement

The tool for bringing down plugs of this type is a simple crane for downward placement or a hydraulic jack for placement in upward-directed holes. Preparation of the plugs used in the maturation experiments, i.e. the piping and extrusion tests, comprised threading the clay blocks onto the metal rod, which was made of steel for this particular experiment (Figure 3-14). In the laboratory test for determining the piping resistance, the clay pieces were simply pushed into the metal tube simulating the borehole.

3.4.3 Maturation – processes and predictions

Water saturation and homogenization

The conditions for maturation of the "Couronne" plug are, in principle, the same as for the "Container" plug except that, in water-filled holes, the clay starts to hydrate already in the placement phase. In holes that have been drained prior to the placement of the plug the conditions and processes after inserting the plug and filling the hole with water are exactly the same as for the "Container" plug. For the relatively short holes that can be sealed with "Couronne" plugs the difference in performance between the two conditions is not believed to be of practical importance and one can therefore estimate the maturing process to be the same as for the "Container" plug. Thus, the initially released clay aggregates from the exposed surface of the clay blocks quickly produce a very heterogeneous, soft and permeable "clay skin" that successively becomes denser by being consolidated by the expanding dense blocks.

There is a difference between the two concepts, however, in that the central rod of "Couronne" plugs implies less clay and hence a lower ultimate density, which is at least partly compensated by the larger outer diameter of the clay blocks. It is expected that sufficient amounts of water will be available for undisturbed saturation of the plug if it is located in rock with normal structure and a groundwater pressure at least 500 kPa. Under these circumstances an appreciable

Figure 3-14. *Preparation of the plug of Couronne type. The blocks are being stacked around the central rod.*

density, at least about 1,400 kg/m^3 (cf Table 3-1) and a high degree of homogeneity of the "clay skin" would theoretically be reached in a few days, while later stages of maturation are expected to develop as a function of the ability of the surrounding rock to give off water as for the other plugs. The "Couronne" plug can be retrieved only within the first few hours after emplacement.

Piping resistance

The same conditions prevail as for "Basic" and "Container" plugs and the performance is expected to be the same as for the "Container" plug. No test for determining the piping resistance was therefore made in the laboratory.

Maturation rate determined in the field

The rate of maturation was determined by extruding a plug of about 3 m length from an 80 mm diameter and 5 m long borehole at 450 m depth at Äspö URL (Sub-project 2) /4/. The loading of this plug gave the data in Table 3-7 for the ultimate "sheared" conditions at the testing events.

The very low shear strength, i.e. about 1/8 of the predicted value after 24 hours and 1/5 after 96 hours (cf Table 3-1), indicates that the consolidation of the initially formed, very soft clay gel was slower than predicted, which can be due to insufficient access to water and quicker rise in electrolyte content than expected. As expected, this plug matured at about the same rate as the "Container" and "Couronne" plugs and significantly quicker than the plug of "Basic" type in the first few days. The displacement of the upper end of the plug could not be accurately measured.

Practical function of the clay plug of "Couronne" type

The following major conclusions from the various findings were drawn:

- The "Couronne" plug matures quicker than the "Basic" plug and nearly at the same rate as "Container" plugs.
- Submerging the plug in a water-filled hole will instantly cause dispersion. Erosion will be substantial if the plug is brought down in deep, water-filled holes. Delay caused by jointing plug units to form a continuous train of plug units will cause intermittently increased dispersion and contribute to make the finally matured plug heterogeneous.
- This plugging technique should be confined to holes with a depth of up to 100 m. Shorter holes, i.e. with a length of a few tens of metres can be drained so that the plug can be placed under dry conditions.
- As for the "Basic" concept it is required to replace the original salt water in the hole to be plugged by tap water for minimizing sedimentation of the large aggregates that result from the dispersion since this can cause variations in density of the ultimately matured plug.

Table 3-7. Force required for displacing the "Couronne" plug and the mobilized shear resistance of the "clay skin".

Time after placement, h	Force required for displacement, t	Maximum displacement, mm Upper/lower	Average shear stress exerted on the "clay skin", kPa
24	3.49	–/4.2	46
48	5.48	–/13.2	73
96	9.96	–/12.0	133
720	> 10	0/> 10	> 133

- After a couple of days the "skin" of the clay plug becomes dense and able to resist piping and after several months the entire clay mass will tend to become homogeneous and sufficiently dense for providing the required tightness. Complete homogeneity may require years or decades and it may in fact never be reached.
- Only clays with Na as major adsorbed cation should be used since Ca-saturated expansive clays behave like clay in salt water.
- The roughness of the borehole wall may cause abrasion of the clay block columns and heterogeneities and variations in density of the ultimately matured plug. Holes with rock fall must be stabilized and re-bored before "Couronne" plugs are emplaced. If the sealing potential of the plugs is not deemed high, pellets can be a suitable alternative method and if effective sealing is required the "Basic" or "Container" types are recommended.
- Plugs of "Couronne" type can be made in segments that are 2–5 m long and jointed together for creating a continuous, successively emplaced plug. The recommended length of a completed plug is estimated to be a few tens of metres.
- For reaching a high net density of the plug the fitting between the central rod and the clay blocks must be very good and the clearance between the borehole wall and the clay blocks be at minimum, i.e. a couple of millimetres for very short holes and 3–4 mm for long ones.
- Before a plug is emplaced, supporting silica concrete that may have been cast in the holes, must have hardened sufficiently much to stay rigid. With a suitable concrete recipe this occurs in one day.
- Emplacement of "Couronne" plugs involves strong erosion but since the length of the plugs is rather small the loss of clay will not be of practical significance.

3.5 The "Pellet" concept

3.5.1 Design, materials and dimensions

Pellets have been used for borehole sealing in different contexts. Thus, NAGRA has conducted several experiments in downwards and upwards oriented boreholes /1/ and oil companies like Texas/Chevron in the US have made experiments with rather large pellets and with mixtures of pellets of two sizes for sealing of abandoned oil and gas production holes. A matter of significance is whether the ultimate dry density of the pellet plug needs to be as high as specified for fulfilling the criterion that the hydraulic conductivity must be lower than that of the surrounding rock, i.e. on the order of 2,000 kg/m^3, corresponding to a dry density of 1,590 kg/m^3. None of the experiments referred to in the literature gave densities of this magnitude for which it is believed that a combination of load and vibration is required.

In practice, it seems that the pellet plugging technique is suitable for sealing holes with a length of up to about 20 m, with a further requirement that it should be used where the sealing function is not very critical, i.e. not in holes extending from deposition tunnels and definitely not in the near-field of canisters. Homogeneous pellet fills require that the boreholes are dry (Figure 3-15).

In the present study pellets with 10% water content were poured in a 5 m long tube in the laboratory for piping tests and in a borehole with 80 mm diameter giving the air-dry fill a density of 1,150 kg/m^3 corresponding to a dry density of 1,035 kg/m^3 and a density at complete water saturation of 1,650 kg/m^3. The detailed design and manufacturing of plugs of this type is described in the report on Sub-projects 1 and 2 /2, 3/.

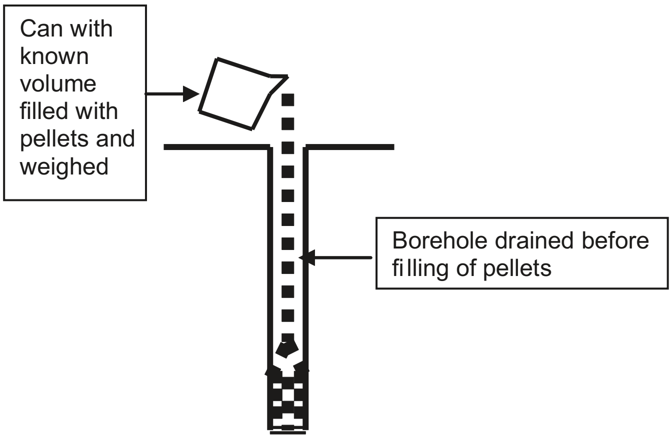


Figure 3-15. *The "Pellet" concept.*

3.5.2 Placement

The tools for bringing down the fill, i.e. a small hopper attached to a tube that reaches down in the hole for minimizing wall friction and a weight for light compaction in the filling phase, can be of simple type. A field-adaptated balance and a container with known volume shall be used for filling the hopper so that the density of the pellet mass can be continuously recorded.

Pellets are available on the market but the density must be suitable and sufficient for reaching the desired tightness. A special type of granular smectite material that may be preferable is screened material from crushed blocks of very strongly compacted smectite clay powder with very low water content. Such material matures less rapidly than ordinary pellets but the ultimately reached density can be substantial.

In the present experiments the pellets were placed by pouring associated with slight compaction at every 0.5 m level (Figures 3-16 and 3-17). Tap water was then filled and a mechanical packer fixed.

3.5.3 Maturation – processes and predictions

Water saturation and homogenization

Figure 3-18 illustrates schematically the maturation process of a pellet fill when water enters it. The pellets contain large numbers of smectite particles and they expand on hydration and release aggregates that rearrange to form soft gels that become consolidated under the pressure exerted by the expanding grains. Variations in density will, however, remain also after complete water saturation. Pellet fills have a large number of continuous voids that are instantly filled with inflowing water and they contain numerous continuous, rather permeable flow paths also after maturation. Their sealing potential will therefore be less good than of the other plug types and the variation in density means that their hydraulic conductivity will be more sensitive to saline water.

The very large voids in a pellet fill will be occupied by water very soon after filling the hole with air-dry pellets. The main difference between the "Pellet" plug and the other plug types is that the latter become wetted from their outer boundary while the "Pellet" plug has a high degree of water saturation in all parts from start, i.e. on the order of 70–80%. This means that the suction, which is the main cause of saturation in the absence of high water pressure, is rather low. Another major difference is that "skin" formation is much less developed in "Pellet" plug. Both phenomena combine to cause a very slow increase in the degree of water saturation

Figure 3-16. *Pouring of pellets in cylinder with known volume for subsequent filling in borehole.*

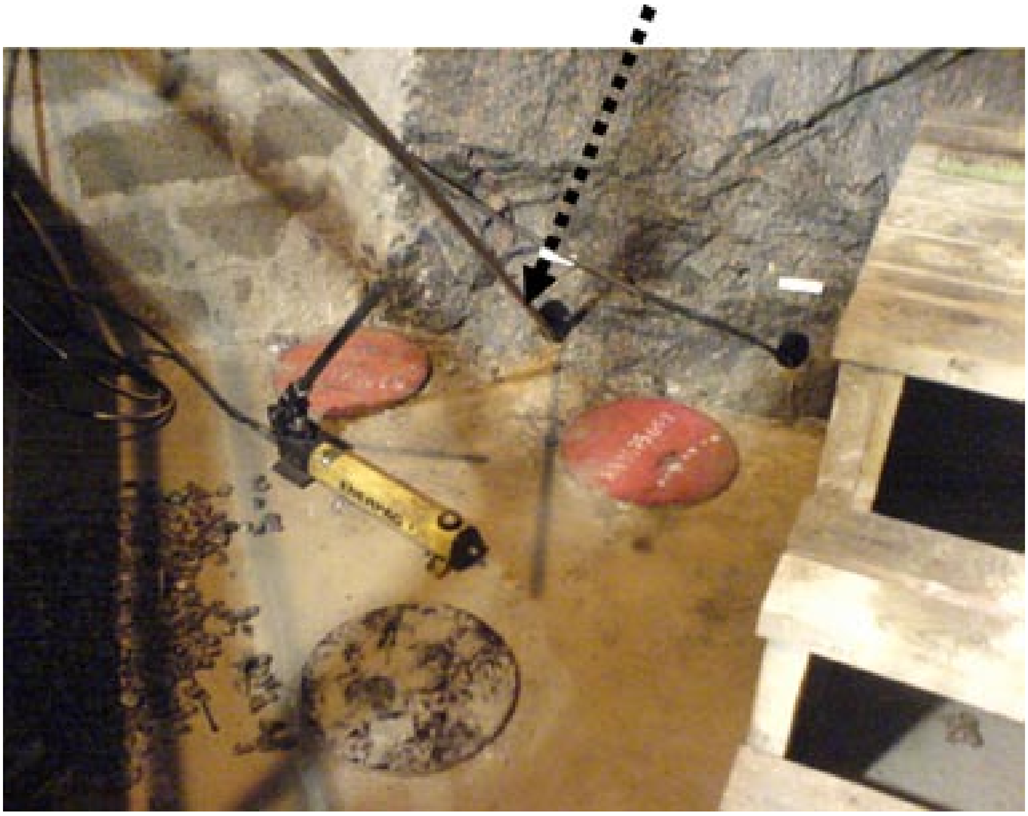


Figure 3-17. *Rod with plate (dotted arrow pointing at it) for slight compaction of the pellet fill.*

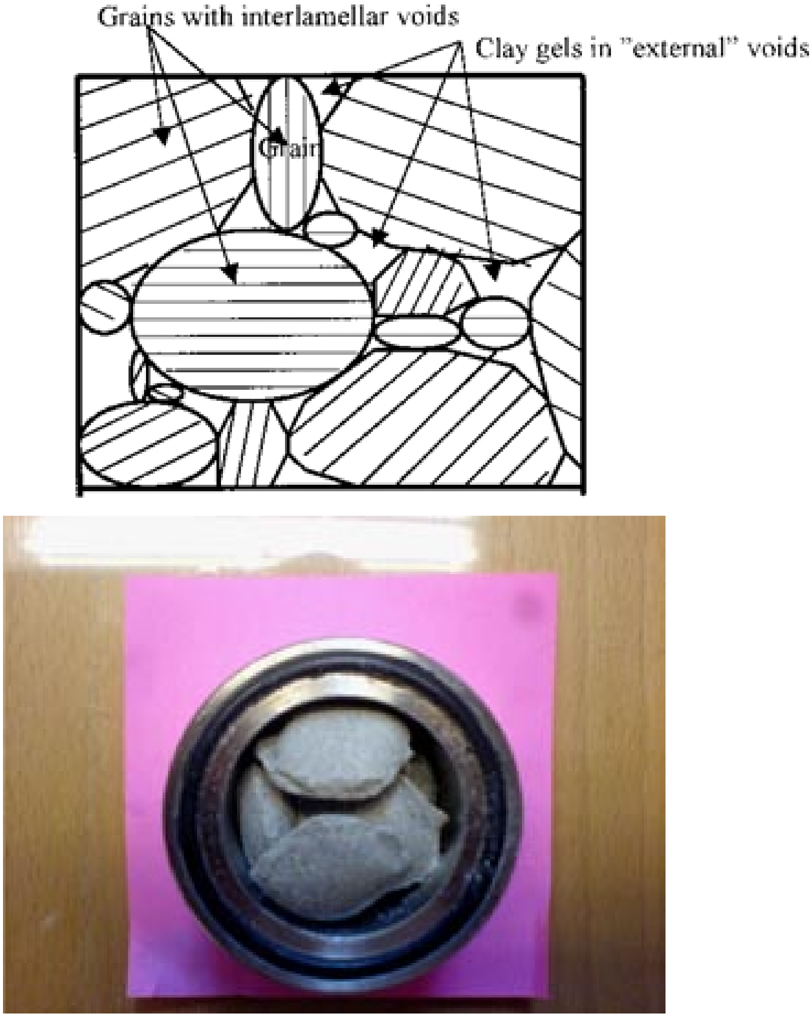


__Figure 3-18.__ Pellet fill. Upper: Schematic picture of the microstructural constitution; the grains take up water from the boundaries by which they expand and give off clay particles that form gels in the voids between the expanded grains. Lower: Pellets with 10% water content in 30 mm cell.

beyond the initial value even if the rock can offer unlimited amounts of water for the plug's maturation. In contrast to the other plug types, flow in the "skin" zone is believed to be less important for this process than flow in the permeable paths that exist throughout the plug. In summary, "Pellet" plugs mature quicker than the other, denser plug types and their microstructural heterogeneity makes them much more permeable.

Piping resistance

Tests were made in the laboratory of Clay Technology AB for investigating the sensitivity to such degradation. The procedure comprised the following steps: 1) Pouring of pellets with 10% water content in a tube with 80 mm diameter, representing a borehole fill with a dry density of 1,035 kg/m^3 and a density at complete water saturation of 1,650 kg/m^3, 2) Maturation under a uniform water pressure of 500 kPa, followed by application of a step-wise increased water pressure at one end of the tube leaving the other open for flow measurement, 3) Repeated pressurizing after 24 hours rest under 500 kPa isotropic water pressure, 4) extrusion of plug for examination.

The outcome of the tests, which are fully reported in Sub-projects 1 and 2 /3, 4/, was interpreted as follows:

- After 6 hours of rest under 500 kPa uniform water pressure the critical pressure for piping was at least 200 kPa, indicating that the plug had started to mature. For pressures exceeding about 300 kPa the plug was compressed or displaced causing some consolidation but no permeation.
- After another 14 hours of rest under 500 kPa uniform water pressure, the critical pressure for piping was at least 800 kPa, indicating substantial microstructural homogenization and strengthening of the clay. For pressures from 1,200 kPa and more the plug started to be displaced, implying that the "skin" had reached a shear strength of around 10 kPa if it had been mobilized over the total length of the plug.
- Extrusion of the plug after the second piping test was made by use of the hydraulic jack used for extruding plugs also in the preceding experiments. The force was found to be 3.5 t (35 kN), which gave the adhesive strength of the plug, i.e. the shear strength of the clay/steel contact. The evaluated adhesion (shear) strength was about 60 kPa /4/.
- The extruded plug, which appeared to be homogeneous (Figure 3-19) broke in about 0.5 m long pieces when the plug was finally pressed out. The water content of differently located samples were determined and found to be as reported in Table 3-7. Since complete water saturation yields an average water content of 59% one concludes that the plug was largely water saturated but that significant variations in density prevailed.

Maturation rate determined in the field

The rate of maturation was determined by extruding a plug of about 3 m length from an 80 mm diameter and 5 m long borehole at 450 m depth at Äspö URL (see Sub-project 2). The loading of this plug gave the data in Table 3-7 for the ultimate "sheared" conditions at the testing events. Mechanical strain gauges were installed for measuring the displacement of the released packer resting on the upper end of the clay plug at the loadings.

The loadings gave evidence of compression of the plug rather than displacement as indicated by the unchanged position of the upper end of the plug and movement of the lower end. The shear strength of the "clay skin" was evaluated by assuming that the strength was mobilized at a strain exceeding 2%, which is estimated to represent about 1/3 of the plug length, assuming the strain to be linearly distributed along the total plug length. The actual strength was in the predicted interval 0–100 kPa indicating that salt water had some impact on the strength, which would have been about 100 kPa for tap water after about two days (Table 3-2).

This verifies the prediction that the initial maturation and growth of strength is quicker for the "Pellet" plug than for the others but that the ultimate adhesive strength is lower.

Table 3-7. Force required for displacing the "Pellet" plug and the mobilized shear resistance of the "clay skin".

Time after placement, h	Force required for displacement, t	Maximum displacement, mm Upper/lower	Average shear stress exerted on the "clay skin", kPa
24	1.66	6.6/–	66
48	1.66	4.8/–	66
96	1.92	9.6/–	77
720	3.50	> 10/–	140

Figure 3-19. *Appearance of the "Pellet" plug extruded from the tube used in the laboratory for the "piping" test. Notice the coherence of the plug which broke by mechanical strain at the expulsion.*

As for the other plugs, larger fracture spacing or lower fracture pressure will delay maturation of the core and make it heterogeneous since only the part of the skin close to a fracture would fully mature in the early stages.

Practical function of clay plugs of "Pellet" type

The following major conclusions from the various test series were drawn:

- The expected quicker water saturation and homogenization of the "Pellet" plug than of the other types were verified.
- The low density of the "Pellet" plug means that its bulk hydraulic conductivity is sensitive to high salt contents, and particularly to Ca, in the groundwater. Thus, for an average bulk density of 1,650 kg/m^3 saturation and percolation with salt-free water the conductivity is estimated at 2E–12 m/s and around E–10 m/s for ocean water.
- Placing of pellet fills requires that the borehole is drained until placement is started since this gives good initial homogeneity and offers a possibility to make some slight compaction. Groundwater will enter from water-bearing fractures and may produce irregular wetting of the fill, which can lead to local expansion and some variation in density along the hole.

- Only clay pellets with Na as major adsorbed cation should be used since the initially formed microstructure will be more homogeneous than if Ca-saturated clay pellets are used.
- Although one can theoretically use the "Pellet" technique in holes with a depth of a hundred metres it should be reserved for holes with a maximum depth of a few tens of metres since significant variations in density can otherwise occur and difficulties with compaction most certainly appear. Furthermore, deep holes can not be kept dry long enough for placing the pellet fill.
- Before a plug is emplaced a previously cast silica concrete plug must have hardened sufficiently much to be able to carry it. With a suitable concrete recipe this is a matter of one day.

4 Stabilization of fracture zones

Principle

Fracture zones intersecting bore holes need to be stabilized for avoiding rock fall in the plugging phase. The technique is to ream the holes where fracture zones are intersected and to cast concrete that is left to harden, after which re-boring is made to the original borehole diameter. The hole is then ready for casting concrete in the stabilized part of the hole. The recipe of the cement-based material is given in Table 4-1 /3, 4, 5/.

Performance

The material has paste consistency and hardens to give a compressive strength of at least 10 MPa in 24 hours. This strength is sufficient to support the rock so that the stabilization work can proceed in other parts of the hole after one day. pH is less than 11. It was used in the plugging of the about 500 m deep borehole OL-KR24 hole at Olkiluto (Sub-project 3 /5/).

The practical outcome of the tests, which are fully reported in Sub-project 3, is interpreted as follows:

- A reaming tool of the type worked out for the project is required. Its performance at large depths needs to be tested and reconfirmed.
- The long-term performance of the concrete with respect to filtering for eliminating loss of fine quartz particles into the stabilized fracture zones has to be demonstrated.

The long-term performance of the concrete with respect to its chemical interaction with nearby clay plugs has to be investigated.

Table 4-1. Concrete for stabilizing boreholes ("lining of reamed hole"), CBI recipe.

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

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

5 Construction of concrete plugs in stabilized parts of boreholes

The technique is to cast concrete in the stabilized borehole and leave it to harden after which clay plugs are placed on it, reaching up to the next stabilized part etc.

The general principle of the Borehole Plugging Concept is to make the boreholes at least as tight as the surrounding rock and to seal them so that they do not serve as conductors of radionuclide-bearing water that may ultimately emanate from the repository. The time perspective is 100,000 years /9/. Where the holes intersect water-bearing fractures zones, plugs do not need to have a low conductivity but must be physically stable for supporting the surrounding rock and the clay plugs that rest on them or are located below them. In the construction phase they must be coherent and soon become strong enough to carry clay plugs without settling.

The property of reaching a relatively high mechanical strength rather quickly requires use of a cement binder and a suitable recipe has been worked out by CBI. For minimizing negative impact on contacting clay plugs the cement content will be very low and low-pH cement will be utilized. Likewise, the amount and type of the superplasticizer, that is required for making the concrete sufficiently fluid, will be at minimum. The cement is not relied on for long periods and it is assumed that it will be dissolved and lost, which requires that the physical stability of the remaining quartz fill is sufficiently stable to provide the rock and neighbouring clay plugs with adequate support. For this purpose the grain size distribution of the quartz grains is of Fuller-type, implying that smaller grains fill up the space between larger grains, a principle that gives a high density and prevents small particles from moving with percolating water.

A preliminary recipe, worked out by CBI, and yielding pH in the range of 10–11 has been selected for use in the project (Table 5-1) /3, 4, 5/.

The concrete is self-compacting and, compared to normal concrete, it is fairly viscous, i.e. like syrup. The experiments at Olkiluoto reported in Sub-project 3 /5/ show that it is possible to construct a plug with low pH concrete in a borehole even at a fairly great depth.

The evolution of strength has been tested by CBI at 5 and 20°C leading to the conclusion that the strength increases slowly, especially at low temperatures. However, the ultimate strength is higher than that of normal construction concrete that comonly contains more than 300 kg of binder (cement).

Table 5-1. Composition of borehole concrete (CBI).

Components	Kilograms per m^3 of concrete
White cement (Aalborg Portland)	60
Water	150
Silica Fume (Elkem)	60
Fine ground α-quartz (Sibelco)	200
Fine ground cristobalite quartz (Sibelco)	150
Superplasticizer (Glenium 51 Modern Betong)	4.38 (dry weight)
Aggregate 0–4 mm (Underås, Jehanders Grus)	1,679

Performance

The material has self-compacting consistency and hardens to give a compressive strength of at least 10 MPa in 24 hours. This strength is sufficient to support the load of a 10 m clay plug segment. pH is less than 11.

The practical outcome of the tests, which are fully reported in Sub-projects 1, 2 and 3 /3, 4, 5/, is interpreted as follows:

- Plugging of holes with CBI silica concrete plugs can be made but casting in horizontal and upwards directed holes as well as in very deep steeply oriented holes needs to be documented.
- The long-term performance of the concrete with respect to its chemical interaction with contacting clay plugs has to be investigated.

6 Upper end seals

6.1 General

The need for effective and lasting sealing of the upper end of deep boreholes led to the development of two concepts that were tested in Sub-project 4 /6/. They represent "mechanical locks" that can be placed rather far down in the holes and that can be covered by other materials like moraine, silica concrete and trimmed rock columns. These covering materials can be allowed to degrade and be lost by glacial erosion while the "locks" need to remain largely intact for protecting the tight seals deeper down. The chemical longevity of the materials selected, metallic copper and silica concrete, is claimed to be sufficient for the plugs to provide adequate sealing of the boreholes for at least 100,000 years /9/. They have the necessary compressive and shear strengths to withstand the pressure from the tight seals in the holes as well as from possibly arising hydraulic gradients.

The experiments in Sub-project 4 comprised determination of the bearing capacity of concrete plugs keyed into the rock and demonstration of the placeability of a copper plug with at least the same bearing capacity as that of the concrete plugs. The experiments had the following form:

- Placement of copper and concrete plugs in 200 mm diameter holes at a depth of a few metres from the ground surface including testing of techniques for reaming the holes, constructing the plugs, and extracting and examining them.
- Casting of concrete plugs at 450 m depth in 1.9 m deep cored boreholes with 200 mm diameter including application of the reaming technique and determination of the force required to extrude the plugs.

The plugs constructed at the ground surface were not tested with respect to their ability to resist axial forces. The major objective was to test the constructability of these types of plugs, the main function of which is to serve as strong, mechanical seals. This was achieved by extracting and sectioning the plugs for visual examination.

6.2 Plugs at the ground surface

6.2.1 Test arrangements and evaluation

Figure 6-1 illustrates schematically the test arrangements. The experiments demonstrated how reaming of 300 mm high recesses could be made in the 200 mm diameter holes that had been percussion-drilled holes and how plugging can be made by using silica concrete and copper metal. No testing of the mechanical properties was made of the plugs in these holes but overcoring by slot-drilling was made for demonstrating their physical constitution and way of performing.

The hole was filled with cement-stabilized sand and gravel to a few dm depth below the intended position of the copper plug, which was then lowered into the hole to fit with the reamed recess and expanded by applying a pulling force of about 20 t (200 kN) to establish an intimate contact with the rock. Concrete was cast below and on top of the plug for making it possible to extract the plug by slot-drilling. Figure 6-2 illustrates the general features and function of the copper plug. Figure 6-3 shows the appearance of the axial section after diamond sawing of the extracted rock.

The concrete was prepared according to the CBI recipe (Table 5-1). Figure 6-3 shows the appearance of the axial section after diamond sawing of the extracted rock. The examination verified that the concrete had filled the reamed slot completely and that the copper plug had been fully expanded and undergone some plastization.

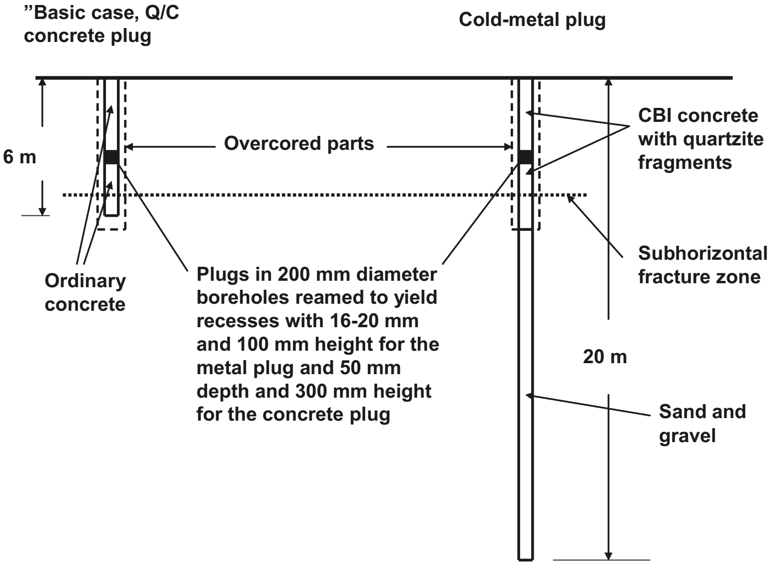


Figure 6-1. *Schematic picture of the 200 mm diameter holes at the ground surface plugged by concrete and copper plugs ("Overcoring" was made by slot drilling).*

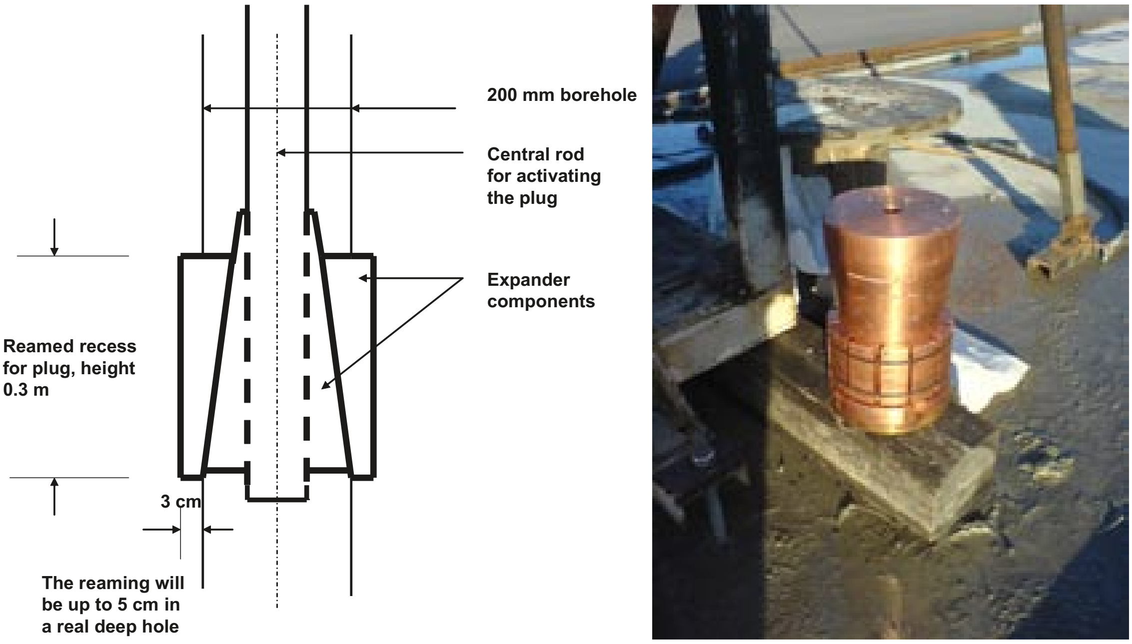


Figure 6-2. *The copper "expander" plug. The photo shows the copper plug turned upside down below the drill rig before lowering it into the 200 mm hole. The O-rings kept the lamellae in contact with the conical body, which moved them outwards into the recess when applying the pulling force.*

Figure 6-3. *Sectioned plugs released from the rock in the shallow plugging experiments. Upper: The concrete plug with porphyry-like appearance, fully occupying the hole and recess. Lower: The shiny copper plug with the lamellae extruded into the recess.*

6.3 Tests at 450 m depth

6.3.1 Principle

Figure 6-4 illustrates the three cored boreholes with 200 mm diameter at 450 m depth in the Äspö URL. They were plugged with concrete of different types and loaded for determining the axial force required to extrude them.

6.3.2 Construction

The concrete was prepared according to the CBI recipe given in Table 5-1 using plain concrete in one hole (K) and adding 10% quartzite with a normal grain size distribution ranging between 0.1 and 10 mm for the plug in the second hole (L), and adding 20% quartzite to the concrete in the third (M). The concrete mixtures had high fluidity and “self-compacted” without vibration or puddling. The concrete was cast on very porous insulation material (Frigolit) as support at the bottom of the holes so that the loadings could be made from above.

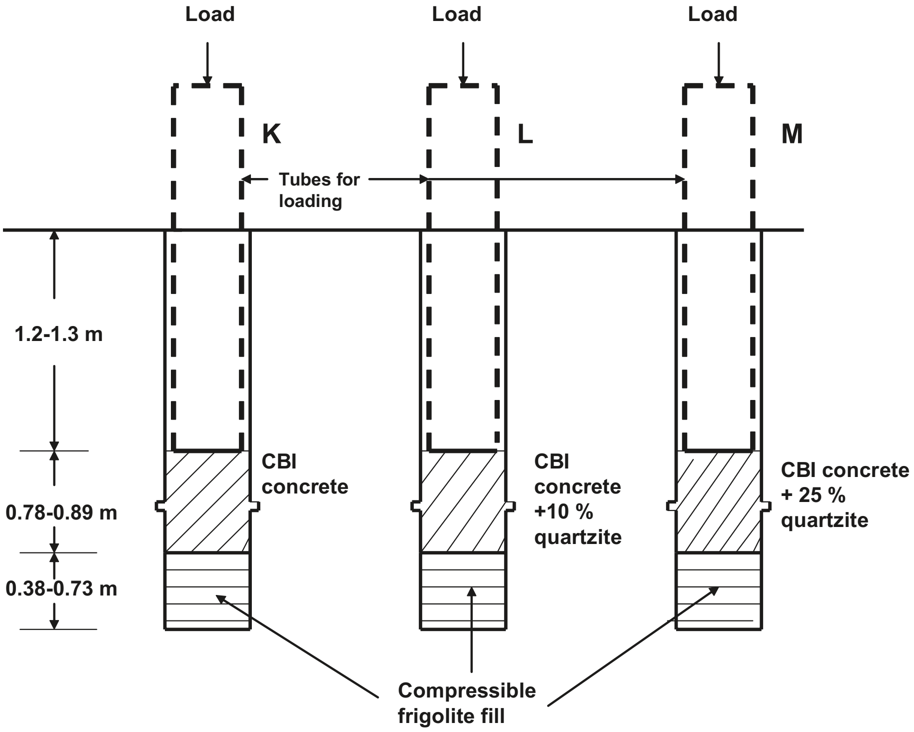


Figure 6-4. *The three 200 mm diameter plugs loaded after 4 weeks of maturation for determining the resistance to punching. Shearing took place at the 30 mm deep and 50 mm high recesses.*

Tap water was used for preparing the concrete, which would therefore undergo hardening in the same way as in constructions above ground. Since the groundwater is saline, cube samples stored in Äspö water were taken for testing cube strength after 28 days, i.e. the time selected for maturation of the big plugs. This was made in order to see whether contact with such water would have any effect on the strength of the plugs. The results from these tests show that the cube strength was 29.1 MPa for a cube with 2,261 kg/m^3 density stored in tap water and 30.2 MPa for a cube with 2,286 kg/m^3 density stored in Äspö water (1% salt content). The close agreement of the results shows that maturation of the concrete in contact with Äspö water did not affect its strength in the 4 week period.

6.3.3 Testing

The test arrangement consisted of a steel beam anchored to the rock by deep rock bolts for taking the load from hydraulic jacks that was required for extruding the plug (Figure 6-5). The displacements of the loading beam and the strong iron tubes that transferred the load to the respective plug were recorded by LVDT-type sensors. The vertical movement of the upper ends of the tubes gave the displacement of the plugs with an estimated accuracy of ± 40 µm.

6.3.4 Test program

Pilot load tests had given information on the shear strength of the three concrete types after 28 days of hardening and these data were used for predicting the required force to extrude the plugs in the 200 mm holes (Table 6-1).

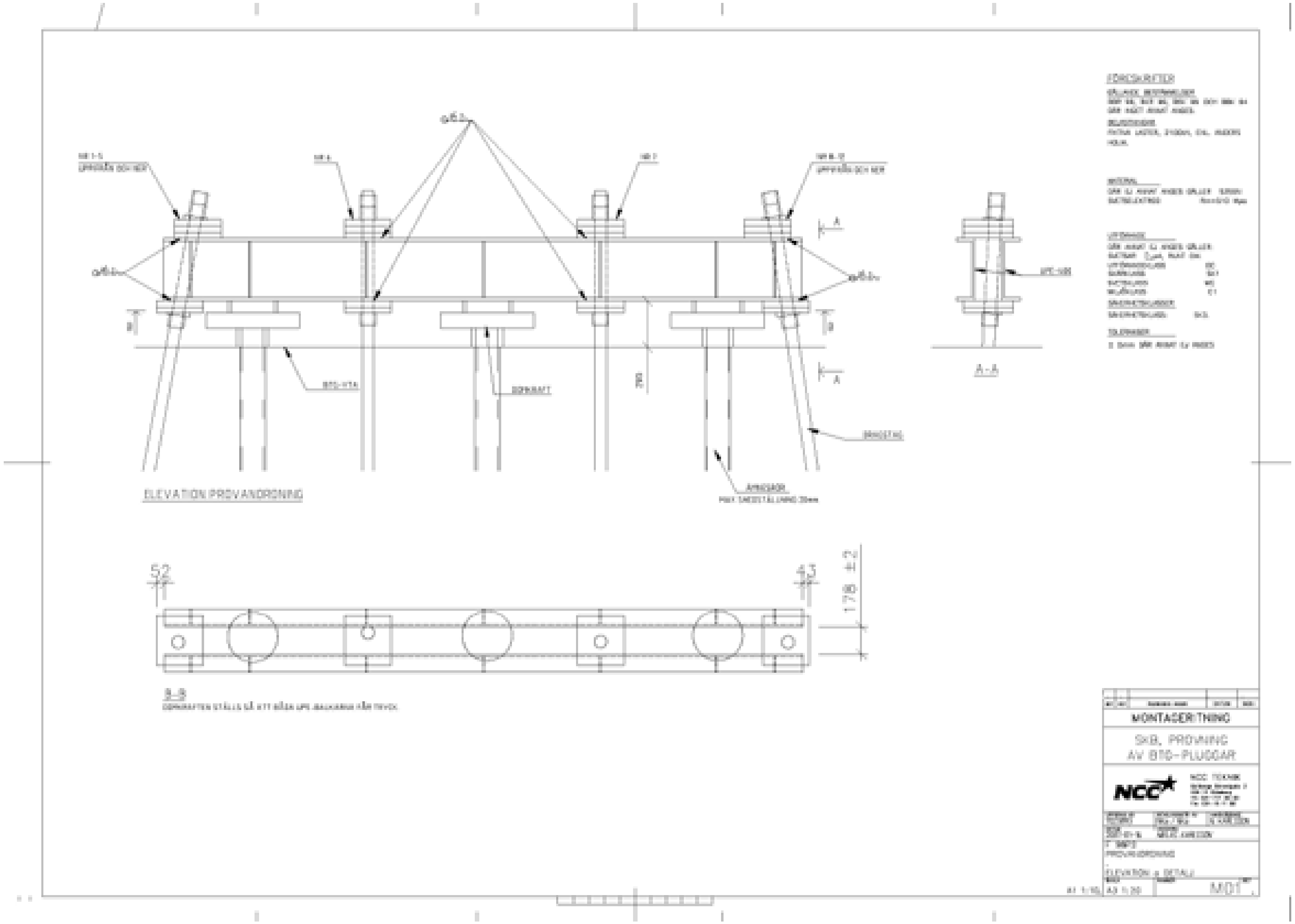


Figure 6-5. Load arrangement for the field punching tests (NCC Construction Co).

Table 6-1. Predicted axial forces for extruding the concrete plugs. The shear strength data emanate from laboratory tests.

Plug type	Sheared section, m^2	Shear strength, MPa	Theoretical extrusion force, t*	Estimated span of extrusion force, t*
CBI	0.03	20	60	40–60
CBI +10% quartzite	0.03	37	111	80–110
CBI +25% quartzite	0.03	50	150	110–175

* Multiplication by 10 gives the force in kN.

The recorded displacement versus load is illustrated by the diagrams in Figure 6-6. They demonstrate that the plugs behaved in a similar fashion and resisted loads well over 100 t (1 MN), corresponding to axial pressures of more than 30 MPa. For the test with no quartzite the load arrangement was found to need stabilization when the load had reached about 70 t (700 kN) and the adjustments can have had some impact on the displacement for loads lower than this value in the repeated load series. The expansive capacity of the piston of the jack was limited for all the loadings, which required several interruptions and unloadings. The graphs show the final loading sequence for the respective plugs.

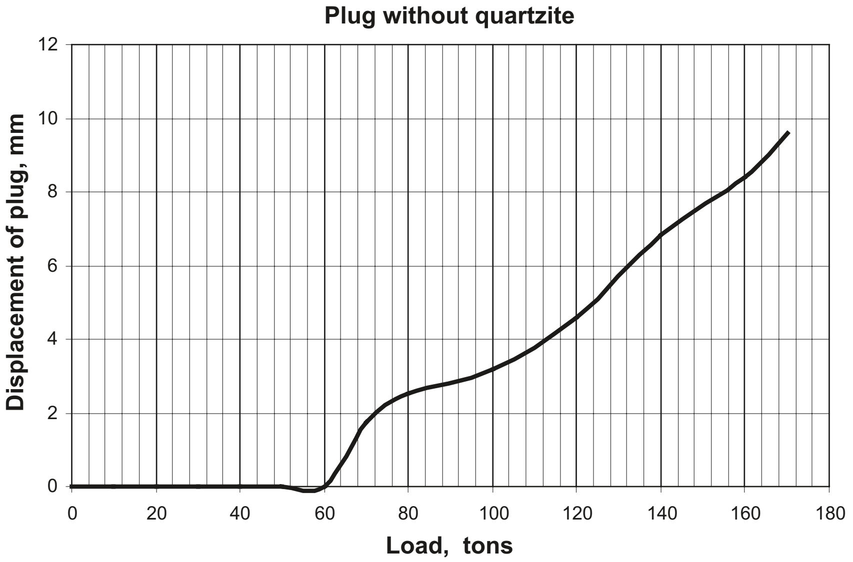
The most important conclusions of the tests are:

- The plug without quartzite fragments behaved in a more ductile manner than those with this additive. The plug with 25% quartzite was the stiffest one (cf Table 6-1).
- The plug without quartz fragments started to plasticize at around 60 t (600 kN) while those with fragments at about 115 t (1.15 MN) for the one with 10% quartzite and about 125 t (1.25 MN) for the one with 25% quartzite. This verifies that addition of quartzite increases the shear strength and deformation modulus of the CBI concrete significantly.
- The predicted failure loads in Table 6-1 agree well with those recorded in the field experiments.

6.3.5 Practical function of upper-end seals

The practical outcome of the tests, which are fully reported in Sub-project 4 /6/, is interpreted as follows:

- Plugging of large-diameter holes can be made by use of copper plugs and CBI silica concrete plugs, which both can take axial pressures of more than 30 MPa.
- The plugs need to be keyed in the rock for which a reaming tool is available.
- The shear strength and deformation moduli of concrete plugs of silica concrete can be significantly improved by mixing in centimetre-sized quartzite fragment.
- The function of plugs of the investigated type has been fully demonstrated. For the concrete plugs the recorded strength in full-scale tests has been found to agree well with predicted values derived from laboratory experiments.
- The long-term performance of the plugs has not been investigated. This is required for assessing their use in practice.



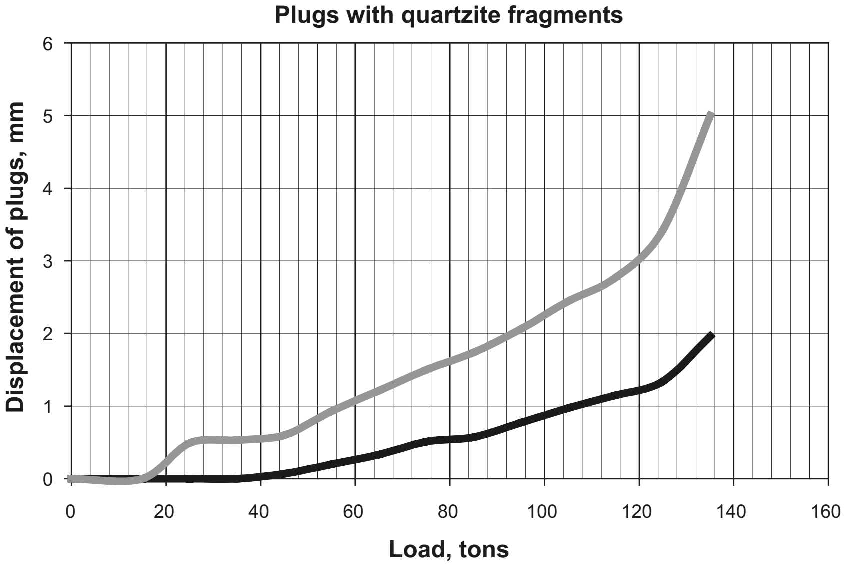


Figure 6-6. *Recorded strain in the loading tests. Upper: Plug without quartzite. Lower: Plugs with 10% quartzite (upper curve, the hump at 25 tons is an artefact caused by inadequate function of the gauges) and 25% quartzite (lower curve).*

7 Full-scale testing of composite plugs – borehole OL-KR24 at Olkiluoto and 5 m boreholes at Äspö

7.1 Introduction

General

Full-scale tests of borehole plugs consisting of smectite-rich clay (MX-80) in contact with silica concrete have been initiated at Olkiluoto, Finland, as a joint SKB/Posiva project, and at Äspö. The firstmentioned has comprised several activities for investigating how deep holes shall be prepared, which was Posiva's task, and how they can be plugged, which was SKB's obligation. It is the first example of very well controlled and successfully performed placing of a clay plug in the about 550 m deep hole OL-KR24. Sampling of concrete and clay for investigating their physical form and chemical interaction will be made when the ongoing ramp excavation gives access to suitable parts of the plug.

The Äspö experiment has comprised placement of short concrete and clay plugs in two 5 m deep boreholes at 220 m depth and will include extraction of the plugs after a period of time not yet decided for investigating the chemical interaction of silica concrete and smectite-rich clay.

The tests at Olkiluoto and Äspö represent Sub-project 3 /5/, the report of which describes the activities performed until spring 2007.

Principles

The general proposed strategy for borehole plugging is to cast cement-stabilized quartz where fractured rock is intersected, primarily for stabilizing it, and place clay plugs where the rock is normally fractured. This principle was applied in the OL-KR24 work /1/. The clay plugs in both field experiments were of "Basic" type, i.e. perforated copper tubes containing well fitting, highly compacted blocks of smectite-rich clay. The concrete recipe was worked out by CBI and applied in both experiments. It is estimated that the quartz component is chemically stable, while the cement, which is of low-pH type, can possibly be dissolved and lost. This is not deemed to be critical to the performance of the fill since its gradation is such that it should not be eroded. However, the contact between the cement-stabilized plugs and the clay plugs can lead to changes in mineral composition and loss in tightness.

Potentially unstable fracture zones intersected by boreholes have to be stabilized for avoiding rock fall in conjunction with subsequent placement of clay plugs. Stabilization is made by reaming the hole and filling it with cement-stabilized quartz concrete followed by re-boring. These activities respecting the OL-KR24 hole are reported separately by Posiva /7/. The following items were in focus in the field tests:

OL-KR24

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

Äspö holes

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

7.2 Plugging of the OL-KR24 hole

7.2.1 Basic conditions

Figure 7-1 illustrates the originally proposed use of the hole OL-KR24 for plugging experiments. The hole, which was bored in 2004, has a diameter of 76 mm and extends from a level some 20 m below the ground surface to somewhat more than 550 m depth from the ground surface. The starting point was on the +9.74 level.

7.2.2 Planned and performed field work at Olkiluoto

The major objectives were to:

1. Investigate the applicability of the "Basic" concept, i.e. placement of segments of jointed units of perforated copper tubes filled with highly compacted Na bentonite blocks, in deep hole plugging.
2. Investigate the efficiency of stabilizing potentially unstable fractured rock that is intersected by the borehole.
3. Investigate the feasibility of filling parts of the borehole that intersect fracture zones with silica concrete.
4. Demonstrate a technique to bring down a dummy for checking the clearance of a real plug segment before installing it.
5. Demonstrate replacing natural water in the hole by tap water.

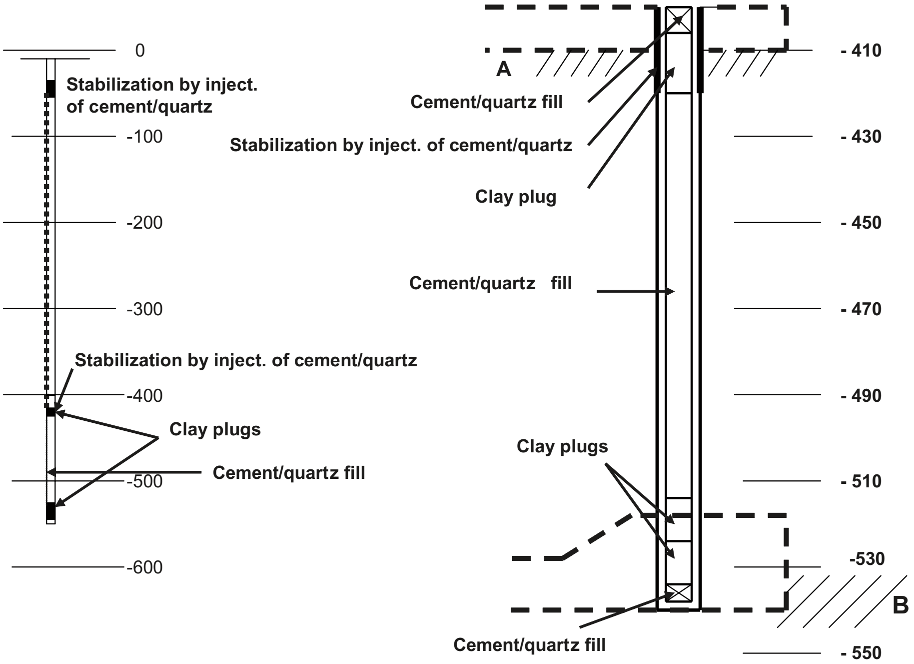


Figure 7-1. *Schematic illustration of the original design of stabilization and plugging. Only the lower part was plugged during the experiment. The actual levels decided are shown in Figure 7-2.*

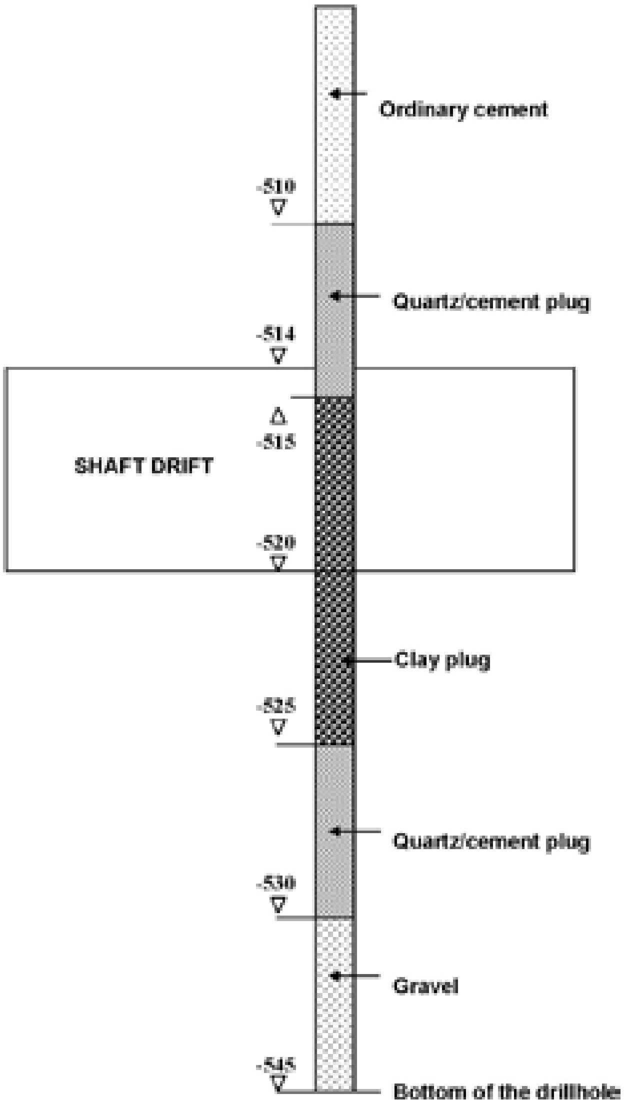


Figure 7-2. *Actual decided levels for plugging.*

These activities were scheduled to take place at Olkiluoto before the end of October 2005. After future excavation of the ramp towards the level –520, a drift reaching to the hole will be made from which the concrete and contacting clay plug would be extractable. At these two levels the concrete and contacting clay plugs would be extractable. Above the firstmentioned plug the hole can be used for guiding the raise-bore at the forthcoming shaft excavation.

After clearing and stabilization of the deep borehole, clay and concrete plugs were placed in the period November 8–14, 2005. The ultimately worked out plan, which had been changed several times because of time restrictions, was to fill the lowest part of the hole with concrete up to level –530.00 followed by casting 5 m cement-stabilized quartz concrete (Q/C) to level –525.00 over which a 10 m long clay plug should be placed and covered by casting a second 5 m cement/quartz concrete. Above this plug, i.e. above level –510.00, ordinary concrete was proposed to be filled in the hole. Hence, only the lower part of the hole was selected for the plugging event.

7.2.3 Actual procedure

The actual levels were different from the planned ones. Thus, the lowest part of the borehole, which extends from the bottom of the hole (–545 level) to the level –530.00 could not be filled with concrete and sand was used instead. It was compacted somewhat by letting the drill string repeatedly drop on the top of the sand fill, the uppermost level of which was at the level –530. The lower concrete plug became 5 m high and had its top at the level –525. Its hardness was found to be acceptable for carrying the 10 m long clay plug, which could be placed without problems. This operation was preceded by testing of whether 2.5 m and 5 m long dummies could be moved down without difficulty in the hole. Since it was verified that even the longer ones could be brought down without hindrance the finally prepared plug segments consisted of a 2.5 m long unit (first installation) and another 7.5 m long segment (second installation) consisted of three 2.5 m long units. The two segments were to be inserted in the hole, hence forming a 10 m long plug of "Basic" type.

The work comprised the following activities: i) Cleaning of the hole, ii) Stabilization of the hole after identifying the parts that needed to be secured, iii) re-boring and second cleaning of the hole, iv) hydraulic testing and structural characterization (optical borehole) of the hole from level –180 to –540 including the stabilized parts (this was not completed) v) manufacturing of clay plugs and cement/quartz concrete for plugging, vi) exchange of water in the hole by tap water, vii) dummy testing, viii) placement of plugs, and ix) temporary sealing of the hole above level –410.

POSIVA was responsible for items i, ii, iii, of which ii, vii and ix were made in cooperation with SKB. Items v; and viii were mabe by SKB's representatives. The work conducted at the site and in the borehole is described by Rautio and Majapuro /8/ (Other relevant reports related to OL-KR24 are available from POSIVA Oy). In the present report focus is on SKB's parts with due reference to rock investigations. They were:

- Manufacturing and storing of plugging materials
  - Copper tubes with compacted clay according to the proposed design Sub-project 1 /3/ but adaptated to 76 mm holes.
  - Cement and quartz materials.
- Emplacement of the plugs
  - Detailed plan of preparation of clay plugs (materials, depths, samplings etc) provided by SKB.
  - Placement of clay and quartz plugs by use of a drill rig, the work being performed by POSIVA under supervision and with assistance of SKB.

7.2.4 Characterization of rock structure and hydraulic conditions

The various hydraulic loggings and fracture mappings carried out before the plugging experiment in OL-KR24 as well as in connection with the experiment gave the large-scale constitution that is shown in Figure 7-3 for the part of potential interest for plugging. One recognizes fracture zones and water-bearing fracture swarms in the interval –520 to –530 where the clay plug is located. This suggests that the rock is sufficiently water-bearing to provide the plugs with water for quick maturation.

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

The borehole passed through several fracture zones that were considered for stabilization in the planning stage but only one depth interval was finally selected, namely –335.63 to –338.13, where the fracture spacing was locally very small. However, stabilization of this part failed due to technical problems and the entire hole remained unsupported.

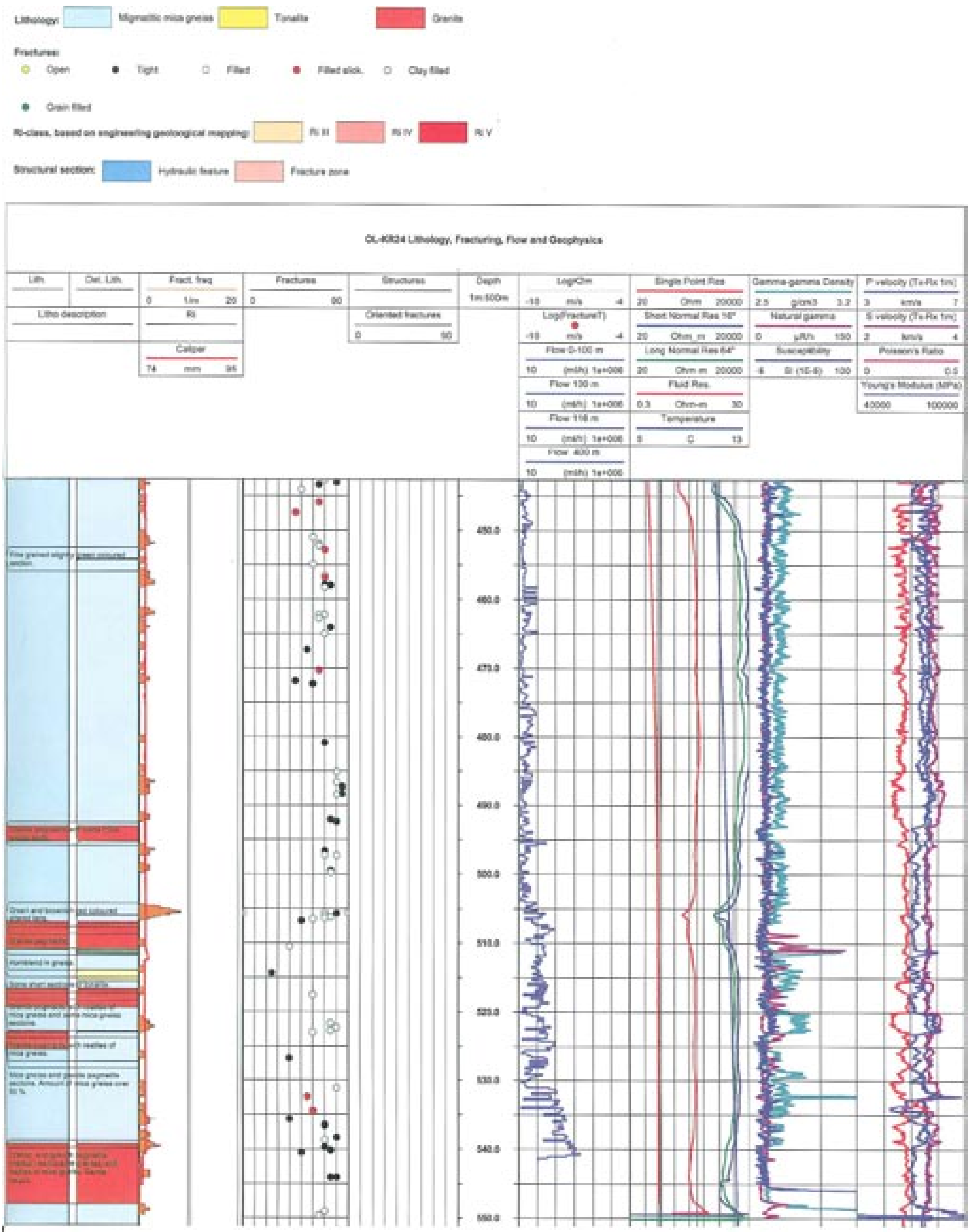


Figure 7-3. *Profile showing the plug components and basic, generalized rock data (From SMOY/POSIVA). Fracture frequency is expressed in number per metre. Flow shown as trend.*

7.2.5 Construction of plugs for OL-KR24

The report of Sub-project 3 /5/ contains a complete description of materials for use in the plugging of the OL-KR24 borehole. They were:

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

Copper tubes

Application of the "Basic" concept implied insertion of perforated copper tubes filled with tightly fitting clay blocks in the hole. The length of unit "Basic" plugs was 2.5 m and jointing was made to yield segments of different lengths for testing with respect to placeability, 5 m, 7.5 m, 10 m etc. Connection of adjacent segments was made on site in conjunction with the insertion of the plug in the hole (cf Sub-projects 1 and 2 /3, 4/).

OL-KR24 has 76 mm diameter while the outer diameter of the tubes was 72 mm. They had 50% perforation ratio with 10 mm diameter holes uniformly distributed in straight rows with every second row displaced by half a hole distance, i.e. 6.75 mm (cf Sub-project 1 /3/). The lowermost tube of a segment of jointed plug units of the "Basic" type was equipped with a copper plate welded to the tube for carrying the clay blocks in the finally decided plug version with four jointed 2.5 m long units.

Jointing of plug units with clay blocks in them was made with the tubes hung in the drill rig. At each jointing event a gripping tool connected to the rig was used for holding the already completed part of the segment for preventing it to drop in the hole (Figure 7-4). The weight in air of the jointed 10 m long clay plug, including clay and perforated copper tubes, was 45 kg. The equipment for all these purposes and the actual jointing operation was provided by Livinstone AB.

Clay material

The clay used for manufacturing the blocks was MX-80 bentonite with 6% water content compacted under 200 MPa pressure. The material was delivered by Askania AB, Gothenburg, Sweden. The preparation of blocks was made by Höganäs Bjuf AB, Höganäs, Sweden, by compacting the clay powder in cylindrical forms. The average dry density of the clay plugs was 2,035 kg/m^3 and the expected average density of the matured plug 2,000 kg/m^3, yielding a swelling pressure on the rock of 1–3 MPa for the salinity conditions prevailing in the Olkiluoto rock, i.e. approximately 10,000 ppm with Ca as dominating cation /5/.

Cement material for borehole stabilization

The recipe of the silica concrete was that described in Table 7-1 (CBI). A force mixer was used for homogenization of the material, which had soft paste consistency and is known to harden to give a compressive strength of at least 10 MPa in 24 hours, which is estimated to be sufficient for supporting the rock so that the stabilization work can proceed deeper down in the hole after one day. pH is lower than 11.

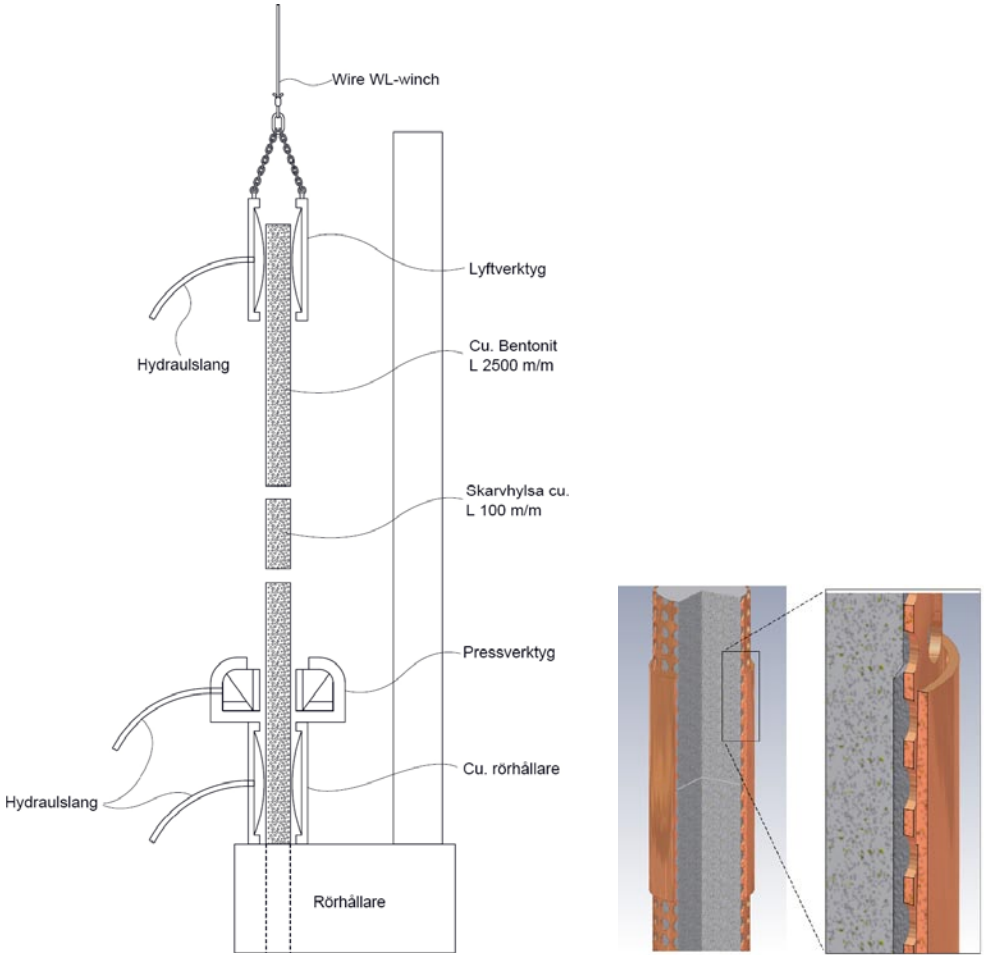


Figure 7-4. *Jointing of plug units. Left: Schematic view of the connecting tube (SWECO). Right: Jointing process /2/. Lyftverktyg = Lifting tool. Hydraulslang = oil tube for operating the lifting tool. Skarvhylsa = connecting tube. Pressverktyg = compression tool. Rörhållare = tube clamp.*

Table 7-1. Concrete for stabilizing boreholes ("lining of reamed hole", CBI).

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

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

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

The recipe of the cement-based material (also termed “silica concrete”) is given in Table 7-2. The purpose of using this material is to minimize the cement content for limiting pH and for maintaining physical stability of the fill even after complete dissolution and loss of the cement component. This concrete was used for filling the hole between levels –525 and –530 and between –510 and –515. Above level –510 ordinary concrete with Portland cement was cast.

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

Concrete filled in the borehole above the plugged parts

Since there were no chemical restrictions on this concrete ordinary cement was used between depth levels –510 and –11. The recipe is as in Table 7-3 and ordinary concrete mixers were used for the preparation. 2.6 m^3 of concrete was pumped from truck into the hole.

The hardened concrete sealed the hole and is believed to provide tightness through its low shrinkage potential. This type of concrete is pumpable and compacts without vibration.

7.2.6 Location of plugs

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

Table 7-2. Concrete (low strength) recipe for plugging of boreholes (CBI).

Components	Amount (kg/m^3 concrete)	Manufacturer
White cement	60	Aalborg Portland
Silica Fume	60	Elkem
Fine ground α-quartz M300	200	Sibelco
Fine ground cristobalite M6000	150	Sibelco
Superplasticizer Glenium 51	4.375 (dry content)	Degussa
Granitic aggregates 0–4 mm	1,700	Jehanders grus
Water	244.27	local

Table 7-3. Approximate composition per m^3 concrete using CBI aggregate.

Component	Mass
Cement CEM 1	350 kg
Silica fume	35 kg
Filler	150 kg
Sand 0–8 mm	1,004 kg
Stone 8–18 mm	670 kg
Water	174 kg
Superplasticizer	Adjusted

This plan had to be changed because it was reported on November 8 that the casting of the lowermost concrete had failed. It was decided to fill the hole with sand to the –530 level, which was also made. The day after, sounding by use of drill string showed that more sand had to be put in and the finally completed sand fill got its upper surface on level –530.29 (corresponding to about 540 m of hole depth from surface). This was hence the starting level for the plug construction. The final upper level of the silica concrete was reported to be –509.94, deviating from the planned level by 6 cm.

Lower concrete plug

The lower silica concrete plug, with its lower end at level –530.29 and its upper at –524.94 was cast successfully by use of the injection tool, which is of the "Container"-type (Sub-project 1), /3/. The 5 m high plug was cast in two steps. The physical state of the concrete the day after casting was checked by core drilling indicating stiff consistency at level –525.29 (hole depth about 535 m from surface). Prior to the casting a dummy test with a 12 m long tool (diameter 72 mm) was made to certify sufficient clearance. The tool went down to the bottom of the borehole. However, there were considerable problems lifting it from the borehole, because of some very fine grained sand that remained from earlier plugging attempts.

Upper concrete plug

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

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

Clay plug

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

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

Figure 7-5 illustrates the jointing of clay plugs in conjunction with placement at more than 500 m depth.

Figure 7-5. *Jointing of two 2.5 m long units at Olkiluoto.*

7.2.7 Prediction of maturation

The proposed principle to place clay plugs between plugs of silica concrete was followed in the sealing of the OL-KR24 hole. Listed from the bottom upwards it contained 1) sand, 2) silica-concrete cast on site, 3) a clay plug of "Basic" type, 4) silica-concrete cast on site, and 5) ordinary concrete. The water pressure in the plugged region is around 5 MPa, which, according to the theoretical models, will guarantee quick maturation of both the concrete and clay since the rock is rich in water-bearing fractures and fissures.

Concrete plugs

The hydration and chemical evolution of the concrete plugs are expected to make them mature fully in a few years from the state they had after 24 hours when contact with the clay plug was established. In this early phase the reactions had not reached maturation but the strength was confirmed to have been sufficient to carry the load represented by the clay plug and the overlying concrete fillings.

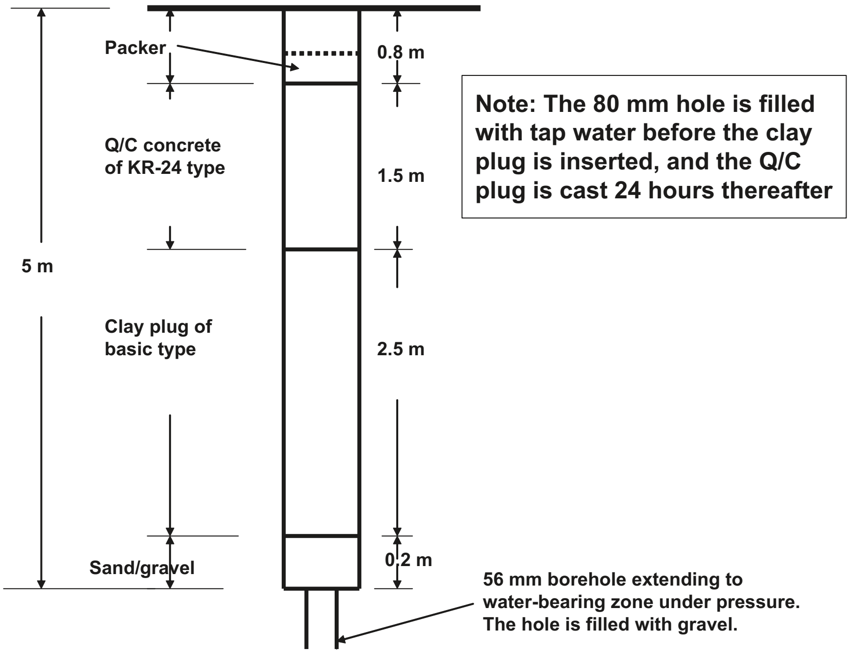
Clay plug

The degree of maturation includes water saturation and homogenization of the clay, as well as chemical reactions with the contacting concrete. According to the theoretical models that are based on the assumption that water is absorbed by being sucked by the dense clay core, nearly complete hydration of the clay plug in rock with a hydraulic conductivity of E–13 to E–10 m/s, can take a few months even at moderate piezometric pressures /3/. At higher pressures water will be pressed into the dense microstructural matrix of the clay and accelerate the wetting process, and under very high pressure, like in OL-KR24, water will penetrate more deeply in wider channels, displacing and compressing air in the voids and the unsaturated matrix. This will yield complete water saturation in a few weeks.

7.3 Plugging of 5 m deep holes at Äspö[2]

7.3.1 Background

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 silica concrete plugs may undergo change and so can the silica concrete plugs. Degradation can have 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 silica concrete can undergo some dissolution and loss in density and strength and become more permeable. Released silica may cause cementation of the clay. The problem is to find out what the degradation process really is and how far into the clay and concrete plugs it proceeds. The latter would require that the test be conducted for an extremely long time but once the process has been identified it should be possible to derive a theoretical model that can be used for predicting the extent of the degradation over 100,000 years or more. This is the purpose of the experiments with 5 m deep holes, which, in contrast to the OL-KR24, are not aimed at investigating placement techniques (Figure 7-6). They were core-bored from the floor of a room with its floor at 220 m depth.



Note: The 80 mm hole is filled with tap water before the clay plug is inserted, and the Q/C plug is cast 24 hours thereafter

Figure 7-6. *Schematic view of two 5 m boreholes (actual depths 6.00 and 5.90 m) with 80 mm diameter for testing of the interaction of quartz/cement and clay. The upper end of the hole is sealed by a mechanical packer. The Q/C concrete plug is the same as used for OL-KR24. The clay plug is of "Basic" type.*

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[2] The project referred to "5 m holes" but the bored holes became 5.90 and 6 m deep, respectively, and they were extended by another 15 m by percussion drilling.

As for the OL-KR24 case the clay plugs in the 80 mm Äspö holes, termed KA1621G01 and KA1621G02, are of *"Basic"* type and hence consist of a perforated copper tube with well fitting highly compacted columns of very dense clay. As in the OL-KR24 case the concrete plugs contacting the clay plug were prepared using the recipe worked out by CBI. The two cases are complementary and can be terminated at different times, the main differences being the water pressure, which is on the order or 5 MPa at Olkiluoto and presumably up to about 1 MPa at Äspö. This implies slower maturation of the Äspö plugs.

7.3.2 Prediction of maturation

The structural constitution of the rock mass in which the holes were core-bored has not been modelled but core examination and inflow measurements indicate that the water pressure and access to water for maturation of the plugs are rather low. This makes a difference between this case and the OL-KR24 case since there will be competition between the clay and concrete in the early phase of maturation at Äspö, which can have an impact on both mineralogy and physical properties of the reactants.

7.3.3 Test arrangements

The holes are filled with gravel up to about 5 m from the floor for providing water from the deeper parts to the plugs. The uppermost part of the fill is sandy for avoiding migration of clay from the clay plug, which is placed directly on it.

Clay plugs

The clay plugs placed in the two 80 mm diameter holes are of "Basic" type with the following data:

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

Concrete plugs

The concrete plugs were constructed in the same way and with the same materials and technique for placement as for the OL-KR24 case. The inserted clay plugs were allowed to mature for 8 hours before the concrete was cast. By this, concrete could not migrate downwards and displace the clay "skin" formed around the clay plugs. On top of the concrete plugs mechanical packers were placed for allowing the water pressure in the hole to rise.

7.3.4 Suggestions for the future work

Programs for analyzing clay and concrete

Detailed laboratory programs have been worked out /5/ for investigating samples that will be taken from the OL-KR24 plugs on the –410 m level when the ramp has been excavated to this depth and a niche to the hole has been excavated. When excavation of the ramp has reached below level –435 a niche will be excavated to the hole and samples taken from the plugs also at this level.

For the Äspö plugs similar testing will be made as of samples from the OL-KR24 plugs. The plugs are planned to be overcored by a 200 mm borehole at a time decided later.

The major features of the testing programs are as follows.

Clay

The examination is intended to reveal possible erosion and effects of chemical interaction of cement/clay and copper/clay, as well as to identify and quantify possible heterogeneities in the form of different density of the central and peripheral parts of the clay columns. Overcoring of the clay plug is made for getting an undisturbed sample of 2 m length. It is investigated with respect to the density distribution, hydraulic conductivity, swelling pressure and shear strength.

Silica concrete plug

Samples are cut from the extracted concrete plugs for laboratory tests including determination of the hydraulic conductivity and strength.

8 Discussion and conclusions

8.1 General

This part of the Borehole Project has dealt with fundamental issues, primarily design of the four plug types that are considered, the ways in which the plugs mature under different rock conditions, their performance in the holes, and manufacturing issues. One of the major requirements is that the matured plug must be tighter than the surrounding rock, which has an average hydraulic conductivity of E–11 to E–8 m/s. This performance criterion is valid for at least 100,000 years /9/.

The principle of plugging long holes proposed in the first phase of the project is basic to the planning, design and construction of such seals, i.e. to make the parts of boreholes where the rock has few fractures and a low hydraulic conductivity tight, and to fill those parts that intersect permeable fracture zones with physically stable material that does not need to be very tight. The tight parts consist of smectite-rich clay in the form of highly compacted blocks or pellets, while the fillings separating them consist of silica concrete with little cement of low-pH type and with aggregates of quartz sand and quartzite. This type of concrete is largely inert with respect to chemical interaction with smectite clay and can be allowed to loose the cement component without jeopardizing its performance by using a gradation of the aggregate grains that prevent the large majority of them to migrate into the rock fractures. This risk is largely eliminated by stabilizing the boreholes that intersect fracture zones by casting cement-poor concrete in reamed parts followed by re-boring. Hence, stabilization and subsequent clearing and cleaning of borehole walls are prerequisites for plugging, which comprises segment-wise placement of clay plugs and casting of silica concrete.

Four different clay-based plugs have been selected and tested: 1) The "Basic" plug type with highly compacted MX-80 clay columns confined in perforated copper tubes, 2) The "Container" plug with highly compacted MX-80 clay blocks contained in a cylinder attached to drilling rods and released when the tip of the cylinder is in the desired position, 3) The "Couronne" plug with annuli of highly compacted MX-80 clay stacked around jointed copper rods that are pushed into the hole, and 4) MX-80 pellets poured into the hole without compaction. The selection of MX-80 was simply for using a very well known smectite-rich clay; it can be replaced by any clay with the same mineral composition. The properties and performance of the investigated clay plugs are as follows:

"Basic" type

The major advantages of this concept are that it is rugged and that plugs can be inserted, theoretically at least, to any depth and in any direction. Also, they are retrievable. Negative features are that the time for placement needs to be short enough to minimize erosion and for avoiding maturation to an extent that the placement becomes difficult. A suitable time interval for bringing a clay plug down to 1,000 m depth is 5–10 hours. More than 10 hours is expected to make adhesion of the clay to the rock significant and cause practically important resistance to the placement. An important fact is that there is sufficient experience of placement and testing of "Basic" plugs to recommend them for practical use.

Using clay of MX-80 type with 6% water content and compression under 250 MPa the ultimately evolved density is acceptable. Thus, the lowest net density of the clay will be found at the lower end of plugs in 1,000 m deep holes, i.e. 1,900 kg/m^3. The corresponding hydraulic conductivity and swelling pressure in saline groundwater are E–12 m/s, and 1.5 MPa, respectively. Plugs placed at 500 m depth, corresponding to the repository level, will undergo less erosion and are estimated to have an average density of 2,000 kg/m^3.

“Container” type

This concept has several advantages compared to plugs of “Basic” type, primarily that the clay can be brought to the required location without exposing it to eroding water. A possible difficulty with plugs of this type is that the container tube must be perfectly tight and strong enough to resist high pressures. The thickness of the tube hence has to be large enough to provide the required strength and small enough to give the clay sufficient density. A prototype has been made but has not yet been tested in the field. The concept is very promising, because holes of any direction can be plugged. Testing on a full scale is recommended.

“Couronne” type

Plugs of this type have been installed without difficulty. The concept is simple and practical but the problem is that erosion and abrasion of the unshielded clay may be significant, which suggests that it should not be applied for sealing boreholes longer than 100 m.

The simple technique and the possibility to get a relatively high plug density means that the technique should be applicable without much further development.

“Pellet” type

Plugs of this type have been used and tested abroad and they can be installed with moderate difficulty. The concept is simple and practical but the problem is that the density of the matured plug is not very high. It is recommended that the borehole is drained before bringing in the pellets implying that the boreholes, which need to be steep and oriented downwards, can not be very deep, i.e. only a few tens of metres. In comparison with the “Couronne” concept the latter is superior at least in small-diameter holes (50–100 mm).

Upper end seals

General aspects on sealing the uppermost part of deep boreholes extending from the ground surface have been given in /1/. The present 3^rd^ phase of the borehole sealing project has been confined to identify and test techniques for constructing “mechanical” seals that are needed for protecting the tight plugs in deeper parts of the boreholes. Two such concepts have been developed and examined through demonstration and underground testing in the Äspö URL. One makes use of a copper expander that was tested in a 200 mm diameter hole and the other involves on-site casting of plugs of silica concrete of which there are three versions. They were all tested with respect to their potential to carry axial loads and turned out to be able to withstand pressures of about 30 MPa, which is also the estimated bearing capacity of the copper plug. Both plug types need to be keyed in the rock for which reaming tools developed in the project can be used. The function of plugs of the investigated type has been fully demonstrated. For the concrete plugs the recorded strength in full-scale tests has been found to agree well with predicted values derived from laboratory experiments. The strength of the plugs will even make them resist an overburden pressure of a 3 km thick glacier.

The long-term performance of plugs of the investigated types has not been investigated but the chemical integrity is believed to be sufficient for a period of 100,000 years /9/. As to their physical constitution in a long-term perspective, glaciation is believed to be the major threat. Two glaciation cycles may, depending on the regional topography, erode up to 100 m of the rock, meaning that at least one “mechanical” seal in a deep hole should be located at or below this depth. The matter needs further consideration in conjunction with future development of borehole plugging techniques.

Experience from full-scale testing

Full-scale tests of borehole plugs consisting of smectite-rich clay (MX-80) in contact with silica concrete have been initiated at Olkiluoto, Finland, as a joint SKB/Posiva project, and at Äspö. The Olkiluoto test is the first example of very well controlled and successfully performed placing of a clay plug at more than 500 m depth. The Äspö experiment has comprised placement of short concrete and clay plugs in two 5 m deep boreholes at 220 m depth. Sampling of concrete and clay for investigating their physical form and chemical interaction will be made at both sites after a period of time not yet decided. The difference between the two sites is that the deeply located plugs have matured much quicker because of better access to water, while the maturation of the clay plugs in the Äspö holes is expected to have proceeded slowly involving also competition between cement and clay in the uptake of water.

8.2 Development of borehole plugging

General

The work made in the present 3rd phase of the borehole sealing project has been successfully pursued with respect to the identification and testing of technical components. Difficulties have been identified as well, particularly in preparing boreholes for the plugging stage, especially in stabilizing fracture zones and casting concrete at depth. This has shown that characterization of a borehole to be plugged is of primary importance for planning stabilization and placing of plugs and that methods for this purpose need to be worked out. It clearly has to involve, as functions of depth, detailed structural description, pressure and flow data, analyses of water chemistry and mineralogical description. This is required since it has become very obvious that the basis of selecting how and where plugs shall be constructed and placed depends on the overall structural and hydraulic performance of a rock mass.

Issues to be included into the future work

The following matters have been identified that deserve attention in future work:

- Characterization of boreholes and formulation of strategies for plugging holes of different length and orientation extending from the ground surface and from the repository, with special respect to the presence of important rock structural features. Use of data from actual deep and short boreholes should be made for simulating complete plugging scenarios using the proposed techniques and identification of risks and ways of minimizing them. This work should also comprise methods of characterizing constructed plugs, including ways of testing them.
- Development of techniques for preparing deep and long boreholes (clearing and stabilization) comprising, in particular, removal of casings etc in their uppermost parts. This work should include improvement of the proposed concepts, except the “Pellet” type, which should involve use of smectitic bore mud in the holes for stabilizing the boreholes, for reducing erosion of clay, as well as for increasing the net density of the matured plugs
- Development of most suitable plug types for use in deep and long holes and constructing such plugs, focusing on the need of reaching high degree of homogeneity of both clay and concrete plug segments.
- Identification of physical and physico/chemical changes of clay and concrete plugs, especially concerning the interaction of clay-based and concrete plug segments.
- Quality issues respecting raw materials, manufacturing and testing.

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