nagra.

Arbeitsbericht NAB 16-10

FEBEX-DP – Plug Overcoring and Concrete-Bentonite Interface Sampling prior to Dismantling

August 2016

Urs Mäder, Kai Detzner, Florian Kober, Hans Abplanalp, Toni Baer & Veerle Cloet

National Cooperative for the Disposal of Radioactive Waste

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

nagra.

Arbeitsbericht NAB 16-10

FEBEX-DP – Plug Overcoring and Concrete-Bentonite Interface Sampling prior to Dismantling

August 2016

Urs Mäder[1], Kai Detzner[2], Florian Kober[3], Hans Abplanalp[3], Toni Baer[3] & Veerle Cloet[3]

[1] Rock-Water Interaction Group, Institute of Geological Sciences, University of Bern
[2] Edi Meier + Partner AG
[3] Nagra, Wettingen

KEYWORDS

FEBEX-DP, concrete-bentonite interface, stabilised overcoring technique, Grimsel Test Site

National Cooperative for the Disposal of Radioactive Waste

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

Table of Contents

Table of Contents ..... **I**

List of Tables ..... **II**

List of Figures ..... **II**

1 Introduction and objectives **1**
1.1 The FEBEX project 1
1.2 Test configuration during FEBEX I 2
1.3 Dismantling Heater 1 and test configuration afterwards (FEBEX II) 3
1.4 Concept of the dismantling of Heater 2 4
1.5 Objectives and contents 5

2 Sampling technique using stabilised overcoring **7**
2.1 Experience with stabilising fractured rock samples from the GTS 7
2.2 Details of stabilised overcoring for claystone and bentonite 7
2.3 Adaptation of the overcoring procedure for FEBEX-DP 9
2.4 Equipment used for overcoring interfaces 12
2.5 Measurement of temperatures at the bentonite/plug interface 16
2.6 Temporary sealing of sampling boreholes 16

3 Field work **19**
3.1 Drilling borehole C-C-32-4 21
3.2 Drilling of C-C-32-5-OC 25
3.3 Drilling of C-C-32-6-OC 28
3.4 Temperatures across the shotcrete/bentonite interface 31

4 Sample treatment and sample preservation **33**

5 Subsampling of bore core material **39**

6 Sample archive and sample distribution **43**

7 Conclusions and lessons learned **47**

8 Acknowledgments **49**

9 References **51**

App. A: Image gallery for C-C-32-4 ..... **A-1**
A.1 Shotcrete samples from the 220 mm approach borehole (C-C-32-4) A-1
A.2 Samples from the 46 mm reinforcement boreholes (C-C-32-4) A-3
A.3 Borehole wall after overcoring (C-C-32-4-OC) A-5
A.4 Sample from 132 mm overcoring (C-C-32-4-OC) A-5
A.5 Subsamples from overcore C-C-32-4-OC A-8

App. B: **Image gallery for C-C-32-5** B-**1**
B.1 Shotcrete samples from the 220 mm approach borehole (C-C-32-5) B-1
B.2 Samples from the 46 mm reinforcement boreholes (C-C-32-5) B-3
B.3 Borehole wall after overcoring C-C-32-5-OC B-4
B.4 Sample from 132 mm overcoring C-C-32-5-OC B-4
B.5 Subsamples from overcore C-C-32-5-OC B-7

App. C: **Image gallery for C-C-32-6** C-**1**
C.1 Shotcrete samples from the 220 mm approach borehole (C-C-32-6) C-1
C.2 Samples from the 46 mm reinforcement boreholes (C-C-32-6) C-2
C.3 Borehole wall after overcoring C-C-32-6-OC C-5
C.4 Sample from 132 mm overcoring C-C-32-6-OC C-5
C.5 Subsamples from overcore C-C-32-6-OC C-8

List of Tables

Tab. 3-1 List of sampling boreholes executed from section 32 19
Tab. 3-2 Summary of borehole paramaters and drilling depths. 21
Tab. 6-1 Summary of samples, sample mass, and distribution 44
Tab. 6-2 List of 46 mm drillcore samples from C-C-32-4 45
Tab. 6-3 List of 46 mm drillcore samples from C-C-32-5 45
Tab. 6-4 List of 46 mm drillcore samples from C-C-32-6 46

List of Figures

Fig. 1-1 Overall layout of FEBEX "in-situ" test (left) and "mock-up" test (right). 1
Fig. 1-2 General layout of the FEBEX "in-situ" test (FEBEX I configuration). 2
Fig. 1-3 Status of the FEBEX "in-situ" test after the partial dismantling (FEBEX II configuration). 4
Fig. 2-1 Illustration of the drilling technique for sampling performed in 2001 for the HPF (Hyperalkaline Plume in Fractured Rock) Project. Plan view of drilling arrangement (see text for details). 7
Fig. 2-2 Templates to fit a 220 mm OD borehole used for drilling six 46 mm OD boreholes for inserting fibre glass reinforcements embedded in epoxy resin. Left: dimension drawing. Right: Templates for 46 mm boreholes and 131 mm overcoring diameter. White plastic parts are for coupling drilling guides and centre the core barrel. 8

Fig. 2-3 Left: 2-meter long fibre glass rods. Middle: Detail of adapter at top (brown, HGW 2082) with a left-hand outer thread and resin injection lines with brass couplings. An aluminium installation tube with a POM coupling piece is seen on the right. Right: Image with borehole camera showing 3 fibre glass rods previously inserted, and 3 just after resin injection and still conncetced to the installation equipment. 9

Fig. 2-4 Drilling procedure for stabilised overcoring developed for the CI Project. See text for explanation. Lower centre image: yellow and blue blocks were removed for better visibility. 9

Fig. 2-5 Procedure for fibre glass reinforced overcoring of shotcrete/bentonite interface samples (see text for explanation). 11

Fig. 2-6 Drilling equipment used for interface sampling. 12

Fig. 2-7 Packer assembly with fibre glass reinforcements. 14

Fig. 2-8 Details of resin injection setup 15

Fig. 2-9 Equipment used for temperature measurement. 16

Fig. 2-10 Equipment used for sealing of sampling boreholes. 17

Fig. 3-11 Layout for sampling shotcrete/bentonite interface from section 32 (plug surface) 19

Fig. 3-2 Vertical section showing the locations for sampling plug/bentonite interfaces. The final as-emplaced plug thickness is 3 m. 20

Fig. 3-3 Images from the approach borehole and shotcrete core, C-C-32-4. 22

Fig. 3-4 Images from drilling stabilisation boreholes and placing reinforcements, C-C-32-4. 24

Fig. 3-5 Images from overcoring, C-C-32-4. 25

Fig. 3-6 Images from approach borehole and shotcrete core, C-C-32-5. 26

Fig. 3-7 Images from drilling stabilisation boreholes and placing reinforcements, C-C-32-5. 27

Fig. 3-8 Images from overcoring, C-C-32-5 28

Fig. 3-9 Images from approach borehole and shotcrete core, C-C-32-6 29

Fig. 3-10 Images from drilling the stabilisation boreholes, C-C-32-6. 30

Fig. 3-11 Images from overcoring, C-C-32-6 31

Fig. 3-12 Temperatures measured across the shotcrete/bentonite interface. The position of the interface is marked as dashed line 32

Fig. 4-1 Vacuum-sealed small shotcrete and bentonite cores from C-C-32-4/12. The interface shotcrete/bentonite is contained in the bag on the lower left. Arrow points dowards deep end of borehole 33

Fig. 4-2 Preservation of overcore C-C-32-4-OC 34

Fig. 4-3 Illustration of resin impregnation of overcore samples 36

Fig. 5-1 Mitre saw with diamond cutting blade 39

Fig. 5-2 Cutting and labelling scheme of shotcrete/bentonite interface samples 39

Fig. 5-3 Illustration of subsampling and protection with epoxy resin 40
Fig. 5-4 Cutting and labelling schematic for half cores and quarter cores, with some characteristic dimensions indicated 40
Fig. 5-5 Cutting of samples containing shotcrete/bentonite interface into half cores, followed by covering surfaces with epoxy resin. 41
Fig. 5-6 Illustration of subsampling and protection with epoxy resin. 42
Fig. 6-1 Schematic of sample allocation 43
Fig. 8-1 Field team in the FEBEX gallery. From left: Urs Mäder, Hans Abplanalp, Kai Detzner, Toni Baer, Florian Kober. 49
Fig. A-1 Images of samples from 220 mm approach borehole, C-C-32-4 .... A-2
Fig. A-2 Schematic for labeling reinforcement boreholes. View direction is downhole. Approach boreholes is 220 mm OD. Reinforcement boreholes of 46 mm OD: 1st set of three (yellow) and 2nd set of three (blue). Orientations are labelled according to clock position. Overcoring diameter is indicated (132/124 mm). A-3
Fig. A-3 Images of samples from all six 46 mm reinforcement boreholes, C-C-32-4 .... A-4
Fig. A-4 Images of borehole wall, associated with C-C-32-4-OC A-5
Fig. A-5 Images of shotcrete sections of overcore C-C-32-4-OC with different materials numbered (see text) A-6
Fig. A-6 Images of overcore C-C-32-4-OC. Arrow marks position of shotcrete/bentonite interface A-7
Fig. A-7 Cutting schematic for subsampling overcores A-8
Fig. A-8 Images of samples cut from 132 mm overcore, C-C-32-4-OC A-8
Fig. A-9 Images of interface region from overcore C-C-32-4-OC, viewed through epoxy layer. A-9
Fig. A-10 Images of cut surfaces from overcore C-C-32-4-OC, viewed through liquid epoxy layer. A-10
Fig. A-11 Images of all sections containing the shotcrete/bentonite interface after resin work. A-11
Fig. A-12 Quarter cores of shotcrete section from C-C-32-4-c after vacuum sealing A-11
Fig. A-13 Half cores and quarter cores of bentonite section A-12
Fig. A-14 Quarter cores cut from C-C-32-4-OC A-13
Fig. B-1 Images of samples from 220 mm approach borehole, C-C-32-5 .... B-2
Fig. B-2 Schematic for labelling reinforcement boreholes. View direction is downhole. Approach boreholes is 220 mm OD. Reinforcement boreholes of 46 mm OD: 1st set of three (yellow) and 2nd set of three (blue). Orientations are labelled according to clock position. Overcoring diameter is indicated (132/124 mm). B-3
Fig. B-3 Images of samples from the 46 mm reinforcement boreholes, C-C-32-5 .... B-4
Fig. B-4 Images of shotcrete section of overcore C-C-32-5-OC with different materials numbered (see text). Hinge is along black scale (cm) marks B-5

Fig. B-5 Images of overcore C-C-32-5-OC. Arrow marks position of shotcrete/bentonite interface B-6

Fig. B-6 Detailed images of overcore C-C-32-5-OC B-7

Fig. B-7 Cutting schematic for subsampling overcores B-8

Fig. B-8 Images of samples cut from 132 mm overcore, C-C-32-5-OC B-8

Fig. B-9 Images of interface region from overcore C-C-32-5-OC, viewed through the epoxy layer B-9

Fig. B-10 Images of cut surfaces from overcore C-C-32-5-OC, viewed through the liquid epoxy layer B-10

Fig. B-11 Images of cut surfaces from overcore C-C-32-5-OC, viewed through a liquid epoxy layer B-12

Fig. B-12 Two quarter cores of shotcrete section from C-C-32-5-c after vacuum sealing B-13

Fig. B-13 Half cores of the bentonite section from C-C-32-5-OC-b B-13

Fig. C-1 Images of samples from the 220 mm approach borehole, C-C-32-6 .... C-2

Fig. C-2 Schematic for labelling reinforcement boreholes. View direction is downhole. Approach boreholes is 220 mm OD. Reinforcement boreholes of 46 mm OD: 1st set of three (yellow) and 2nd set of three (blue). Orientations are labelled according to clock position. Overcoring diameter is indicated (132/124 mm). C-3

Fig. C-3 Images of samples from all six 46 mm reinforcement boreholes, C-C-32-6 .... C-4

Fig. C-4 Images of the borehole wall, associated with C-C-32-6-OC C-5

Fig. C-5 Images of shotcrete section of overcore C-C-32-6-OC with different materials numbered (see text) C-6

Fig. C-6 Images of overcore C-C-32-6-OC. The yellow arrow marks position of the shotcrete/bentonite interface. C-7

Fig. C-7 Cutting schematic for subsampling overcores C-8

Fig. C-8 Images of samples cut from 132 mm overcore, C-C-32-6-OC C-8

Fig. C-9 Images of interface region from overcore C-C-32-6-OC, viewed through the epoxy layer C-9

Fig. C-10 Images of cut surfaces from overcore C-C-32-6-OC, viewed through a liquid epoxy layer C-10

Fig. C-11 Images of cut surfaces from overcore C-C-32-6-OC, viewed through a liquid epoxy layer C-13

Fig. C-12 Quarter cores cut from C-C-32-6 after vacuum sealing. Left: shotcrete sections; middle: shotcrete/bentonite sections; right: bentonite sections C-14

Fig. C-13 Half cores and quarter cores of bentonite section from C-C-32-6-OC-b C-14

1 Introduction and objectives

1.1 The FEBEX project

FEBEX (Full-scale Engineered Barrier Experiment in Crystalline Host Rock) is a research and demonstration project that was initiated by Enresa (Spain).

The aim of the project is to study the behaviour of near-field components in a repository for high-level radioactive waste in granite formations. The main objectives of the project may be grouped in two areas:

- Demonstration of the feasibility of constructing the engineered barrier system in a horizontal configuration according to the Spanish concept for deep geological storage (AGP), and analysis of the technical problems to be solved for this type of disposal method
- Better understanding of the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) processes in the near field, and development and validation of the modelling tools required for interpretation and prediction of the evolution of such processes

The project consists of two large-scale tests (see Fig. 1-1) – "in situ" and "mock-up" (the latter is managed by CIEMAT in Spain) – a series of laboratory tests, and THM and THG modelling tasks.

The full-scale heating test ("in-situ" test), to which this document refers, was performed at the Grimsel underground laboratory in Switzerland, also known as Grimsel Test Site (GTS) or Felslabor Grimsel (FLG in German). A complete description of the FEBEX project objectives and test program may be found in the "FEBEX Full-scale Engineered Barriers Experiment in Crystalline Host Rock. Pre-operational stage summary report" (Fuentes-Cantillana et al. 1998).

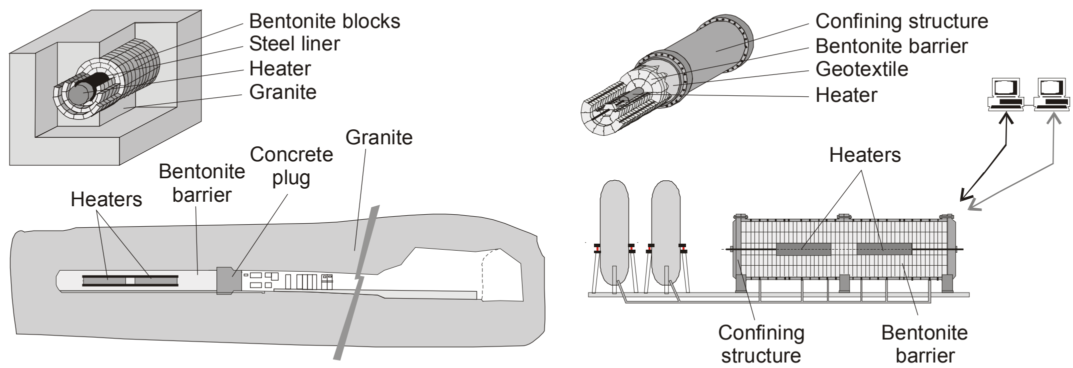


Fig. 1-1 Overall layout of FEBEX "in-situ" test (left) and "mock-up" test (right).

The project started in 1994, and has been supported by the European Commission through consecutive contracts, identified as FEBEX I (contract nº FI4W-CT-95-0006) for the period January 1996 to June 1999, and FEBEX II (contract nº FIKW-CT-2000-00016), from September 2000 to December 2004. Afterwards, NF-PRO took place from January 2005 to December 2007. Finally, in January 2008 the "in-situ" test was transferred from Enresa to a consortium composed of SKB (Sweden), POSIVA (Finland), CIEMAT (Spain), Nagra (Switzerland) and more recently KAERI (South Korea), and named the FEBEXe Consortium, which supports it currently.

The "in-situ" experiment excavation was carried out in 2015 and new partners, interested in taking part in the planned sampling and analysis operations, have been incorporated into the Consortium (now called FEBEX-DP) for that purpose, namely US DOE (USA), Obayashi (Japan), RWM (UK), Andra (France), BGR (Germany) and SURAO (Czech Republic).

1.2 Test configuration during FEBEX I

The installation of the "in-situ" test was carried out at the GTS. A horizontal drift with a diameter of 2.28 m was excavated in the Grimsel granodiorite especially for this experiment using a TBM (a Tunnel Boring Machine). Two electrical heaters, of the same size and of a similar weight as the reference canisters, were placed in the axis of the drift. The gap between the heaters and the rock was backfilled with compacted bentonite blocks, up to a length of 17.40 m, this requiring a total 115'716 kg of bentonite. The backfilled area was sealed with a plain concrete plug placed into a recess excavated in the rock and having a length of 2.70 m and a volume of 17.8 m^3. Fig. 1-2 shows schematically the dimensions and layout of the test components.

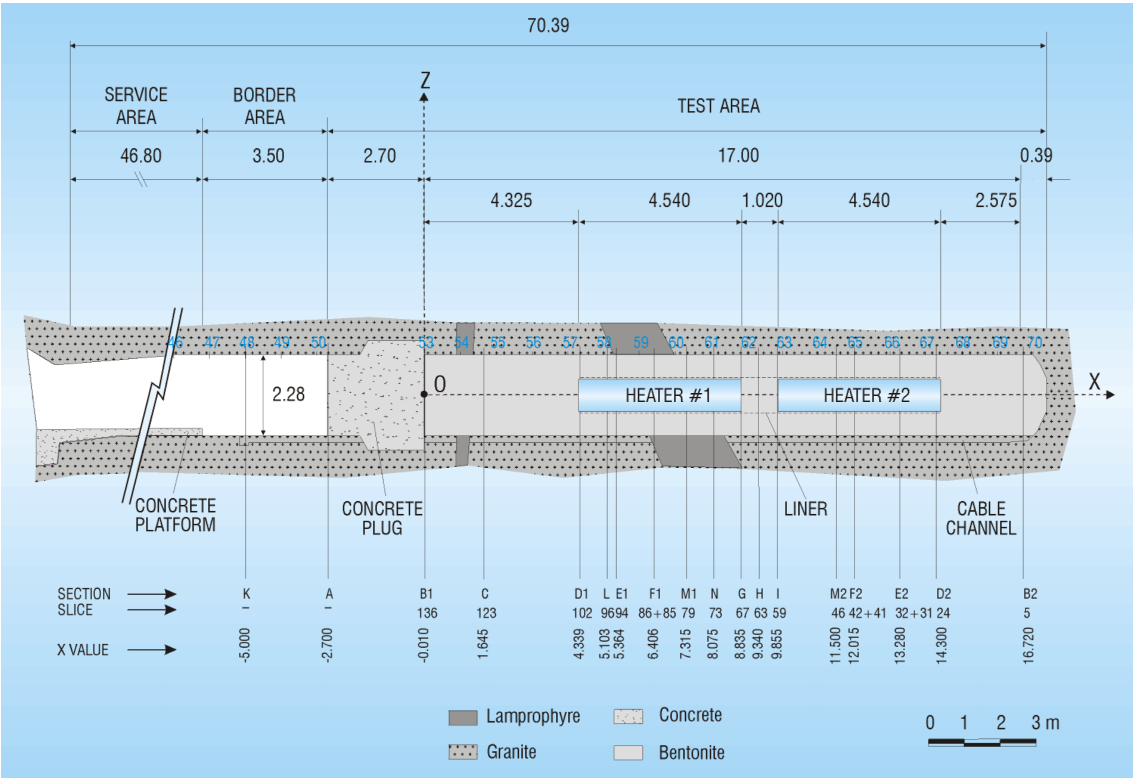


Fig. 1-2 General layout of the FEBEX "in-situ" test (FEBEX I configuration).

A total of 632 instruments were placed in the system along a number of instrumented sections, both in the bentonite buffer and in the host rock, to monitor relevant parameters such as temperature, humidity, total and pore pressure, displacements, ... etc. The instruments were of many different kinds and their characteristics and positions are fully described in the report titled "FEBEX Full-scale Engineered Barriers Experiment in Crystalline Host Rock. Final design and installation of the in-situ test at Grimsel" (Fuentes-Cantillana & García-Siñeriz 1998).

A Data Acquisition and Control System (DACS) located in the service area of the FEBEX drift collected the data provided by the instruments. This system recorded and stored information from the sensors and also controlled the power applied to the electrical heaters, in order to maintain a constant temperature at the heaters/bentonite interface. The DACS allowed the experiment to be run in an automated mode, with remote supervision from Madrid. Data stored at the local DACS were periodically downloaded in Madrid and used to build the experimental Master Data Base.

The construction of the concrete plug was completed in October 1996, and the heating operation started on 28 February 1997. A constant temperature of 100 °C was maintained at the heaters/bentonite interface, while the bentonite buffer slowly hydrated with water naturally issuing from the rock. A complete report that includes both the installation of the test and the results gathered after two years of operation is given in "FEBEX full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock Final Report" (Enresa 2000).

1.3 Dismantling Heater 1 and test configuration afterwards (FEBEX II)

A partial dismantling of the FEBEX "in-situ" test was carried out during the summer of 2002, after 5 years of continuous heating. The operation included the demolition of the concrete plug, the removal of the section of the test corresponding to the first heater, and the sealing with a new shotcrete plug. A large number of samples from all types of materials were taken for analysis. A number of instruments were subsequently dismantled, as well as a few new ones installed. Accordingly, system design was adapted, and the physical layout was changed in order to ease the partial dismantling operation.

The buffer and all components were removed up to a distance of 2 metres from heater #2 to minimise disturbance of the non-dismantled area. A dummy steel cylinder with a length of 1 m was inserted in the void left by heater #1 in the centre of the buffer. Some new sensors were installed in that one additional metre of bentonite buffer.

Additional sensors were introduced in boreholes drilled in the buffer parallel to the drift. To simplify this operation, the new concrete plug was constructed in two phases: an initial temporary plug measuring just 1 m in length, which was built immediately after dismantling, and a second section to complete the plug length to the 3 m planned in the design of the experiment. Unlike FEBEX I, the new plug was a parallel plug, without a recess excavated in the rock, constructed by shotcreting.

The description of the partial dismantling operation is given in the report titled "Dismantling of the Heater 1 at the FEBEX "in situ" test. Description of operations" (Bárcena et al. 2003). The configuration of the test, after completing the partial dismantling operation and construction of the full plug length, is shown in Fig. 1-3.

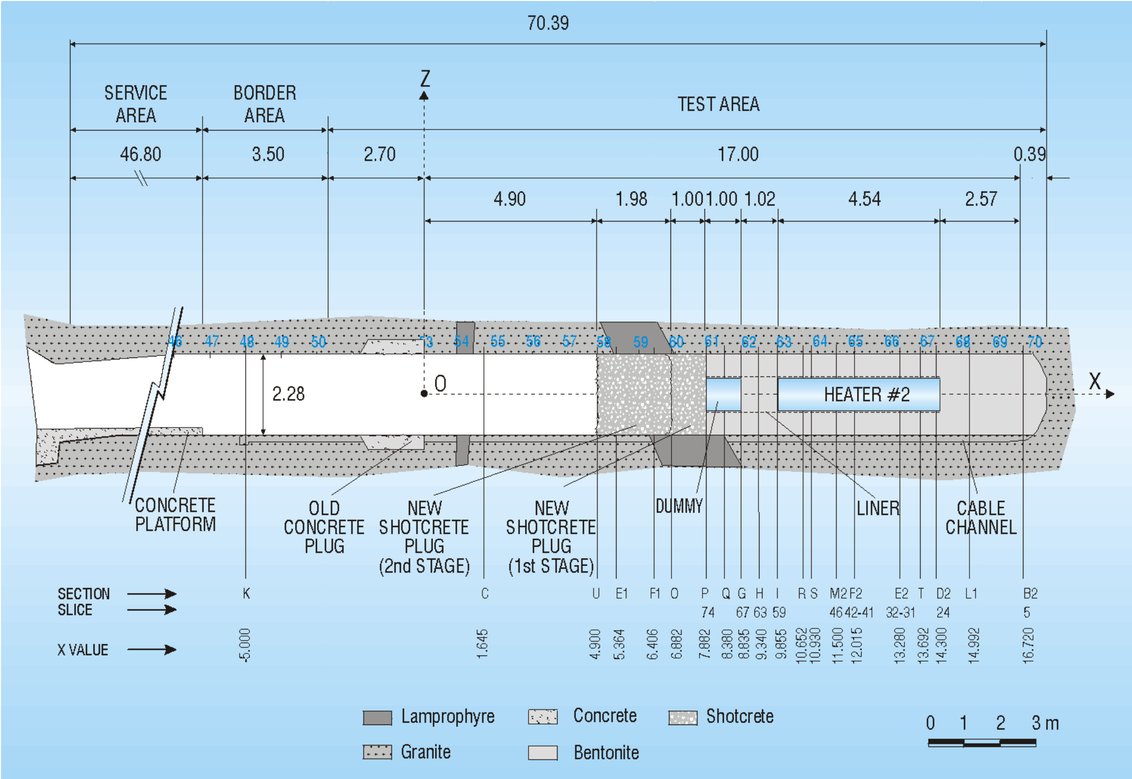


Fig. 1-3 Status of the FEBEX "in-situ" test after the partial dismantling (FEBEX II configuration).

A more comprehensive report that describes the test from the conception up to two years of operation after the partial dismantling is given in the document titled "FEBEX Full-scale Engineered Barriers Experiment. UPDATED FINAL REPORT 1994 – 2004" (Enresa 2006).

1.4 Concept of the dismantling of Heater 2

The objective of the second dismantling operation, carried out throughout 2015, was to dismantle all the remaining parts of the "in-situ" test, including the heater #2. This operation includes carrying out a complete sampling of the bentonite, rock, relevant interfaces, sensors, metallic components and tracers so as to allow the analysis of the barriers' condition after 18 years of heating and natural hydration.

Analytical results will be compared with data obtained from the partial dismantling (Enresa 2006); the monitoring data (Martinez et al. 2016) as well as with the results derived from modelling efforts (Lanyon & Gaus 2013). The results are expected to increase the current knowledge and confidence for the FEBEX-DP partners on bentonite performance with a focus on thermo-hydro-mechanical (THM) and thermo-hydro-chemical (THC) processes as well as on corrosion and microbial activity. The reporting of the laboratory analysis and dismantling results is expected to be complete by the end of 2016 with a final integrated report issued in early 2017.

All details about the planned dismantling operation and sampling program are given in the reference documents: "FEBEX-DP (GTS) Full Dismantling Test Plan" (Bárcena & García-

Siñeriz 2015a), "FEBEX-DP (GTS) Full Dismantling Sampling Plan" (Bárcena & García-Siñeriz 2015b) and its update (Rey et al. 2015).

All sample logs of the dismantling operation are documented in AN 15-578 Sample Log Book 34 to 62 FEBEX-DP (Abós & Martínez 2015).

1.5 Objectives and contents

One of the objectives of FEBEX-DP (FEBEX Dismantling Project) is to obtain adequate sample material of bentonite, concrete, steel liner, metal coupons, select radioactive tracers and various other equipment and instrumentation parts for the intended comprehensive analytical programme (Bárcena, I. & García-Siñeriz 2015a, b). Among the materials of interest are also the interface regions between concrete and bentonite, specifically the interface between the shotcrete plug and the bentonite block section.

Sampling of mechanically weak interfaces requires some form of stabilisation technique. This in turn is a relatively complex and time-consuming procedure with a need for flexibility in work progress and schedule. It was decided to perform the sampling of the concrete plug/bentonite interface prior to dismantling the plug, for at least two reasons: (1) to avoid potential mechanical disturbance of the interface by mechanically forced plug dismantling with a hydraulic hammer, and (2) to complete work ahead of heavy-equipment activities so that delays in the overall workflow could be avoided.

It was decided that the University of Bern, Geological Sciences, would take the technical lead for this sampling task based on previous experience with such drilling techniques at Mont Terri URL and the Grimsel Test Site. The on-site technical team at GTS was chosen for carrying out drilling operations, and this team also has plenty of relevant experience with stabilised overcoring techniques, both at GTS and Mont Terri.

The work described in this report was carried out between 20 February and 26 March, 2015. It was preceded by dismantling of surface equipment on the plug and in its vicinity by Aitemin, and by drilling three boreholes through the shotcrete plug by the GTS on-site drilling team for obtaining concrete samples. Sampling of the interface region was followed by dismantling of the shotcrete plug and sampling of the entire FEBEX installation section-by-section (García-Siñeriz et al. 2016). The heater was still in operation during sampling of the plug/bentonite interface and was turned off before dismantling of the plug started.

2 Sampling technique using stabilised overcoring

This section outlines the technical details of stabilised overcoring and the history and experience of Nagra and associated partners with overcoring techniques to achieve intact interface samples. Initially, a technique for interface stabilisation with resin and fibre glass was developed for the CI (Long-Term **C**ement-Clay **I**nteraction) Project at the Mont Terri rock laboratory for the purpose of retrieving undisturbed interfaces between different types of concrete and either Opalinus Clay or MX-80 bentonite. Details are provided in Mäder et al. (2015) and a summary is published in Jenni et al. (2014). The design allowed to work from a distance of up to 10 m from the interface to be sampled, and to retrieve sample cores of up to 1.6 m length, with a diameter of 101 mm containing multiple interfaces.

2.1 Experience with stabilising fractured rock samples from the GTS

A technique was developed some 20 years ago to retrieve core samples containing fractured rock mostly for the purpose of laboratory experiments and mineralogical/geochemical studies on fault rock. Small-diameter boreholes were placed around the circumference of a future core (No. 1 in Fig. 2-1). These holes were filled with epoxy resin and provided stability and prevented shear forces or core spinning for subsequent drilling. As a second step, a cylindrical groove was drilled that cut across the pilot holes but without breaking the core at its base (No. 2 in Fig. 2-1). Again, the drilled groove was filled with epoxy resin. This annulus of hardened resin provided full protection for the interior of the core. The entire setup was subsequently overcored approximately following the outer envelope of the pilot holes (No. 3 in Fig. 2-1), and the core was forcefully detached at its base and retrieved. A typical size for such a rock core was approximately 170 mm in diameter and 400 mm in length.

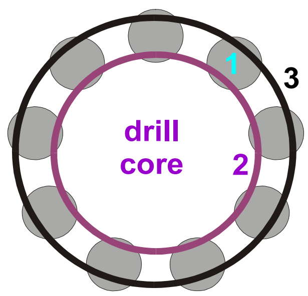


Fig. 2-1 Illustration of the drilling technique for sampling performed in 2001 for the HPF (Hyperalkaline Plume in Fractured Rock) Project. Plan view of drilling arrangement (see text for details).

2.2 Details of stabilised overcoring for claystone and bentonite

The concept tested at the Grimsel Test Site (Fig. 2-1) with several small-diameter boreholes for resin stabilisation arranged in a circular fashion was thought particularly appropriate also for drilling across concrete/bentonite and concrete/claystone interfaces. Six auxiliary boreholes were judged to be sufficient. Rather than just using epoxy resin as reinforcement, it was decided to embed relatively thick-walled fibre glass tubes with epoxy resin, and pre-fill the fibre glass tubes with cement. This would provide excellent stiffness and also make diamond drilling during overcoring much easier than just cutting epoxy resin that tends to be too soft for diamond drilling. Rather than overcoring on the outside of the resin reinforcements it was decided to cut right through these reinforcements with a diameter of 131 mm (double-barrel equipment with additional acrylic liner). This procedure provided optimal stability and specifically allowed drilling bentonite that otherwise would tend to cause clogging. Air tightness of the drilling guides had to be ensured so that the exhaust air would not dissipate and deposit drilling dust. An OD of 220 mm was chosen for the approach boreholes into which the drilling templates were installed. A special reamer was fabricated to produce a squared-off surface at the base of the 220 mm OD approach boreholes for a flush installation of the lowermost drilling template. The drilling templates (Fig. 2-2) were manufactured in segments of 2 m length.

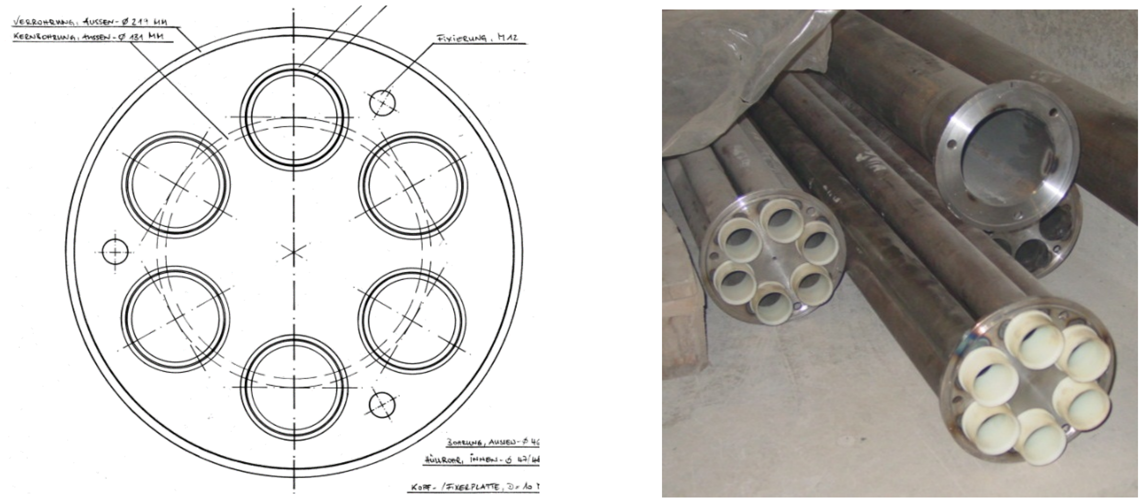


Fig. 2-2 Templates to fit a 220 mm OD borehole used for drilling six 46 mm OD boreholes for inserting fibre glass reinforcements embedded in epoxy resin. Left: dimension drawing. Right: Templates for 46 mm boreholes and 131 mm overcoring diameter. White plastic parts are for coupling drilling guides and centre the core barrel.

A key feature of the stabilisation technique is the glass fibre rods embedded with epoxy resin into 46 mm OD boreholes arranged parallel and in a circular arrangement (Fig. 2-3). The rods were prepared from 2-metre long segments of standard 36/32 mm fibre glass tubes. The tubes were closed off at the lower end. A 6/4 mm flow line for resin injection was inserted in the base of the assembly. The fibre glass rod was filled with rapidly setting cement slurry to provide extra mass and abrasive properties important for overcoring with a diamond drill bit. The top was furnished with a glued-in adapter made of HGW 2082 (a fabric reinforced epoxy-based construction material) furnished with a 30 mm diameter left-hand thread. The adapter at the top was coupled to standard 32 x 1.5 mm OD aluminium installation tubes with a coupling piece made of POM (polyoxymethylene). The purpose of the left-hand thread was to remove the aluminium tubes connected with right-hand threads easily by just turning clockwise and thus undoing the left-hand thread at the top of the fibre glass rods.

Fig. 2-3 Left: 2-meter long fibre glass rods. Middle: Detail of adapter at top (brown, HGW 2082) with a left-hand outer thread and resin injection lines with brass couplings. An aluminium installation tube with a POM coupling piece is seen on the right. Right: Image with borehole camera showing 3 fibre glass rods previously inserted, and 3 just after resin injection and still conncetced to the installation equipment.

The procedure followed for the work at Mont Terri is illustrated below (Fig. 2-4). It included drilling an approach borehole with 220 mm OD, followed by reaming a flat base. Three stabilisation boreholes were drilled and fibre-glass rods embedded in resin. This was repeated for a 2nd set of 3 stabilisation boreholes and rods. The overcoring was performed with 131 mm OD to retrieve a core laminated with resin and fibre glass strips of 101 mm diameter.

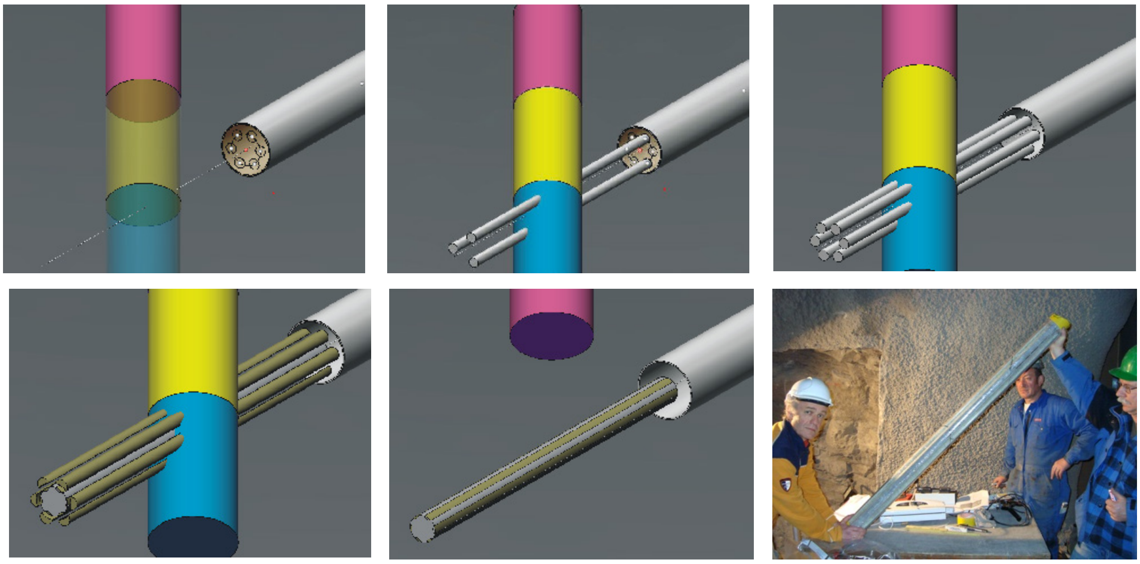


Fig. 2-4 Drilling procedure for stabilised overcoring developed for the CI Project. See text for explanation. Lower centre image: yellow and blue blocks were removed for better visibility.

2.3 Adaptation of the overcoring procedure for FEBEX-DP

The procedures described above were slightly modified for the FEBEX-DP circumstances. The aim was to use relatively small drilling equipment, core barrels with thin cutting segments (without core catcher), and only a single-barrel tool for overcoring. Compared to the example outlined in Figure 2-4, the cement-bentonite interface at FEBEX is oriented perpendicular to the horizontal drilling direction. Also, drilling horizontally required the use of small packers for resin injection, as opposed to simply using gravity in case of the example shown above.

The procedure is detailed below and illustrated in Figure 2-5. A schematic of the drilling and stabilisation sequence is shown in the central image on the 3rd row.

- The basic geometry of the setup from Mont Terri (Figs. 2-2, 2-3) was adopted, using the existing drilling guides fabricated for the CI Project, Mont Terri URL. The procedure of drilling and filling 3 reinforcement boreholes at a time was also adopted.
- Wet drilling was employed for drilling the approach borehole in concrete with 220 mm diameter, to ca. 2.7 m depth from the plug surface, leaving ca. 30 cm of shotcrete before the interface with bentonite. Core was broken manually with crow bar and long chisels.
- A smaller-diameter pilot borehole was drilled for the 2nd and 3rd overcoring. This lessened the forces required for breaking core, and also allowed the use of a heavy-duty mechanical packer to assist in the retrieval of core segments.
- Extra distance from the interface was needed to allow for the length required by the packers (ca. 15 cm).
- A first set of three reinforcement boreholes 12, 4 and 8 o'clock orientation was drilled first.
- Drilling of the reinforcement boreholes of 46 mm OD diameter was done initially by wet drilling for the first 20 cm in the shotcrete, and then by compressed air cooling. This proved to be difficult because of the wetness left in the concrete section that disturbed the exhaustion of the bentonite dust during drilling in bentonite. All small boreholes were therefore dry-drilled after the first one.
- Drilling the 46 mm boreholes in bentonite to a depth of ca. 40 cm from the interface proved to be relatively easy. The coarse-grained Febex-type bentonite could be cut and exhausted rather efficiently. This drilling depth would recover a little more than the thickness of three bentonite block layers (12.5 cm each).
- The fibre glass rods were inserted with small packers at their proximal ends. A resin injection line and resin back-flow line was used to inject resin into the space between the fibre glass rod and bentonite.
- Injection of resin was preceded by applying moderate vacuum to the back-flow line as best as possible. The progress of resin injection was monitored by placing the resin injection tank on a balance. Injection was driven by compressed nitrogen.
- A 2nd set of three boreholes were drilled and reinforced at 2, 6, and 10 o'clock orientation.
- Overcoring with 132 mm OD was done with the existing drilling guides. The first 30 cm in concrete could be drilled wet in principle, but this was done only for the first core. Dry drilling turned out to be quite efficient also for the shotcrete plug. Drilling through the fibre glass reinforced bentonite section was quite efficient.
- It was expected that the core would be stuck in the core barrel after drilling beyond the fibre glass reinforcements. This was not the case – all three cores remained firmly attached to its bentonite base. The cores were loosened by long wedges and some torsion until they could be retrieved with an empty core barrel.
- The empty boreholes (132 mm diameter, ca. 70 cm long) were closed with a dummy fabricated from PVC.

- Temperatures across the interface were measured at different positions in the central borehole after overcoring (the heater was still in operation during overcoring, and these are the only direct measurements at the interface position).
- The expected time required was 5-6 working days for each of the three overcoring boreholes.

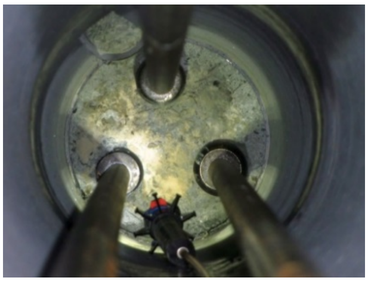

Pilot borehole for retrieving cores

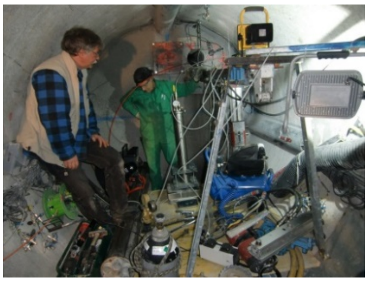

Approach borehole, 220 mm OD

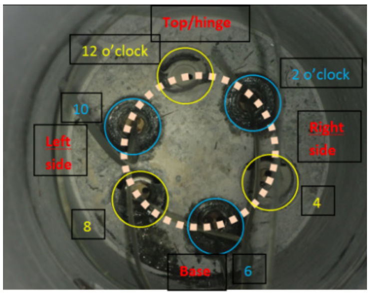

Flat base at 2.66 m depth


Drilling template for 6 x 46 mm


Packer systems with fibre glass rods


Emplacement of packer systems


Resin injection;
drill next 3 x 46 mm



After stabilisation, with trace line for overcoring.


After overcoring,
before core retrieval


Retrieving core from C-C-32-5

Borehole after overcoring with remnants of resin and fibre glass

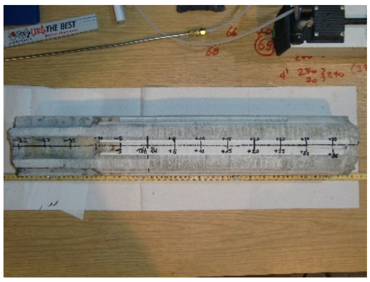

Extracted core from C-C-32-6

Fig. 2-5 Procedure for fibre glass reinforced overcoring of shotcrete/bentonite interface samples (see text for explanation).

2.4 Equipment used for overcoring interfaces

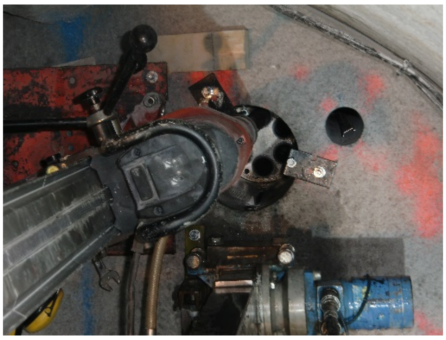
Drilling equipment (Fig. 2-6) included a SIG SL14 hydraulic motor (460 Nm) on a lightweight hydraulic rig (SIG Mounty 2000/90H, 12 kN retrieving force, 1.3 m travel) and a SIG Mounty 91H hydraulic generator (22 kW, 200 bar), all supplied by LUMESA. The rig was equipped with a hydraulic clamp (HZ100, 100 kN). The drill rig was left in place once positioned for drilling the approach borehole (220 mm) and was also used for overcoring (132 mm) after reinforcement with resin and fibre glass.

Small 46 mm diameter reinforcement boreholes were drilled with a small Hilti electric drill and a standard short manual rig mounted on a steel plate that was bolted to the concrete surface and that had to be shifted and re-mounted for all 6 small boreholes.

The hydraulic generator for the LUMESA equipment was positioned outside the FEBEX gallery to reduce noise emission. This required long hydraulic extension hoses, and some associated loss of power due to friction. Compressed air for dry drilling was generated at the drilling site. A ventilation system was installed to remove dust. Dust levels were elevated during dry-drilling.

Core barrels from Hilti were used, with standard cutting segments fitted to custom-length barrels, covering a range of lengths from 40 - 160 cm.

SIG (LUMESA) hydraulic motor mounted on rig



Hilti drill used for 46 mm boreholes

Drilling 46 mm borehole with Hilti machine and template.

Preparation for overcoring with 132 mm core barrel (red) and drilling template

Fig. 2-6 Drilling equipment used for interface sampling.

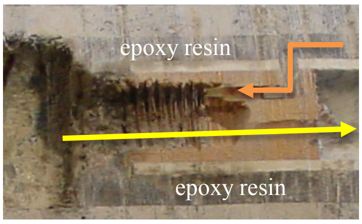
Assemblies with fibre glass tubes for stabilisation with epoxy resin were composed of the following parts:

- Fibre glass tube, 30 mm OD, 24 mm ID
- Adapter piece made of HGW (fabric reinforced epoxy construction material) to connect the fibre glass rod to the packer with a left-hand inner thread.
- A standard COMDRILL mechanical packer to fit 46 mm diameter (CMP 46–150), with extensions to manipulate the packer from a distance of ca. 3 m. The expandable packer sleeve (rubber) is 15 cm long.
- Resin injection line (6/4 mm polyamide)
- Resin back-flow line (4/3.2 mm polyamide)

The adapter piece (HGW) is fitted with an internal left-hand thread to connect to the mechanical packer (Fig. 2-7, top). The left-hand thread allows to undo this joint after resin injection with clock-wise rotation, e.g. without undoing other right-hand threaded connections. The adapter also contains a 6 mm and 4 mm borehole for the resin injection and resin back-flow lines (Fig. 2-7, top). The 4 mm borehole does not feed through the adapter piece but leads at right angle through the fibre glass tube to allow resin to flow back.

In a first step, the resin back-flow line is glued into the adapter piece. Then, the injection line is fed through and also glued in. Next, the adapter with flow lines is glued into one end of the fibre glass tube. Then, the tubes are filled with cement slurry for easy drilling during overcoring (Fig. 2-7).

On-site preparation includes cutting the cement-filled fibre glass rods to the drilled length, and mounting them on the packer (left-hand thread, Fig. 2-7), feeding the flow lines through the stem and sleeve of the extension tubes for the mechanical packer. Beforehand, a groove is cut into the resin injection line close to the packer to provide a breaking point when pulling the resin lines after stabilisation and before overcoring. Finally, the rubber part of the packer is generously greased for easy removal of the packers after resin injection and polymerisation.



Section of adapter piece after overcoring with flow of resin indicated. Fibre glass tube (white) extends to the right, packer was on the left

Fibre glass rods filled with cement slurry

Cutting a groove into a resin injection line as breaking point pulling resin lines afterwards

Attaching fibre glass rod to packer

Resin flow lines emerging from the extended stems of packers

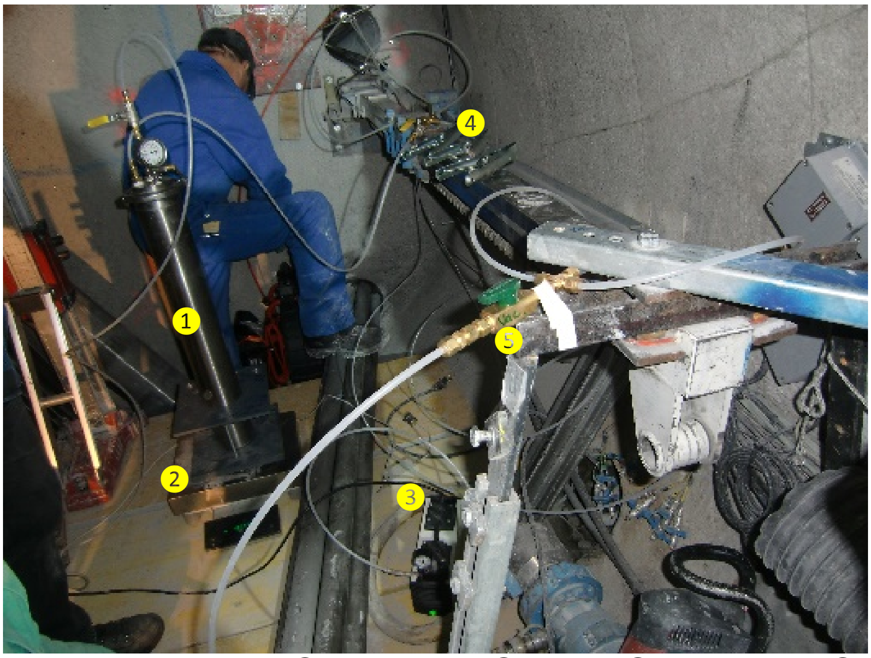
Three packer assemblies ready for installation

Fig. 2-7 Packer assembly with fibre glass reinforcements.

The resin injections system consisted of the following parts:

- Pressure tank with PVC insert to hold the resin mix
- 24 kg capacity high-resolution balance for the injection tank to monitor progress of resin injection
- Compressed nitrogen to apply gas pressure for resin injection
- Injection valve followed by a distribution fitting (Swagelok® brass fittings) to feed three resin injection lines simultaneously
- Vacuum pump (membrane pump from KNF Neuberger) to which initially all back-flow lines are connected until arrival of resin
- Clamps for back-flow lines with which a specific resin injection can be stopped if required
- Equipment for mixing resin (Sikadur® 52)

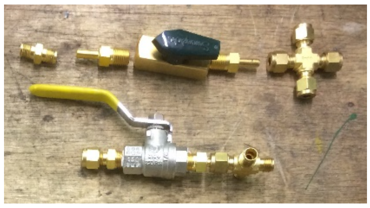
Figure 2-8 illustrates the setup for resin injection with system components as listed above. Also shown are how the quality of resin injection could be inspected after removal of the packer systems. The gap between fibre glass and bentonite could not be completely filled in several cases, and an air-filled gap remained along the top. This was mainly due to the fact that applying vacuum was not always effective presumably due to air leakage through shotcrete bypassing the packer.



Setup for resin injection (C-C-32-4). ❶ injection tank; ❷ balance; ❸ vacuum pump; ❹ Injection valve; ❺ valve to collect back-flow lines leading to vacuum pump

Reinforced 46 mm borehole after removal of packer. Resin is completely filling region between fibre glass rod and bentonite. The slimy appearance of the shotcrete surface is due to grease used around the packer

Reinforced 46 mm borehole after removal of packer and resin back-flow line. There is a gap not filled by resin along the upper side of the borehole. HGW adapter is visible in the centre (buff), and the fibre glass tube (white)



Resin injection ball valves with Swagelok® cross fitting for 3 resin injection lines

Fig. 2-8 Details of resin injection setup

It turned out to be nearly impossible to insert the packer systems as purchased from COMDRILL. The reason was that the small tolerance chosen was not sufficient for the packer to slide into the shotcrete studded with steel fibres. It was therefore necessary to dismantle the packers and grind down the rubber sleeves by about 2 mm in diameter.

It also turned out that the resin injection lines were tough to break at the pre-grooved location at the base. The reason for this was that the polymerized resin contained in the flow lines was providing extra strength. A special tool was therefore used in form of a small metal plate containing a hole with sharp edges to fit the resin line. This plate was connected to a string, slid down along the resin line to the packer and then the resin line could be snapped and ripped by pulling on the string.

2.5 Measurement of temperatures at the bentonite/plug interface

Temperatures were measured in all three overcoring boreholes at four locations across the shotcrete/bentonite interface. These temperatures are close to the in-situ temperatures because the heater was not turned off yet at the time of drilling. The readings for C-C-32-4 were measured two days after drilling, which may cause slightly lower readings, although the borehole was provisionally closed to prevent excessive heat loss. Data are presented in section 3.4.

The equipment was a self-made taped foam cylinder that contained two exposed metal-sheeted type K thermocouple tips (Fig. 2-9). The two measuring points were 40 cm apart. The equipment was placed into the overcoring borehole with the thermocouple tips located along the base of the borehole and insulated towards air. Readings were taken after 30-60 minutes when a stable temperature was reached. The equipment was repositioned once to obtain readings at four locations across the interface. A calibration check was made at room temperature against one another and against a standard before the measurements. Temperature readings are thought to be accurate to ±0.5 K. Deviations induced by drilling, removal of core mass, and exposure to air may have led to small but not exactly known shifts in temperature and gradients compared to in-situ conditions.

The equipment was originally intended to fit into one of the 46 mm boreholes for optimal measurement conditions. The steel fibres contained in the shotcrete prevented inserting the tool into these boreholes, and so the larger overcoring boreholes were used instead.

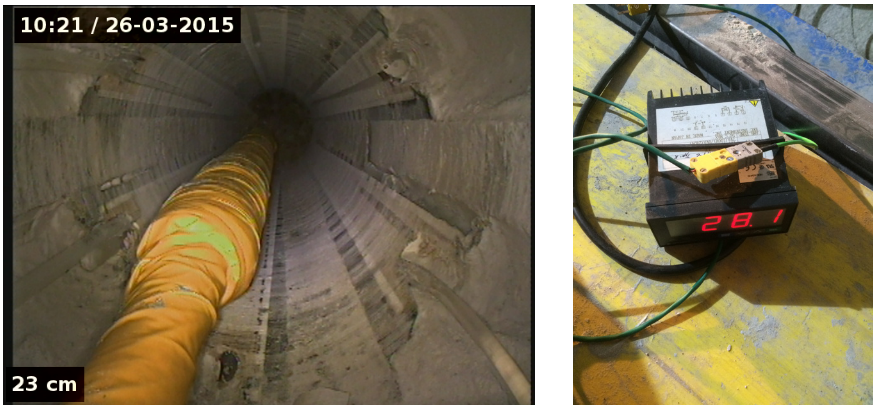


Fig. 2-9 Equipment used for temperature measurement.

2.6 Temporary sealing of sampling boreholes

All three overcoring boreholes were sealed with a heavy-walled PVC dummy that was pushed into the 132 mm OD borehole. This was done to prevent loss of moisture during dismantling of the plug. The dummies were fabricated from thick-walled industrial-grade PVC tubes. A PVC stopper was pushed in on one side to close the cylinders.

The closed cylinders were pushed in with the Lumesa hydraulic rig with full force (1-2 tons).

PVC dummy, with one end closed

PVC dummy emplaced in C-C-32-4

Fig. 2-10 Equipment used for sealing of sampling boreholes.

3 Field work

Drilling operations for specialised sampling of shotcrete/bentonite interfaces were performed before the plug was dismantled and before the heater was turned off. Site preparation included the removal of equipment and instruments at the plug surface by Aitemin (García-Siñeriz et al. 2016). Subsequently, the on-site drilling team installed a work platform and a ventilation system. The outside surface of the shotcrete plug represents sampling section 32 (Fig. 3-1) and this is used as root name for all boreholes and samples recovered by drilling from this level, regardless of the depth location.

Table 3-1 lists the time table for the three overcoring boreholes. Work was preceded by three boreholes drilled across the plug for sampling concrete. The layout of section 32 (plug surface, Fig. 3-1) shows the planned locations of the three locations at which the stabilised interface sampling was performed (large purple circles). The image on the right shows the borehole locations after completion of work. Borehole C-C-32-5 was slightly shifted to the left (ca. 5 cm) compared to the original plans to provide sufficient clearance for drilling operations.

Tab. 3-1 List of sampling boreholes executed from section 32

Time period	Borehole	Activity
17.02.2015-18.02.2015	C-C-32-1	Sampling of shotcrete
18.02.2015-19.02.2015	C-C-32-2	Sampling of shotcrete
19.02.2015	C-C-32-3	Sampling of shotcrete
24.02.2015-03.03.2015	C-C-32-4	Sampling of shotcrete/bentonite interface
04.03.2015-11.03.2015	C-C-32-5	Sampling of shotcrete/bentonite interface
16.03.2015-26.03.2015	C-C-32-6	Sampling of shotcrete/bentonite interface

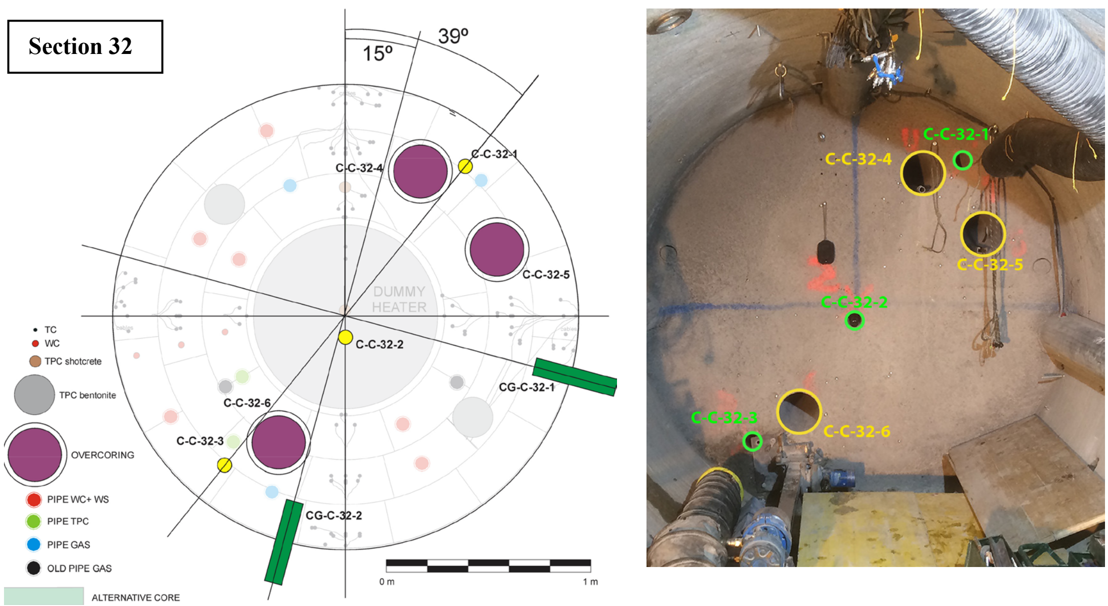


Fig. 3-11 Layout for sampling shotcrete/bentonite interface from section 32 (plug surface)

The drilling locations were chosen so as not to interfere with the steel dummy located in the central part (Fig. 3-2) behind the plug, and also not to interfere with any equipment contained in the plug and in the first few sections of bentonite. The steel dummy marks the location of the first heater that was removed during the first excavation period in 2002. Fig. 3-2 shows the approach boreholes of 220 mm OD, and the overcoring section of 132/124 mm OD/ID. The shotcrete plug is composed of two sections (Fig. 3-2): (1) a 1-meter thick first section containing steel fibres and emplaced next to the bentonite, and (2) a 2-meter thick section not containing steel fibres. The two sections are separated by an impermeable sealing layer of 1-2 cm thickness.

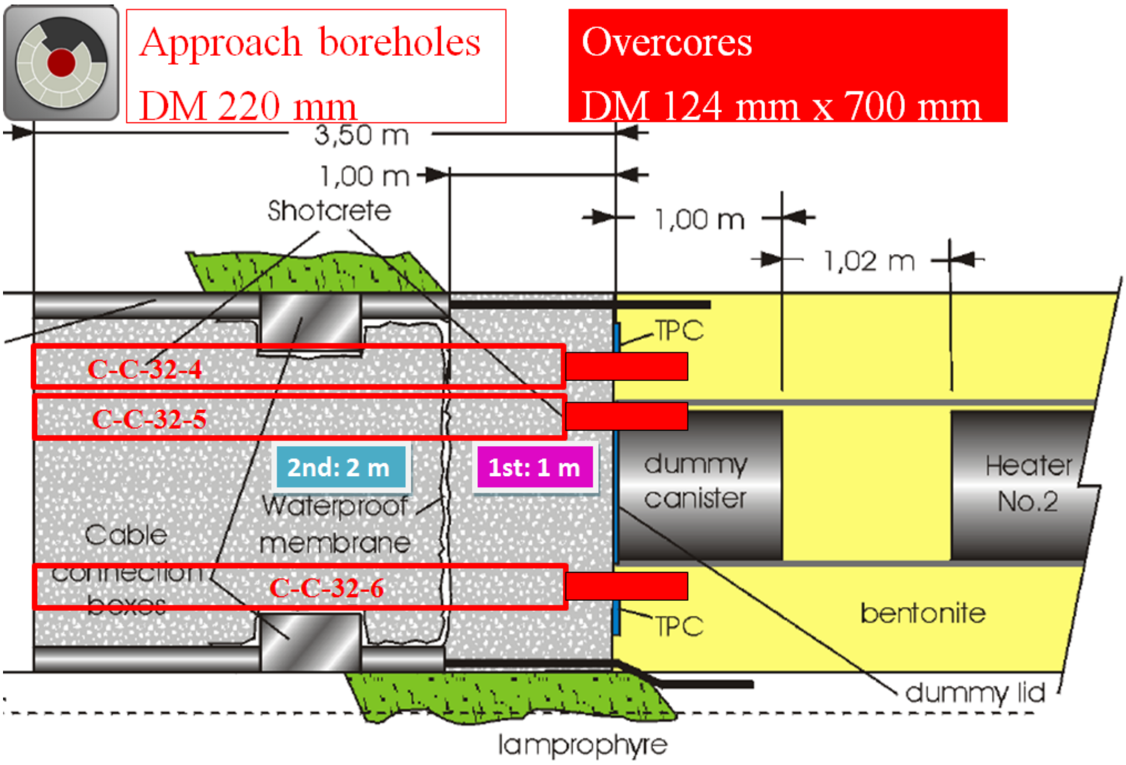


Fig. 3-2 Vertical section showing the locations for sampling plug/bentonite interfaces. The final as-emplaced plug thickness is 3 m.

Drilling operations for stabilised coring started 24 February, 2015, with C-C-32-4 (Tab. 3-1, Fig. 3-1) and were completed by 26 March, 2015, with C-C-32-6. All cores were retrieved in a perfect state of physical and chemical integrity.

Table 3-2 is a summary of borehole parameters and drilled depths for the three boreholes for retrieving the plug/bentonite interfaces. All length measurements are relative to the plug surface (section 32).

Tab. 3-2 Summary of borehole paramaters and drilling depths.

Borehole	Approach in shotcrete	Stabilisation with fibre glass and epoxy resin	Overcore containing interface
	OD = 220 mm	OD = 46 mm	OD = 132 mm Core DM: 124 mm
C-C-32-4	0 – 2.66 m	6 x 2.66 – 3.34 m	2.66 – 3.35 m
C-C-32-5	0 – 2.70 m	6 x 2.70 – 3.38 m	2.70 – 3.40 m
C-C-32-5	0 – 2.75 m	6 x 2.75 – 3.40 m	2.75 – 3.41 m

The field team included Urs Mäder (technical lead, sampling), Hans Abplanalp and Toni Baer (drilling team), Kai Detzner (documentation, technical support, sampling), and Florian Kober (FEBEX-DP project PM, general support).

3.1 Drilling borehole C-C-32-4

Drilling C-C-32-4 started 24 February and was completed 3 March 2015 with retrieving the first stabilised shotcrete/bentonite interface.

Drilling the approach borehole in shotcrete

There were no major difficulties in drilling the approach borehole (220 mm) to a depth of 266 cm, but a number of minor issues:

- Breaking core was not easy, especially across the elastic but tenacious sealing layer, and within the front section containing steel fibres. The movement induced by a chisel/crow bar was not sufficient to break all steel fibres. A central small borehole had to be drilled into the last core section that could not be removed. A heavy-duty packer was used that allowed to pull the core after breaking it at its base with a chisel. Maximum pulling force of 1-2 tons delivered by the Lumesa hydraulic rig was required to separate the core held by steel fibres.
- A pilot borehole was drilled first for all subsequent approach boreholes so that a packer could be used to pull core if needed in addition to prying with chisels.
- An empty borehole was encountered in the front section of the plug. It was a remnant of a sampling borehole used for concrete quality tests performed after installing the first section of the plug. This borehole ended 35 cm short of the interface, at the same level as the approach borehole.

Some features of the shotcrete core and borehole are illustrated in Fig. 3-3, and more images of the core material are provided in appendix A.

Shotcrete core from 0-245 cm. Arrow points to deep end of borehole.

Core segment partially retrieved from borehole with white sealing layer separating the two plug sections.

End of approach borehole at 266 cm depth. Old sampling borehole is located at top left.

Approach borehole before the last core segment was pulled out. Old sampling borehole is located at top left. White sealing layer marks 200 cm depth.

Close-up of the end of the old sampling borehole (ca. 7 cm DM). The shotcrete surface appears perfectly fresh even though it was drilled in 2002.

Shotcrete core from 185-266 cm. Arrow points to deep end of borehole. The white sealing layer separates the two plug sections. The scale is drawn along the hinge line.

Detail of deep end of shotcrete core. Steel fibres are well visible, and are causing difficulties to pry and retrieve core segments.

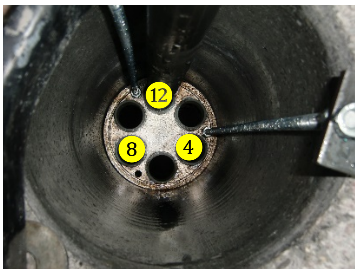
Fig. 3-3 Images from the approach borehole and shotcrete core, C-C-32-4.

Drilling the 46 mm boreholes for stabilisation with fibre glass and epoxy resin

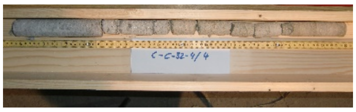
Drilling of the first three 46 mm reinforcement boreholes was performed 26 February, 2015, followed by installing the packer systems with fibre glass rods and resin injection, as described in section 2.4 and shown in Figure 3-4. The boreholes were located at 12, 4 and 8 o'clock positions. A second set of three boreholes at 2, 6 and 10 o'clock positions were drilled and equipped on 27 February, and resin injection was performed on 2 March, 2015.

Core quality for the shotcrete section was generally good, but segmentation in the bentonite section was significant, nevertheless core loss was usually minimal. A likely cause was that the core barrel had too much play in the drilling guide and thus was not rotating smoothly. This play was reduced in later samplings by inserting a reducing bushing made of POM at the deep end of the drilling guide. Core quality was not a major issue because sampling these cores was not part of the original sampling plan.

Core samples from all six small boreholes (ca. 40 mm core diameter) were inspected and vacuum-packed (details in section 5 and appendix A). A sample list and details of drilled depths and positions of shotcrete/bentonite interface are listed in section 6.



Drilling template for 46 mm boreholes. Clock position indicated.



Core retrieved from C-C-32-4/4, i.e. from the 4 o'clock position. Shotcrete section is on the left, segmented bentonite on the right side.


Core retrieved from C-C-32-4/4 after vacuum packing

Deep end of C-C-32-4/8 in bentonite. The diameter is 46 mm


Packer systems with fibre glass rods (white) ready for installation


Installed reinforcements, just before resin injection.

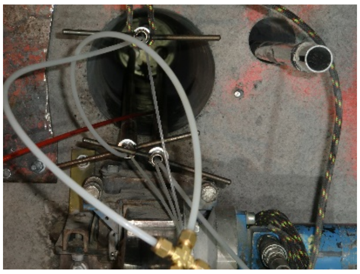

Resin injection was carried out simultaneously for 3 reinforcements at a time. Three handlebars mark the end of the mechanical packer systems.


Image after removal of packers of the first 3 reinforcements at 12, 4 and 8 o'clock orientation, with two resin flow lines still attached.


Image after the second set of 3 reinforcements installed at 2, 6 and 10 o'clock positions. Wetness is from small outflows of groundwater from the shotcrete section.

Detail of small outflow of porewater from shotcrete out of borehole C-C-32-4/8. The source is from within shotcrete and not from the interface region

Detail of borehole at 12 o'clock position. A gap is seen at top where resin is not present (yellow arrow)

Detail of boreholes located at 10 and 4 o'clock position. Gap is seen at top where resin is not present (yellow arrow). The silvery reflectance marks the resin, caused by the grease that was used to separate the resin from the steel end-plate of the packer.

Fig. 3-4 Images from drilling stabilisation boreholes and placing reinforcements, C-C-32-4

Overcoring and retrieving the core sample with shotcrete/bentonite interface

Overcoring with 132 mm OD was started 3 March, 2015 (Fig. 3-5). The core remained firmly attached after reaching a depth just beyond the extent of resin and fibre glass reinforcements. The core was loosened by gently prying with chisels, and could be recovered eventually with the core barrel. It was extracted, temporarily wrapped in plastic and carried to the sample preparation table located just outside the FEBEX gallery. This completed the overcoring of the shotcrete/bentonite interface C-C-32-4-OC. All overcores have the suffix OC to their name for clarity

Details of sample treatment are provided in section 4, and detailed images of the overcore in appendix A.

Ready for overcoring with 132 mm core barrel inserted into drilling guide.

View after completion of drilling with core still firmly attached to its bentonite base.

Temporary protection of core for transport from borehole to sample preparation table.

Core C-C-32-4-OC after marking hinge line, and before packing.

Fig. 3-5 Images from overcoring, C-C-32-4

3.2 Drilling of C-C-32-5-OC

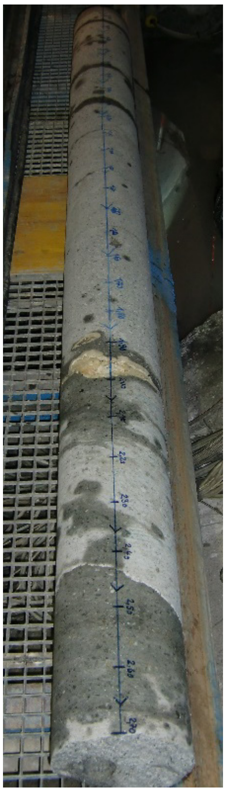
Drilling C-C-32-5 started on 4 March and was completed by 11 March 2015 with retrieving the second stabilised shotcrete/bentonite interface.

Drilling the approach borehole

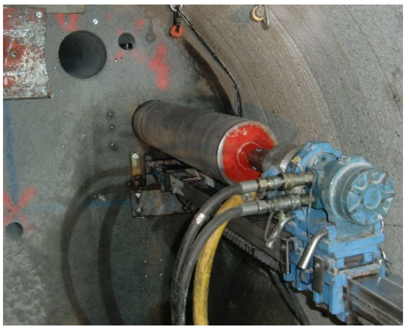
There were no major difficulties in drilling the approach borehole (220 mm) to a depth of 270 cm (Fig. 3-6). This time, a 46 mm pilot borehole was drilled first to a depth of 270 cm in order to use a heavy-duty packer for pulling the core in addition to prying with chisels.

Some stainless steel tubes were intersected at 185 cm depth just before the sealing layer (Fig. 3-6). Apparently, these lines connected to some equipment became loose, detached from the gallery wall and became entangled in the shotcreting action.

Some features of the shotcrete core and borehole are illustrated in Fig. 3-6, and more images of the core material are provided in appendix B.



Shotcrete core from 0-270 cm. Arrow points to deep end of borehole.



Lumesa drilling machine and rig during drilling of 220 mm approach borehole in shotcrete.

End of approach borehole at 270 cm depth. End of pilot borehole (46 mm) is seen at same depth.

Sealing layer (white) and 1st plug section towards end of borehole. White spots section are from equipment (see image on right).

Irregular sealing layer positioned at 195 cm separating plug sections. White spots contain steel tubing that was caught in shotcreting activity.

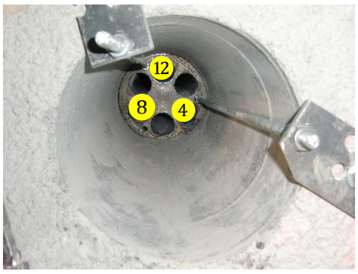
Fig. 3-6 Images from approach borehole and shotcrete core, C-C-32-5

Drilling the 46 mm boreholes for stabilisation with fibre glass and epoxy resin

Drilling of the first three 46 mm reinforcement boreholes was performed on 9 March, 2015, followed by the installation of packer systems with fibre glass rods and resin injection, as described in section 2.4 and shown in Figure 3-7. The boreholes were located at 12, 4 and 8 o'clock positions. A second set of three boreholes at 2, 6 and 10 o'clock positions were drilled and equipped on 10 March, and resin injection followed the same day.

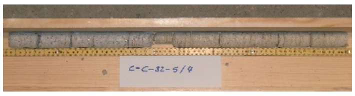
Core quality in the bentonite section did improve due to reducing the play of the 46 mm drilling barrel in the drilling guide. This resulted in less segmentation. Core quality was not a major issue because sampling was not part of the original sampling plan.

Core samples from all six small boreholes (ca. 40 mm core diameter) were inspected and vacuum-packed (details in section 5 and appendix B). A sample list and details of drilled depths and positions of shotcrete/bentonite interface are listed in section 6.



Drilling template for 46 mm boreholes. Labelling is according to clock position.


Drilling of C-C-32-5/4 with Hilti drilling machine.

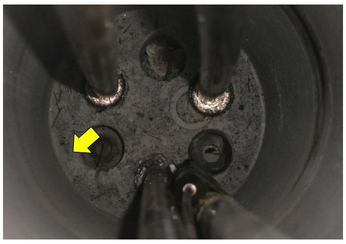

Core retrieved from C-C-32-5/4, i.e. from the 4 o'clock position.Shotcrete section is on the left, bentonite on the right side.

Deep end of C-C-32-5/12 in bentonite. The diameter is 46 mm.

Bentonite/shotcrete interface in C-C-32-5/12. The diameter is 46 mm.

Installed reinforcements, just before resin injection.


Resin injection was carried out simultaneously for 3 reinforcements at a time.


Second set of 3 reinforcements installed at 2, 6 and 10 o'clock positions. Trace of the end of the 46 mm pilot borehole is visible close to 2 o'clock reinforcement.

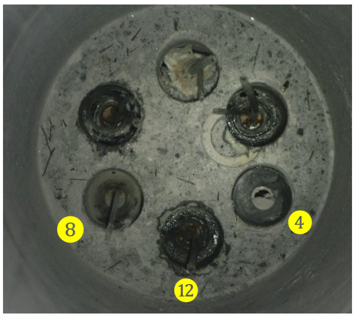
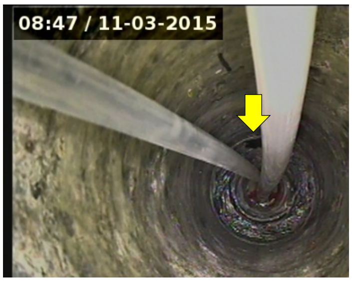


Image after removing packers – all boreholes reinforced. Some remnants of resin lines visible

Reinforcement at 12 o'clock: air gap along top (yellow arrow).

Reinforcement at 10 o'clock: small air gap along top (yellow arrow).



Reinforcement at 2 o'clock: small air gap along top (yellow arrow).

Fig. 3-7 Images from drilling stabilisation boreholes and placing reinforcements, C-C-32-5.

Overcoring and retrieving the core sample

Overcoring with 132 mm OD was started on 11 March, 2015 (Fig. 3-8). The core remained firmly attached after reaching a depth just beyond the extent of resin and fibre glass reinforcements. The core was loosened by gently prying with chisels, and eventually could be recovered with the core barrel. It was extracted, temporarily wrapped in plastic and carried to the sample preparation table located just outside the FEBEX gallery. This completed overcoring of the shotcrete/bentonite interface C-C-32-5-OC.

Details of sample treatment are provided in section 4, and detailed images of the overcore in Appendix B.

View after completion of drilling with core still firmly attached to its bentonite base.

Temporary protection of core for transport from borehole to sample preparation table.

Measuring temperature along the wall of the overcoring borehole.

Borehole after inserting PVC sealing plug.

Fig. 3-8 Images from overcoring, C-C-32-5

3.3 Drilling of C-C-32-6-OC

Drilling C-C-32-6 started on 16 March and was completed by 24 March 2015 with retrieving the third and last stabilised shotcrete/bentonite interface.

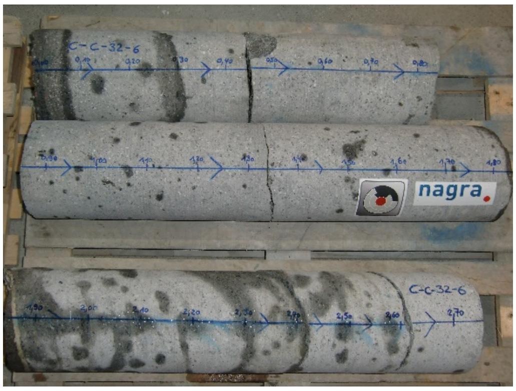
Drilling the approach borehole

There were no major difficulties in drilling the approach borehole (220 mm) to a depth of 275 cm (Fig. 3-9), carried out 16 to 17 March. A 46 mm pilot borehole was drilled first to a depth of 270 cm in order to use a heavy-duty packer for pulling the core in addition to prying with chisels. The sealing layer was encountered at a depth of 1.95 m. The last core rip left an uneven surface and a flat plate reamer was used to grind down the surface in preparation for drilling the reinforcement boreholes.

Some features of the shotcrete core and borehole are illustrated in Fig. 3-9, and more images of the core material are provided in appendix C.

Installation and alignment of drilling rig.

End of approach borehole at 275 cm depth. A flat reamer was used to smoothen the borehole end.



Shotcrete core from 0-275 cm. Arrow points to deep end of borehole.

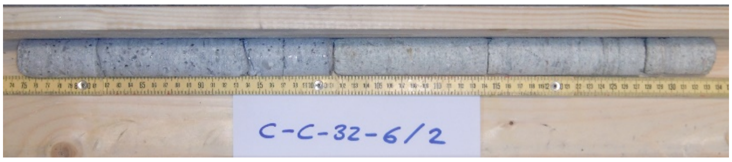
Sealing layer positioned at 195 cm separating plug sections.

Fig. 3-9 Images from approach borehole and shotcrete core, C-C-32-6

Drilling the 46 mm boreholes for stabilisation with fibre glass and epoxy resin

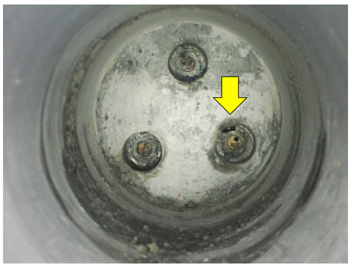
Drilling of the first three 46 mm reinforcement boreholes was performed on 19 March, 2015, followed by installing the packer systems with fibre glass rods and resin injection, as described in section 2.4 and shown in Figure 3-10. The boreholes were located at 12, 4 and 8 o'clock positions. A second set of three boreholes at 2, 6 and 10 o'clock positions were drilled and equipped on 24 to 25 March, and resin was injected on 25 March, 2015.

Core quality was good and similar to that of C-C-32-5. Core samples from all six small boreholes (ca. 40 mm core diameter) were inspected and vacuum-packed (details in section 5 and appendix C). A sample list and details of drilled depths and positions of shotcrete/bentonite interface are listed in section 6.



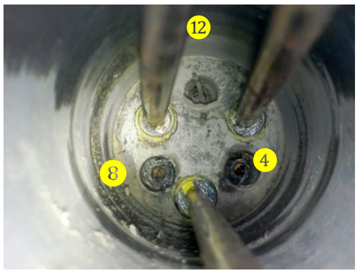
Core from 46 mm borehole at 2 o'clock orientation from the 2nd set of 3 boreholes.

Packers (sleeves covered in grease) with fibre glass rods (white).

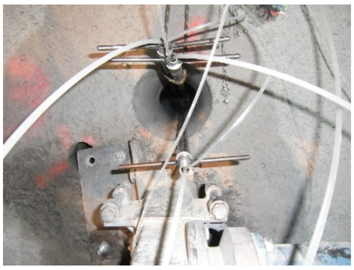


After first set of reinforcements. Small air gap is visible (arrow).

After drilling 2nd set of 3 boreholes 46 mm OD.



Packers installed, before resin injection.



Resin injection was carried out simultaneously for 3 reinforcements at a time.

Image after removing packers - all boreholes reinforced. Some remnants of resin lines visible.

Fig. 3-10 Images from drilling the stabilisation boreholes, C-C-32-6

Overcoring and retrieving the core sample

Overcoring with 132 mm OD was started on 26 March, 2015 (Fig. 3-11). The core remained firmly attached after reaching a depth just beyond the extent of resin and fibre glass reinforcements. The core was loosened by gently prying with chisels, and eventually could be recovered with the core barrel. It was extracted only partially and had to be retrieved with a special tool in form of KG pipe (PVC drainage pipe) cut in half lengthwise and attached to an aluminium extension bar. The core was wrapped in plastic and carried to the sample preparation table located just outside the FEBEX gallery. This completed overcoring of the shotcrete/bentonite interface C-C-32-6-OC.

Details of sample treatment are provided in section 4, and detailed images of the overcore in Appendix C.

View after completion of drilling with core still firmly attached to its bentonite base.

Retrieving overcore form borehole.

Measuring temperature along the wall of the overcoring borehole.

Borehole after inserting PVC sealing plug.

Fig. 3-11 Images from overcoring, C-C-32-6

3.4 Temperatures across the shotcrete/bentonite interface

Temperatures were measured in all three overcoring boreholes at four locations near the shotcrete/bentonite interface (section 2.5). These temperatures are close to the in-situ temperatures because the heater was not turned off yet at the time of drilling. The readings for C-C-32-4 were measured two days after drilling, which may explain the slightly lower readings, although the borehole was provisionally closed to prevent excessive heat loss. Temperatures in C-C-32-6 were only measured a two positions.

The temperatures at the interface and at the deep end of the bentonite section were all measured in the overcoring boreholes at the 6 o'clock position. The radial distance for the measurements between the rock surface and the measuring position are largest for C-C-32-4 and almost equal for C-C-32-5 and C-C-32-6. The temperatures at the interface are quite similar, 28-29 °C, highest for C-C-32-5. The measurements are accurate (±0.5 K), but the accuracy with respect to the true in-situ temperature before drilling is not exactly known, but should not deviate by more than 2-3 K. Temperatures 40 cm from the interface into the bentonite are 32 °C for C-C-32-4 and C-C-32-5, but only 29.5 °C at C-C-32-6. These data may indicate a slight asymmetry of the temperature field in the bentonite, slanted a bit upwards.

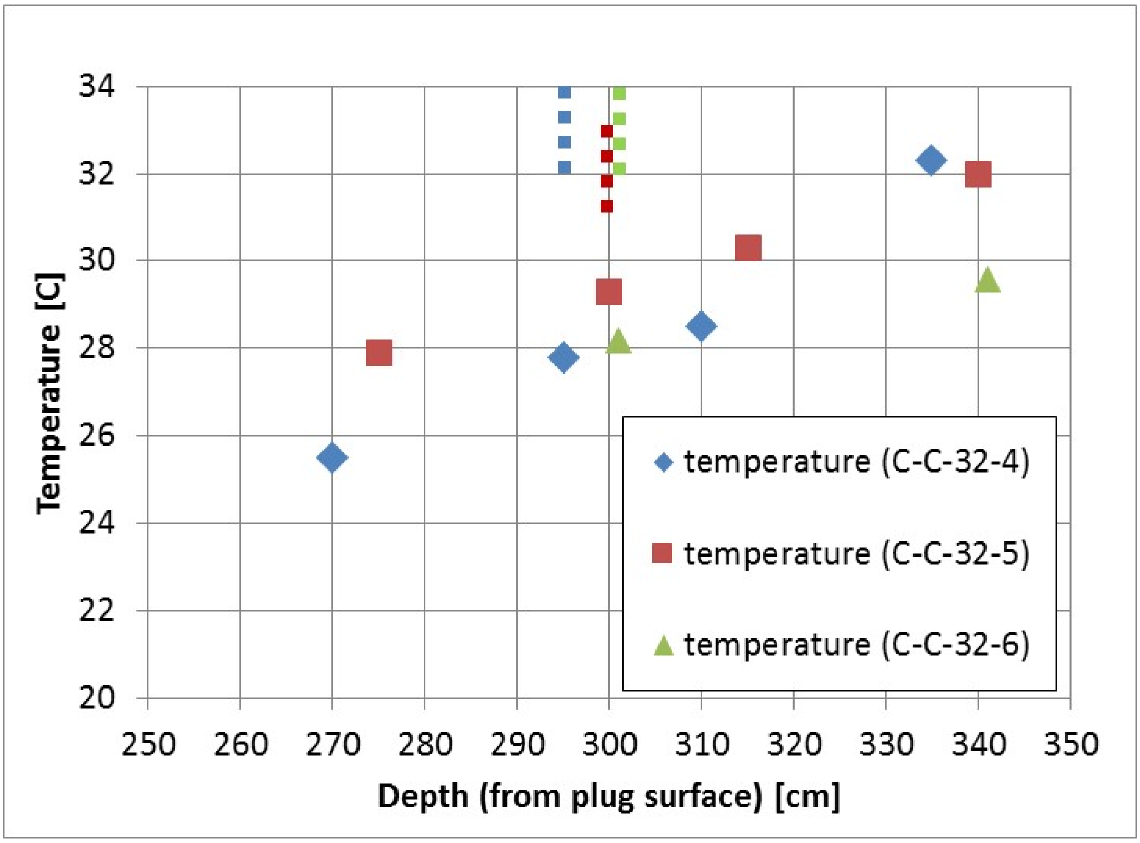


Fig. 3-12 Temperatures measured across the shotcrete/bentonite interface. The position of the interface is marked as dashed line.

4 Sample treatment and sample preservation

Shotcrete samples were not specifically protected or preserved, but were metered, marked and inspected. The availability of these large-scale samples was communicated. The cores are presently kept at a Nagra storage facility.

All small samples from the 46 mm boreholes (3x6 boreholes) across the shotcrete/bentonite interface were vacuum-sealed in plastic bags (Fig. 4-1) and kept initially in cold storage at the University of Bern. Some samples were requested by CIEMAT later during 2015. The remaining samples are still archived but no longer under cold storage conditions. These samples were not part of the original sampling plan, but were archived because the core quality turned out to be much better than expected.

Fig. 4-1 Vacuum-sealed small shotcrete and bentonite cores from C-C-32-4/12. The interface shotcrete/bentonite is contained in the bag on the lower left. Arrow points dowards deep end of borehole.

The overcores containing the shotcrete/bentonite interface were temporarily wrapped in plastic for transportation from the borehole to the sample preparation table located just outside of the FEBEX gallery (Fig. 4-2). Cores were then marked and photographed. Sealing for preservation of moisture was done in three layers: plastic foil (food wrap), and an additional protection against the steel fibres contained in shotcrete; an inner vacuum-sealed plastic bag; an outer vacuum-sealed plasticised aluminium bag.

Core samples developed some small amount of condensation inside the temporary wrap due to the elevated temperature of the core (ca. 30 °C) and the ambient temperature of ca. 15 °C. Also, the effects of thermal contraction were evident. The bentonite was commonly observed to separate from the fibre glass reinforcement in several locations, but only forming a discontinuous hairline gap.

Samples were transported to the University of Bern and put in cold storage until further subsampling as described in section 5.

Temporary protection for transport from borehole sample preparation table

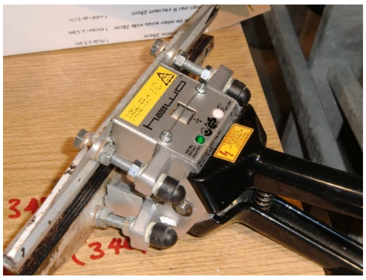
Plastic foil (food wrap) applied for protecting to bentonite section

Protection from steel fibres contained in shotcrete with a foam mat

Outer protection with plasticised aluminium foil sealed under vacuum

Inner protection by vacuum-sealed plastic bag

Inner vacuum plastic bag.



Heating clamp for plastisized aluminium

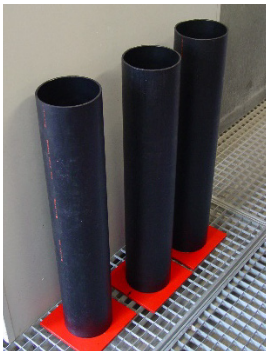
Preparing plastisized aluminium bag

Fig. 4-2 Preservation of overcore C-C-32-4-OC

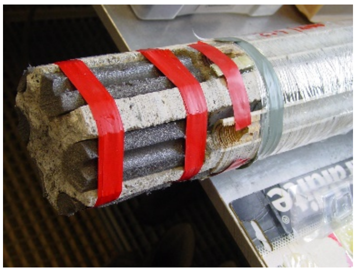
Subsampling the overcores required additional stability and protection. Also, the air-filled gaps that resulted from incomplete in-situ resin impregnation needed to be filled with resin such as not to allow for too much relaxation of the bentonite unconstrained surfaces. A good method is to encase the entire overcores in epoxy resin, to provide a firm outer support and fill all air-filled voids.

Moulds were prepared from PE tubes and base plates were fitted (Fig. 4-3). First, a small amount or resin was filled in and polymerized to provide a firm and resin-tight base plate (1-2 cm). The moulds were placed on a heating plate. This sped up waiting time and ensured that polymerisation started from the bottom upwards. This was an advantage so that shrinkage associated with polymerisation could be compensated by the resin from the top that was still liquid.

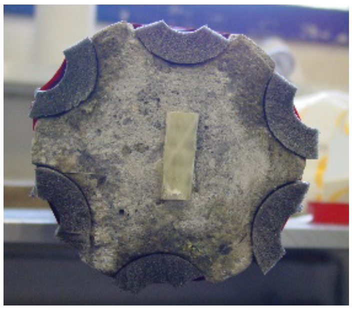
As a first step, the concrete ends that contained 6 packer seats were fitted with foam pieces (standard insulation material used for heating pipes) to reduce dead volume, such that resin polymerisation would not create excessive exothermic heat (Fig. 4-3). The bentonite part was protected by plastic foil during this step.



Moulds made from PE tubes



Reducing dead volume with foam at concrete section

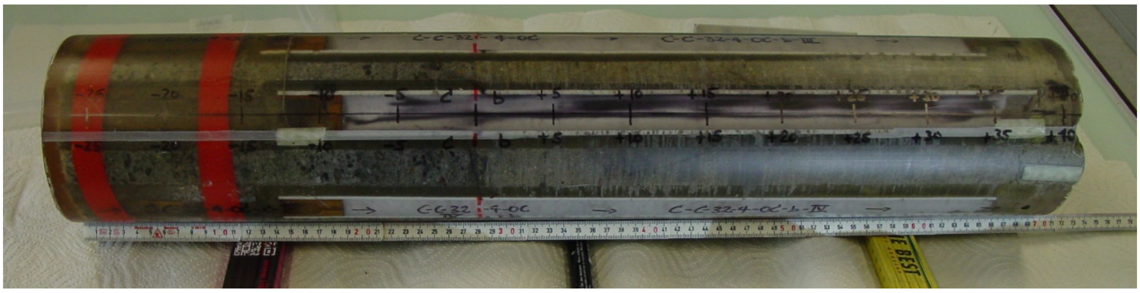


Same as image on left. Spacer is glued to base to ensure access of resin

Types of epoxy resins used for impregnation: Sikadur 52 on left side, Araldite XW 396 in the middle and associated hardener XW 397 on the right side

Top view (bentonite) of core covered with Araldite XW 396 resin. Former air gaps are visible at three reinforcement locations due to incomplete in-situ resin impregnation.

Moulds positioned on heating plate waiting for polymerisation



Example of a completed core after moulding in epoxy resin (C-C-32-4-OC).

Fig. 4-3 Illustration of resin impregnation of overcore samples

Two different resins were used for moulding: Sikadur 52 for the lower sections containing shotcrete, and Araldite XW 396 (with hardener XW 397) for the upper section containing the shotcrete/bentonite interface and all bentonite. Sikadur 52 was mixed and an appropriate amount filled into the moulds. Then, the overcore samples were carefully lowered into the mould. Vacuum was applied for a few minutes. The moulds were covered with foil. After polymerisation started, Araldite XW 396 resin was mixed and filled until it covered the entire core samples. Again, vacuum was applied to ensure that all void spaces were filled. The moulds were then left to polymerize.

The moulds had to be destroyed to take out the impregnated cores. Two cuts were milled along the PE cylinders cutting just the PE wall. It was then possible to remove a strip of cylinder wall and pry apart the mould to free the core samples.

5 Subsampling of bore core material

A Bosch mitre saw custom-equipped with a diamond cutting disc was used for dry-cutting of all samples (Fig. 5-1). The cutting discs are normally used in hand-held high speed dry cutters. This is a very efficient and precise way of cutting. The forces exerted on the sample are quite small due to the high speed and heat development during cutting is minimal. Different back stops are used to hold samples firmly in position during cutting. The maximum cutting depth is approximately 80 mm. The cores from FEBEX-DP (124 mm + resin skin) therefore had to be cut in two turns. The cutting width is 2-3 mm depending on the type of cutting disc used. It is possible to make delicate cuts on small samples.

This cutting procedure generates a lot of dust. Cutting was therefore performed outside, with two industrial vacuum cleaners attached as shown on Figure 5-1 to capture most of the cutting dust. Compressed air was used to clean samples after cutting.

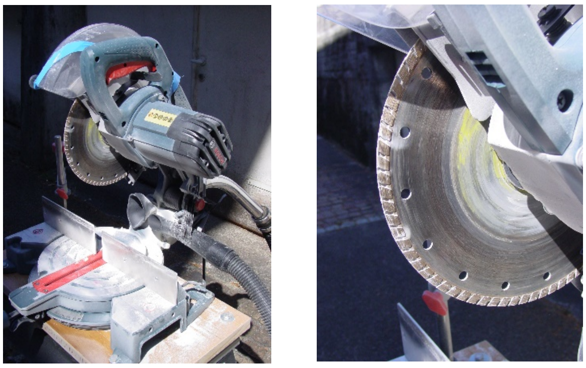


Fig. 5-1 Mitre saw with diamond cutting blade

Each core sample from the three overcoring boreholes containing a shotcrete/bentonite interface was completely encased in epoxy resin as described in section 4. First, cores were cut into three segments as shown in Figure 5-2. This resulted in a cylindrical segment containing shotcrete only, one containing the interface and one with bentonite only. The labelling scheme is also indicated.

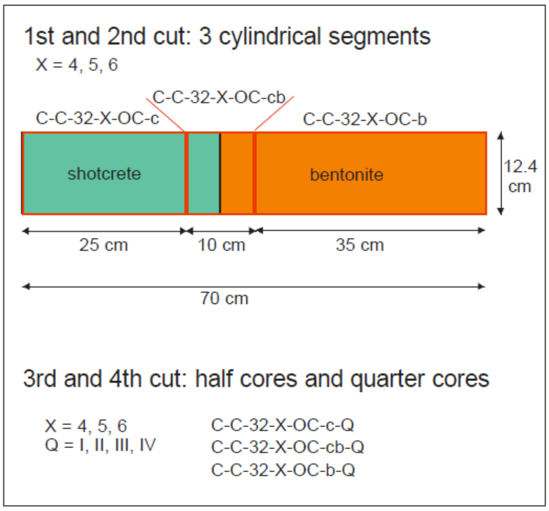


Fig. 5-2 Cutting and labelling scheme of shotcrete/bentonite interface samples

All freshly cut surfaces were temporarily protected with plastic wrap and covered shortly afterwards with Araldite XW 396 epoxy resin (Fig. 5-3). This resulted in 3x3 sample cylinders, perfectly preserved, and ready for further cutting.

Freshly cut surface in shotcrete.

Covering cut surfaces with epoxy resin

Fig. 5-3 Illustration of subsampling and protection with epoxy resin

Cylindrical samples were cut into half cores and quarters as indicated in Figure 5-4. Depending on the material (shotcrete, bentonite, interface), the procedures for subsampling diverged.

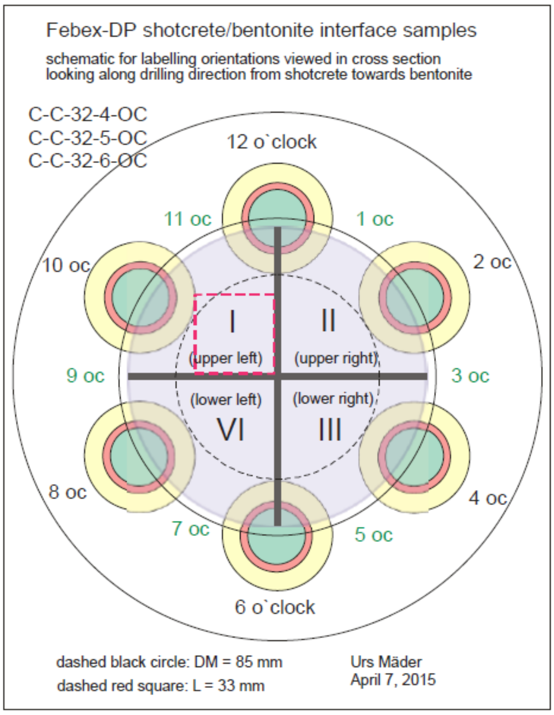
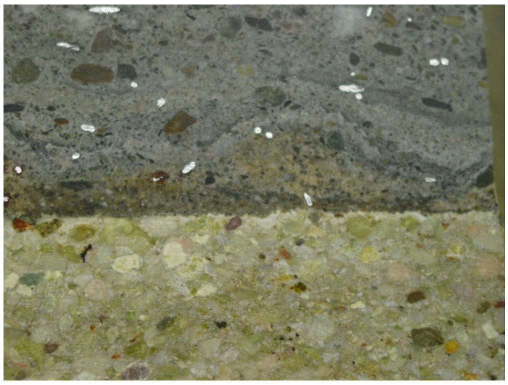


Fig. 5-4 Cutting and labelling schematic for half cores and quarter cores, with some characteristic dimensions indicated

Surfaces of half cores containing the shotcrete/bentonite interface were also protected with Araldite resin XW 396 (Fig. 5-5), but surfaces of quarter cores were simply vacuum-sealed in plastic to make subsequent analytical work easier.

Covering cut surfaces with epoxy resin



Example of sample quality, with shiny steel fibres.

Fig. 5-5 Cutting of samples containing shotcrete/bentonite interface into half cores, followed by covering surfaces with epoxy resin.

Shotcrete sections were cut in half cores and quarter cores and vacuum-sealed in plastic. Bentonite sections were cut in half cores (Fig. 5-6). Four cuts from different sides had to be performed for these large samples due to a limited cutting depth available. Likewise, quarter cores were cut. The freshly cut bentonite surfaces were not resin covered but simply vacuum-sealed in plastic as requested by the laboratories performing subsequent analysis. All samples were vacuum-sealed in plasticised aluminium foil. Samples intended for shipment were secured with a second layer of vacuum-sealed plasticised aluminium foil.

Freshly cut surface in bentonite, producing half cores

Cut quarter cores of bentonite section

Inner layer of vacuum-sealed plastic, bentonite quarter cores.

Quarter cores cut from one overcore: left sections (shotcrete), middle sections (interface), right sections (bentonite). C-C-32-4-OC.

Samples wrapped in a second layer of vacuum-sealed plasticised aluminium foil.

Fig. 5-6 Illustration of subsampling and protection with epoxy resin

Images of all subsamples are included in appendices A, B and C. A complete sample list is included in section 6.

6 Sample archive and sample distribution

Samples form the three overcores were distributed to different laboratories as indicated in Figure 6-1. Each allocated quarter core consists of three samples (Fig. 5-2): one containing shotcrete only, one containing the shotcrete/bentonite interface, and one containing bentonite only.

A complete sample list for the material from overcoring is included in Table 6-1, including sample mass and sample allocation.

Samples from the 18 small 46 mm reinforcement boreholes are listed in Tables 6-2, 6-3 and 6-4, grouped according to the overcoring borehole. A sample is a vacuum-sealed plastic bag that contains several segments. The depth allocation is listed, as well as the number of segments. Also, the materials are indicated (shotcrete, bentonite and interface). A limited number of these samples was shipped to CIEMAT for further analysis.

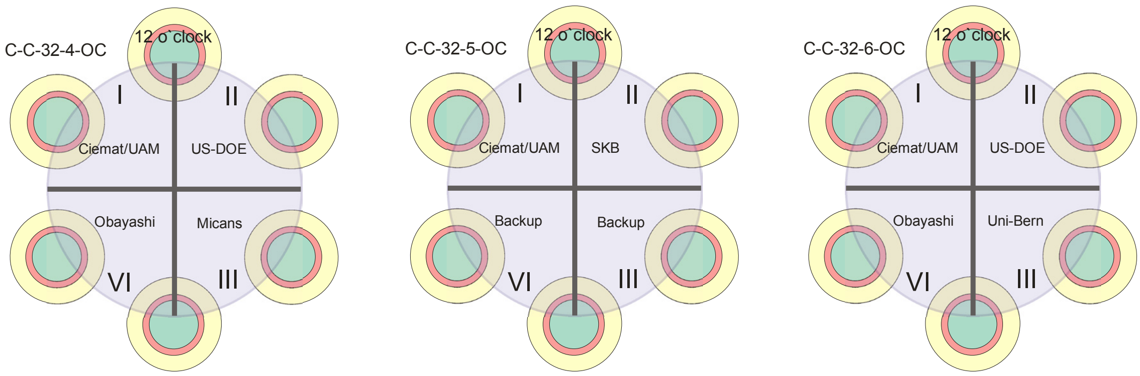


Fig. 6-1 Schematic of sample allocation

Tab. 6-1 Summary of samples, sample mass, and distribution

Destination	Sample label	Mass [g]	Shipped [g]
Obayashi	C-C-32-4-OC-b-IV	2002.90	9250
	C-C-32-4-OC-cb-IV	613.87	
	C-C-32-4-OC-c-IV	1359.84	
	C-C-32-6-OC-b-IV	2017.17	
	C-C-32-6-OC-cb-IV	656.80	
	C-C-32-6-OC-c-IV	1195.62	
US-DOE	C-C-32-4-OC-b-II	1960.05	9500
	C-C-32-4-OC-cb-II	604.27	
	C-C-32-4-OC-c-II	1285.34	
	C-C-32-6-OC-b-II	2080.13	
	C-C-32-6-OC-cb-II	654.19	
	C-C-32-6-OC-c-II	1318.64	
Micans	C-C-32-4-OC-b-III	2043.63	4600
	C-C-32-4-OC-cb-III	610.52	
	C-C-32-4-OC-c-III	1197.55	
Ciemat/UAM	C-C-32-4-OC-b-I	1881.54	13900
	C-C-32-4-OC-cb-I	591.39	
	C-C-32-4-OC-c-I	1058.78	
	C-C-32-5-OC-b-I	2077.47	
	C-C-32-5-OC-cb-I	630.43	
	C-C-32-5-OC-c-I	1235.64	
	C-C-32-6-OC-b-I	1991.86	
	C-C-32-6-OC-cb-I	625.01	
	C-C-32-6-OC-c-I	1122.36	
	C-C-32-4/6 299-317	289.59	
	C-C-32-4/6 317-335	304.94	
	C-C-32-5/12 307-327	319.98	
	C-C-32-5/12 327-340	204.77	
SKB	C-C-32-5-OC-c-II	1574.90	4920
	C-C-32-5-OC-cb-II	595.12	
	C-C-32-5-OC-b-II	1800.99	
Uni BE	C-C-32-6-OC-c-III	1289.26	
	C-C-32-6-OC-cb-III	616.02	
	C-C-32-6-OC-b-III	2082.65	
Backup	C-C-32-5-OC-c-III	1249.29	
	C-C-32-5-OC-cb-III	615.96	
	C-C-32-5-OC-b-III+IV	> 5000.00	
	C-C-32-5-OC-c-IV	1175.41	
	C-C-32-5-OC-cb-IV	664.99	

Shipped: total mass of parcel shipped to customers

Tab. 6-2 List of 46 mm drillcore samples from C-C-32-4

Position	Sample ID	Date drilled	from [cm]	to [cm]	material	interface [cm]	preservation	re-sealed	segments #
12 o'clock	C-C-32-4/12 265-284	26.02.2015	265	284	shotcrete		vacuum-sealed after 2 hrs	26.02.2015	4
	C-C-32-4/12 284-300	26.02.2015	284	300	shotcrete, bentonite	294	vacuum-sealed after 2 hrs		3
	C-C-32-4/12 300-320	26.02.2015	300	320	bentonite		vacuum-sealed after 2 hrs		3
	C-C-32-4/12 320-333	26.02.2015	320	333	bentonite		vacuum-sealed after 2 hrs		3
4 o'clock	C-C-32-4/4 266-288	26.02.2015	266	288	shotcrete		vacuum-sealed 1 day later		2
	C-C-32-4/4 288-304	26.02.2015	288	304	shotcrete, bentonite	298	vacuum-sealed 1 day later		3
	C-C-32-4/4 304-321	26.02.2015	304	321	bentonite		vacuum-sealed 1 day later		3
	C-C-32-4/4 321-335	26.02.2015	321	335	bentonite		vacuum-sealed 1 day later		1
8 o'clock	C-C-32-4/8 266-286	26.02.2015	266	286	shotcrete		vacuum-sealed 1 day later	02.03.2014	5
	C-C-32-4/8 286-301	26.02.2015	286	301	shotcrete, bentonite	295	vacuum-sealed 1 day later		3
	C-C-32-4/8 301-316	26.02.2015	301	316	bentonite		vacuum-sealed 1 day later		2
	C-C-32-4/8 316-333	26.02.2015	316	333	bentonite		vacuum-sealed 1 day later		5
10 o'clock	C-C-32-4/10 266-294	27.02.2015	266	294	shotcrete, interface	294	vacuum-sealed 15 minutes later		2
	C-C-32-4/10 294-305	27.02.2015	294	305	interface, bentonite	294	vacuum-sealed 15 minutes later		2
	C-C-32-4/10 305-314	27.02.2015	305	314	bentonite		vacuum-sealed 15 minutes later		1
	C-C-32-4/10 314-330	27.02.2015	314	330	bentonite		vacuum-sealed 15 minutes later		1
2 o'clock	C-C-32-4/2 266-287	27.02.2015	266	287	shotcrete		vacuum-sealed after 2 hrs		4
	C-C-32-4/2 287-308	27.02.2015	287	308	shotcrete, bentonite	295	vacuum-sealed after 2 hrs		3
	C-C-32-4/2 308-333	27.02.2015	308	333	bentonite		vacuum-sealed after 2 hrs		7
6 o'clock	C-C-32-4/6 266-288	27.02.2015	266	288	shotcrete		vacuum-sealed after 2 hrs	02.03.2015	4
	C-C-32-4/6 288-299	27.02.2015	288	299	shotcrete, bentonite	296	vacuum-sealed after 2 hrs		2
	C-C-32-4/6 299-317	27.02.2015	299	317	bentonite		vacuum-sealed after 2 hrs	02.03.2015	1
	C-C-32-4/6 317-335	27.02.2015	317	335	bentonite		vacuum-sealed after 2 hrs	02.03.2015	1

Tab. 6-3 List of 46 mm drillcore samples from C-C-32-5

Position	Sample ID	Date drilled	from [cm]	to [cm]	material	interface [cm]	preservation	re-sealed	segments #
12 o'clock	C-C-32-5/12 270-294	09.03.2015	270	294	shotcrete		vacuum-sealed after 0.5 hrs	26.02.2015	4
	C-C-32-5/12 294-307	09.03.2015	294	307	shotcrete, bentonite	300	vacuum-sealed after 0.5 hrs		3
	C-C-32-5/12 307-327	09.03.2015	307	327	bentonite		vacuum-sealed after 0.5 hrs		3
	C-C-32-5/12 327-340	09.03.2015	327	340	bentonite		vacuum-sealed after 0.5 hrs		3
4 o'clock	C-C-32-5/4 270-283	09.03.2015	270	283	shotcrete		vacuum-sealed 0.5 hrs later	09.03.2015	2
	C-C-32-5/4 283-295	09.03.2015	283	295	shotcrete		vacuum-sealed 0.5 hrs later		3
	C-C-32-5/4 295-304	09.03.2015	295	304	shotcrete, bentonite	300	vacuum-sealed 0.5 hrs later		
	C-C-32-5/4 304-325	09.03.2015	304	325	bentonite		vacuum-sealed 0.5 hrs later		3
	C-C-32-5/4 325-340	09.03.2015	325	340	bentonite		vacuum-sealed 0.5 hrs later	10.03.2015	1
8 o'clock	C-C-32-5/8 270-288	09.03.2015	270	288	shotcrete		vacuum-sealed 2 hrs later	02.03.2014	5
	C-C-32-5/8 288-306	09.03.2015	288	306	shotcrete, bentonite	299	vacuum-sealed 2 hrs later		3
	C-C-32-5/8 306-321	09.03.2015	306	321	bentonite		vacuum-sealed 2 hrs later		2
	C-C-32-5/8 316-333	09.03.2015	321	340	bentonite		vacuum-sealed 2 hrs later		5
2 o'clock	C-C-32-5/2 270-287	10.03.2015	270	287	shotcrete				2
	C-C-32-5/2 287-317	10.03.2015	287	317	shotcrete, bentonite	300			2
	C-C-32-5/2 317-340	10.03.2015	317	340	bentonite				1
10 o'clock	C-C-32-5/2 270-288	10.03.2015	270	288	shotcrete				4
	C-C-32-5/2 288-309	10.03.2015	288	309	shotcrete, bentonite	299			3
	C-C-32-5/2 309-330	10.03.2015	309	330	bentonite				7
6 o'clock	C-C-32-5/6 270-291	10.03.2015	270	291	shotcrete				4
	C-C-32-5/6 291-305	10.03.2015	291	305	shotcrete, bentonite	299			2
	C-C-32-5/6 305-323	10.03.2015	305	323	bentonite				1
	C-C-32-5/6 323-339	10.03.2015	323	339	bentonite				1

Tab. 6-4 List of 46 mm drillcore samples from C-C-32-6

Position	Sample ID	date drilled	from	to	material	interface	preservation	segments
			[cm]	[cm]		[cm]		
12 o'clock	C-C-32-6/12 275-292	19.03.2015	275	292	shotcrete		vacuum-sealed	2
	C-C-32-6/12 292-307	19.03.2015	292	307	shotcrete, bentonite	300	vacuum-sealed	2
	C-C-32-6/12 307-324	19.03.2015	307	324	bentonite		vacuum-sealed	2
	C-C-32-6/12 324-340	19.03.2015	324	340	bentonite		vacuum-sealed	2
4 o'clock	C-C-32-6/4 (at CIEMAT)	19.03.2015	275	?	shotcrete		vacuum-sealed	?
	C-C-32-6/4 (at CIEMAT)	19.03.2015	?	315	shotcrete, bentonite		vacuum-sealed	?
	C-C-32-6/4 315-228	19.03.2015	315	328	bentonite		vacuum-sealed	2 + crumbs
8 o'clock	C-C-32-6/8 275-295	19.03.2015	275	295	shotcrete		vacuum-sealed	3
	C-C-32-6/8 295-311	19.03.2015	295	311	shotcrete, bentonite	302	vacuum-sealed	5
	C-C-32-6/8 311-335	19.03.2015	311	335	bentonite		vacuum-sealed	2
10 o'clock	C-C-32-6/10 (at CIEMAT	24.03.2015	275	?	shotcrete		vacuum-sealed	?
	C-C-32-6/10 (at CIEMAT	24.03.2015	?	310	interface, bentonite		vacuum-sealed	?
	C-C-32-4/10 305-314	24.03.2015	310	335	bentonite		vacuum-sealed	
2 o'clock	C-C-32-6/2 275-294	24.03.2015	275	294	shotcrete		vacuum-sealed	2
	C-C-32-6/2 294-314	24.03.2015	294	314	shotcrete, bentonite	301	vacuum-sealed	3
	C-C-32-6/2 314-333	24.03.2015	314	333	bentonite		vacuum-sealed	2
6 o'clock	C-C-32-6/6 275-295	25.03.2015	275	295	shotcrete		vacuum-sealed	2
	C-C-32-6/6 295-313	25.03.2015	295	313	shotcrete, bentonite	303	vacuum-sealed	3
	C-C-32-6/6 313-337	25.03.2015	313	337	bentonite		vacuum-sealed	2

7 Conclusions and lessons learned

The effort for performing the three sampling boreholes with a sophisticated stabilised overcoring technique was considerable. Approximately five working days per borehole were required with a work force of 3-4 persons present, not counting planning, preparation and logistics. A detailed planning stage was essential and a variety of custom-made equipment and tools had to be prepared or invented ad hoc. The costs per sample are therefore considerable.

Recognizing that good sample quality is the paramount requirement for any subsequent analytical work, this sampling effort is offset by an impeccable quality of the samples including the interface region and a relatively long and well-preserved bentonite section. There are approximately eight scientific teams that were furnished with good sample material in a well-preserved state.

There was no failure of any part of the complicated procedure. The method is thus judged to be reliable and robust, but requires skilled and experienced personnel. The method is flexible, can be scaled to larger or smaller diameters or to a sample length of up to approximately two metres. The technique can therefore be applied whenever mechanically weak materials need to be stabilised in situ prior to extraction.

A practical issue is that such a procedure is difficult to carry out within a tight work schedule due to unexpected delays and the intensity of the work that requires concentration and attention to detail. The situation for the FEBEX work was ideal, with a generous time window preceding the dismantling of the shotcrete plug. Also, the work could be safely carried out while the heater was still in operation, and thus true operating conditions were encountered at the time of sampling.

Not all steps could be executed perfectly. The most significant issue was that resin impregnation was not complete for several of the reinforcement boreholes. The reason for this is that it was relatively easy to trap air when injecting resin in a horizontal position. It turned out that the orientation of the fibre glass packer systems was not always perfect with the resin back-flow line located at exactly the hinge position. Also, the coarse and steel fibre studded shotcrete did not always allow to employ a significant vacuum during injection that was expected to prevent air gaps. Nevertheless, this issue did not impact sample quality in a significant way as revealed by sample inspection on site and also by X-ray tomography. All air gaps were filled with resin when the entire cores were cast in resin in cylindrical moulds shortly after completion of the overcoring work.

8 Acknowledgments

The CI Project at Mont Terri URL and HPF and LCS Projects at the Grimsel Test Site were crucial in developing the stabilised overcoring technique. The engineers from Aitemin were involved in the planning stage to establish drilling locations that would not interfere with equipment, sensor components and other sampling activities. The analytical teams contributed sample requirements for planning the number of boreholes and the type of subsampling. René Dorrer, Niels Giroud and Ann-Sofi Dorrer lent a helping hand when needed.

Meet the field team: flexibility, improvisation and good team work led to success!

Fig. 8-1 Field team in the FEBEX gallery. From left: Urs Mäder, Hans Abplanalp, Kai Detzner, Toni Baer, Florian Kober.

9 References

Abós, H. & Martínez, V. (AITEMIN) (2015): Sample Log Book 34 to 62 FEBEX-DP. AN 15-578 September 2015.

Bárcena, I., Fuentes-Cantillana, J.L. & García-Siñeriz, J.L. (2003): Dismantling of the Heater 1at the FEBEX "in situ" test. Description of operations. Enresa Technical Report 9/2003, Enresa, Madrid.

Bárcena, I. & García-Siñeriz, J.L. (2015a): FEBEX-DP (GTS) Full Dismantling Sampling Plan. Nagra Arbeitsbericht NAB 15-14.

Bárcena, I. & García-Siñeriz, J.L.(2015b): FEBEX-DP (GTS) Full Dismantling Test Plan. Nagra Arbeitsbericht NAB 15-15.

Bárcena, I., Fuentes-Cantillana, J.L. & García-Siñeriz, J.L. (2003): Dismantling of the Heater 1 at the FEBEX "in situ" test. Description of operations. Enresa Technical Report 9/2003.

Enresa (2000). FEBEX Project. Full-scale Engineered Barriers Experiment for a Deep Geological Repository for High Level Radioactive Waste in Crystalline Host Rock. Final Report. Enresa Report 1/2000, Enresa, Madrid.

Enresa, 2006. Full-scale Engineered Barriers Experiment. Updated Final Report 1994-2004. Enresa Report 05-0/2006, Enresa, Madrid.

Fuentes-Cantillana, J.L., García-Siñeriz, J.L., Obis, J., Pérez, A.; Alberdi, J., Barcala, J.M., Campos, R., Cuevas, J., Fernández, A.M., Gamero, E., García, M., Gómez, P., Hernández, A., Illera, A., Martín, P.L., Melón, A.M., Mingarro, M., Ortuno, F., Pardillo, J., Pelayo, M., Rivas, P., Rodríguez, V., Turrero, M.J., Villar, M.V.; Caballero, E., Jiménez de Cisneros, C., Linares, J.; Martínez, M.A.; Samper, J., Delgado, J., Juncosa, R., Molinero, J.; Alonso, E.,Carrera, J., Gens, A., García-Molina, A.J., Guimera, J., Guimaraes, L.do N., Lloret, A.,Martínez, L.; Elorza, F.J., Borregón, J.L.; Fariña, P. & Farias, J. (1998). "FEBEX Full-scale Engineered Barriers Experiment inCrystalline Host Rock. Pre-operational Stage Summary Report". Enresa Technical Report 1/98, Enresa, Madrid.

Fuentes-Cantillana, J.L. & García-Siñeriz, J.L (1998): "FEBEX Full-scale Engineered Barriers Experiment in Crystalline Host Rock. Final Design and Installation of the “In Situ” Test at Grimsel ". Enresa Technical Report 12/98, Enresa, Madrid.

García-Siñeriz, J.L., Abós, H., Martínez, V., De la Rosa C., Mäder, U., Kober, F. (2016): "FEBEX-DP Dismantling of the heater 2 at the FEBEX "in situ" test. Nagra Arbeitsbericht NAB 16-11.

Jenni, A., Mäder, U., Lerouge, C., Gaboreau, S. & Schwyn, B. (2014). In situ interaction between different concretes and Opalinus clay. Physics and Chemistry of the Earth, Parts A/B/C 70–71, 71-83.

Lanyon G.W., Gaus Irina (2013): Main outcomes and review of the FEBEX In Situ Test (GTS) and Mock-Up after 15 years of operation. Nagra Arbeitsbericht NAB 13-096.

Mäder, U., Eul, A., Jenni, A., Frieg, B. & Dolder, F. (2015). CI Experiment: Sampling by stabilized overcoring for the 2nd campaign (2012). Unpublished Mont Terri Technical Note TN 2014-80, Mont Terri Project.

Martinez V., Abos, H., Garcia-Sineriz Martinez José Luis (2016): FEBEXe: Final Sensor Data Report (FEBEX "in situ" Experiment). Nagra Arbeitsbericht NAB 16-019.

Rey M., Bárcena I. & García-Siñeriz J.L. (2015): Full Dismantling Sampling Plan. Rev. 5.

Villar M, et al. (2016): FEBEX-DP Postmortem THM/THC Analysis Report. Nagra Arbeitsbericht NAB 16-017.

App. A: Image gallery for C-C-32-4

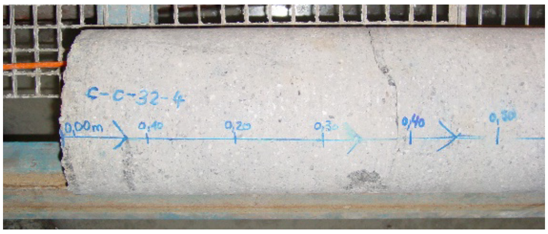
This appendix contains detailed images of all sample materials recovered from C-C-32-4, including shotcrete from the approach borehole (section A.1), small cores from the 46 mm reinforcement boreholes (section A.2), and the overcore containing the shotcrete/bentonite interface (section A.4, A.5). Also included are images from the borehole wall recorded after extracting the overcore (section A.3).

Below is a list of summary paramaters and work schedule for work associated with C-C-32-4.

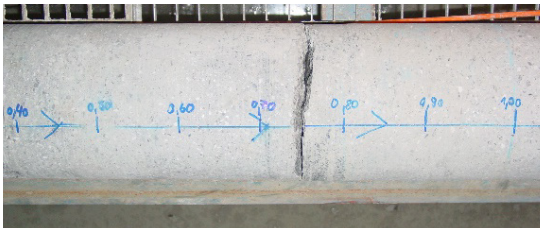
Site preparation	23.02.2015 – 24.02.2015
Approach borehole, 220 mm OD:	24.02.2015 – 25.02.2015
1st set of boreholes 46 mm DM for reinforcements:	26.02.2015
Emplacement of fibre glass reinforcements (resin):	26.02.2015
2nd set of boreholes 46 mm DM for reinforcements:	27.02.2015
Emplacement of fibre glass reinforcements (resin):	02.03.2015
Overcoring, extraction of overcore:	03.03.2015
Depth location of overcore (from plug front):	266 – 335 cm
Depth location of interface shotcrete/bentonite:	295 cm

A.1 Shotcrete samples from the 220 mm approach borehole (C-C-32-4)

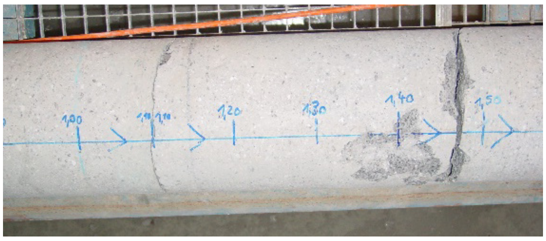
Core segments extracted from drilling the 220 mm OD approach borhole in the shotcrete plug (Fig. A-1) are compact, displaying the usual macro-porosity common to shotcrete. While the 2nd plug section (0-1.95 m) is textureless, the 1st section (1.95 – 2.75 m) displays a layered texture arising from shotcreting. The white sealing layer that separates the two plug sections is extremely well-bonded to the shotcrete, and did not separate during core wedging and extraction. Details of the flat-end steel fibres (Fig. A-1, lower right) explain why core separation was difficult: the wedge-shaped ends are firmly held in concrete, and fibres bridging a fractured core still provide a lot of strength. All fibres have a fresh, uncorroded appearance.



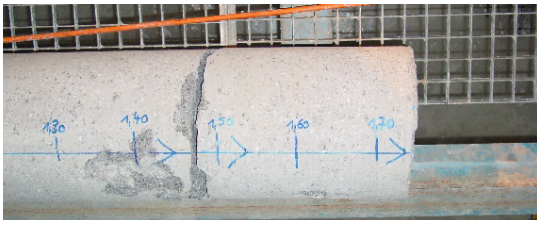
Shotcrete, C-C-32-4, 0-0.55 m



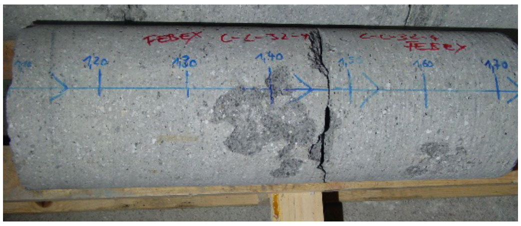
Shotcrete, C-C-32-4, 0.4-1 m



Shotcrete, C-C-32-4, 0.9-1.55 m



Shotcrete, C-C-32-4, 1.25-1.75 m



Shotcrete, C-C-32-4, 1.1-1.75 m, moist surface.

Shotcrete, C-C-32-4, 1.85-1.65 m, wet surface. White sealing layer between plug sections.

Shotcrete plug, section without steel fibres, but with polymer fibres. Moist surface.

Shotcrete plug, section with flat-end steel fibres. Wet surface

Fig. A-1 Images of samples from 220 mm approach borehole, C-C-32-4

A.2 Samples from the 46 mm reinforcement boreholes (C-C-32-4)

The schematic for positioning and labelling the 46 mm reinforcement boreholes is shown in Figure A-2. A complete sample list is provided in section 6.

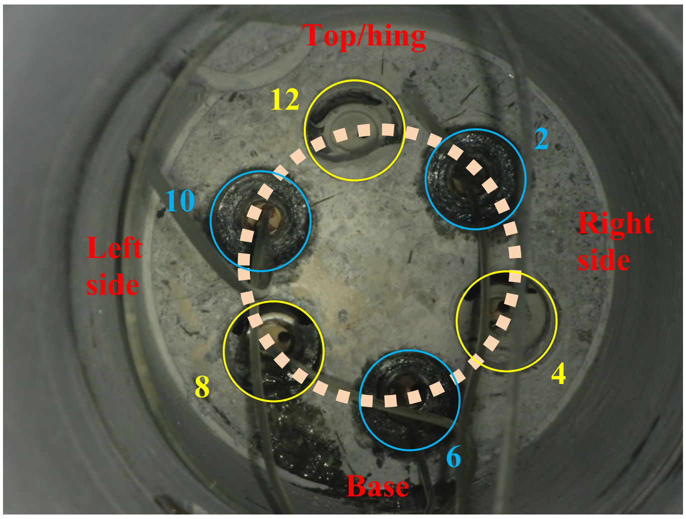


Fig. A-2 Schematic for labeling reinforcement boreholes. View direction is downhole. Approach boreholes is 220 mm OD. Reinforcement boreholes of 46 mm OD: 1st set of three (yellow) and 2nd set of three (blue). Orientations are labelled according to clock position. Overcoring diameter is indicated (132/124 mm).

Cores from all six 46 mm diameter reinforcement boreholes were vacuum-sealed in plastic bags (Fig. A-3). Cores separated at the shotcrete/bentonite interface in all boreholes during drilling. Unlike for all other overcorings to follow, the first 20 cm of shotcrete were drilled with water for C-C-32-4/12 and C-C-32-4/4 (Fig. A-3). This was no longer done for all subsequent boreholes.

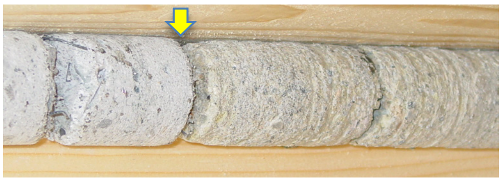
Some details of core material from C-C-32-4/4 are shown (Fig. A-3). The steel fibres are evident in all pieces of shotcrete. The colour change from shotcrete to bentonite is quite subtle on first sight. Bentonite sections were much more segmented compared to shotcrete sections. Core loss was rather small for all boreholes.

Moisture content is not preserved in these samples. Bentonite tends to dry out already during dry-drilling. Packaging of samples was therefore not done on a rigorous schedule, but rather when time permitted. Observations on the position of block boundaries relative to core segmentation are included in the report on results from bentonite studies (Villar et al. 2016).

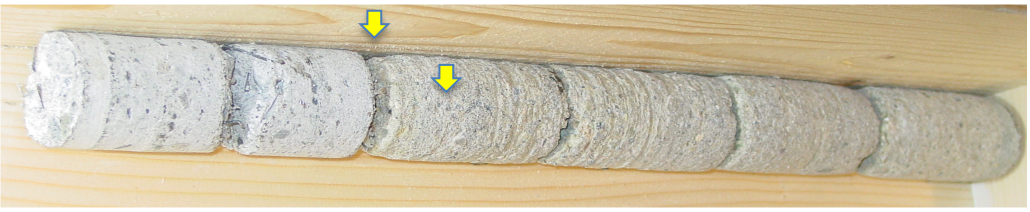
Samples from C-C-32-4/12 (left), C-C-32-4/4 (middle), C-C-32-4/8 (right).

Samples from C-C-32-4/10 (left), C-C-32-4/2 (middle), C-C-32-4/6 (right).

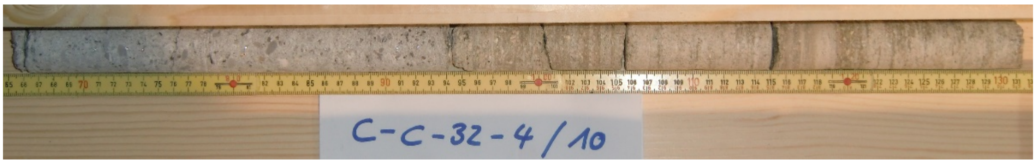
Shotcrete core, C-C-32-4/4 (18 cm long). Start of drilling was from the right side. Wet core surface.



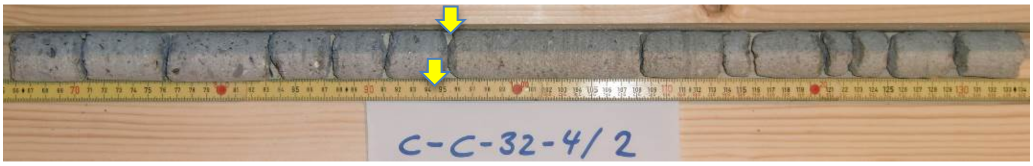
Shotcrete core, C-C-32-4/4, detail of interface (arrow), bentonite on right side.



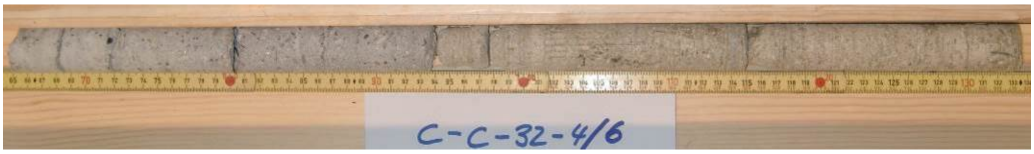
Shotcrete/bentonite core, C-C-32-4/4, 38 cm long. Interface is marked by arrow. Bentonite section (right side) is 28 cm long. Shotcrete section is 10 cm long.



Shotcrete/bentonite core, C-C-32-4/10. Interface is marked by arrow. Bentonite is on right side.



Shotcrete/bentonite core, C-C-32-4/2. Interface is marked by arrow. Bentonite is on right side.



Shotcrete/bentonite core, C-C-32-4/6. Interface is marked by arrow. Bentonite is on right side.

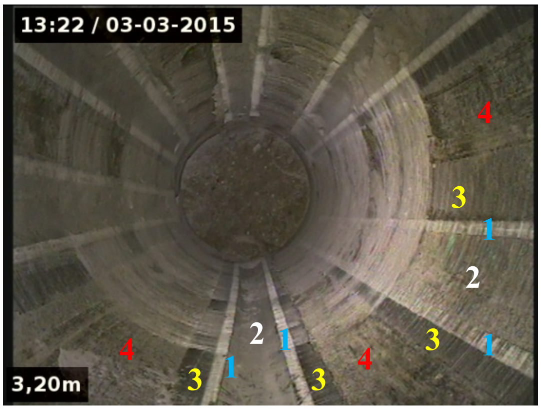
Fig. A-3 Images of samples from all six 46 mm reinforcement boreholes, C-C-32-4

A.3 Borehole wall after overcoring (C-C-32-4-OC)

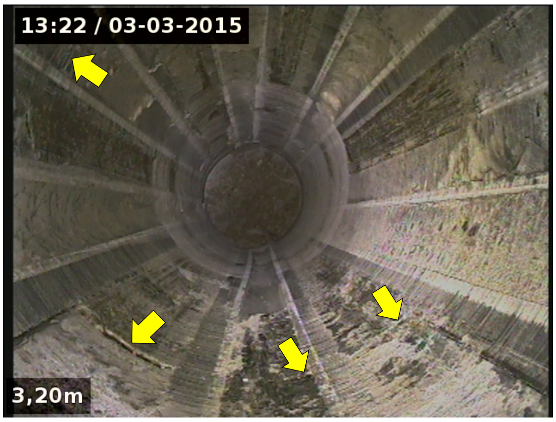
The borehole walls after extraction of the overcore were inspected by a borehole camera (Fig A-4). The leftover fibre glass and resin reinforcements are well visible and also stabilise the borehole walls, and thus inhibit convergence and deformation of adjacent bentonite regions

The interface between shotcrete and bentonite is difficult to detect. It is marked rarely by visible discontinuities. This is in agreement with observations during sample cutting that the interface region was always physically intact.

View of end of overcoring borehole in bentonite.



View of the bentonite section of the 132 mm OD borehole after extracting the overcore. The white fibre glass "lamellae" are well visible (1), with mortar in-fill (2), resin (3) and bentonite (4). The fish-eye effect of the borehole camera is distorting the arrangement of the reinforcements a bit. The quality of the borehole walls is excellent, and drilling performed expertly.



View of the interface between shotcrete and bentonite, with inferred trace marked by yellow arrows.

Fig. A-4 Images of borehole wall, associated with C-C-32-4-OC

A.4 Sample from 132 mm overcoring (C-C-32-4-OC)

The core quality appears to be excellent. There is no mechanical disturbance visible at the shotcrete/bentonite interface. The features seen on a fibre glass and resin reinforced core are explained in Figure A-5 for clarity. Depicted is the shotcrete part, right side of core, with hinge line along top. Visible are reinforcements positioned at 2 o'clock (upper fibre glass tube, from 2nd set of drilling) and at 4 o'clock (lower fibre glass tube, from the 1st set drilling). Numbers in Figure A-5 refer to packer seats, with some grease on shotcrete surface (1), fibre glass rods (2), adapter made of HGW with threading that was connected to the packer (3), injected resin (4), air-filled gap along the top of the 46 mm borehole that was not filled with resin (5) (1st set of reinforcements, 4 o'clock position), and shotcrete (6). The air gap is running along most of the length of the fibre glass rod. This issue of imperfect resin impregnation was resolved for the 2nd set of reinforcements that were perfectly impregnated, like the one seen above, at the 2 o'clock position.

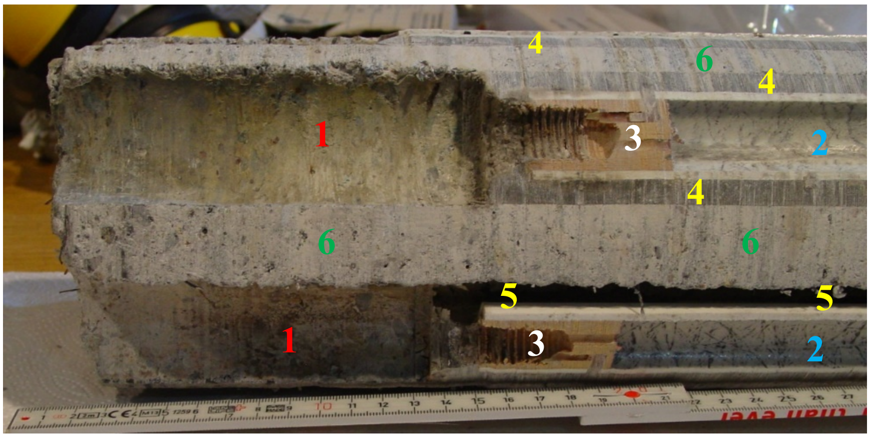
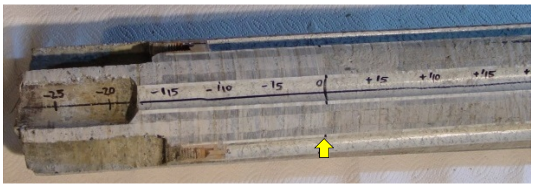


Fig. A-5 Images of shotcrete sections of overcore C-C-32-4-OC with different materials numbered (see text)

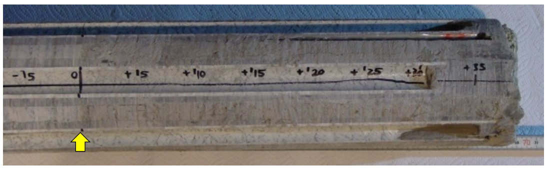
One issue is that 2 of the 6 reinforcement rods were not completely embedded in epoxy resin. This led to a gas-filled open space along the top of two fibre glass rods (at 4 and 10 o'clock position). The air gap present at the 12 o'clock position is not relevant because only the resin-filled lower portion is present in the core. It may be advisable that fabric analysis, density measurements and water-content measurements should not be done right in contact with these void areas. These voids were filled with resin after encasing the entire cores in epoxy resin (section 4, and images below).

Images taken from four sides from the concrete part and the bentonite part are compiled in Figure A-6. Also shown are the rear end (left, shotcrete) and front end (right,) of the core. See explanations with Figure A-5 for materials and features.

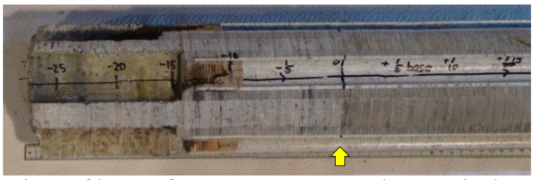
The scale marked in cm along the hinge line and along the base line is set to 0 at the location of the shotcrete/bentonite interface. Negative numbers refer to the shotcrete side, positive ones to the bentonite side. These photographs were taken just before wrapping and vacuum-sealing the core samples.



View of top (hinge, scale) of overcore. Deep end towards the right. 0-mark is placed at interface position. Shotcrete on left, and bentonite on right (positive length scale).

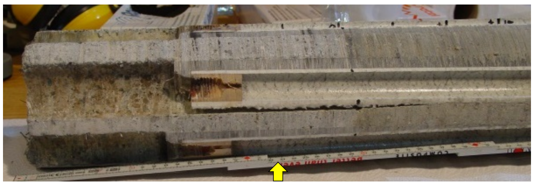


Continuation from left image. Mainly bentonite.

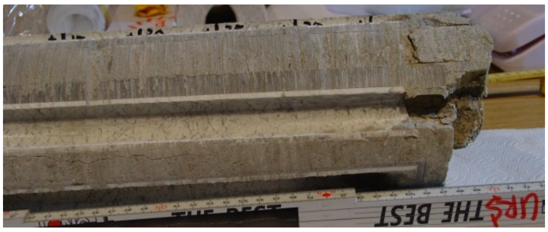


View of base of overcore. Deep end towards the right. 0-mark is placed at interface position

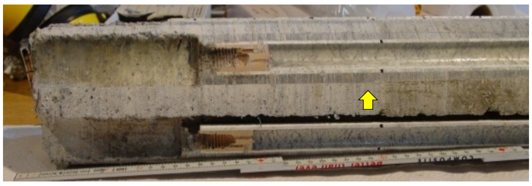
Continuation from left image. Mainly bentonite.



View of left side of overcore (hinge at base). Deep end towards the right.



Continuation from left image. Mainly bentonite.



View of right side of overcore (hinge at top). Deep end towards the right.

Continuation from left image. Mainly bentonite.

View of top end of core (shotcrete) with steel fibres.

View of base of core (bentonite).

Fig. A-6 Images of overcore C-C-32-4-OC. Arrow marks position of shotcrete/bentonite interface

A.5 Subsamples from overcore C-C-32-4-OC

The cutting scheme is reproduced in Figure A-7 for clarity. Figure A-8 shows the entire overcore after encasing it in epoyxy resin. Details of the interface region are shown in Figure A-9.

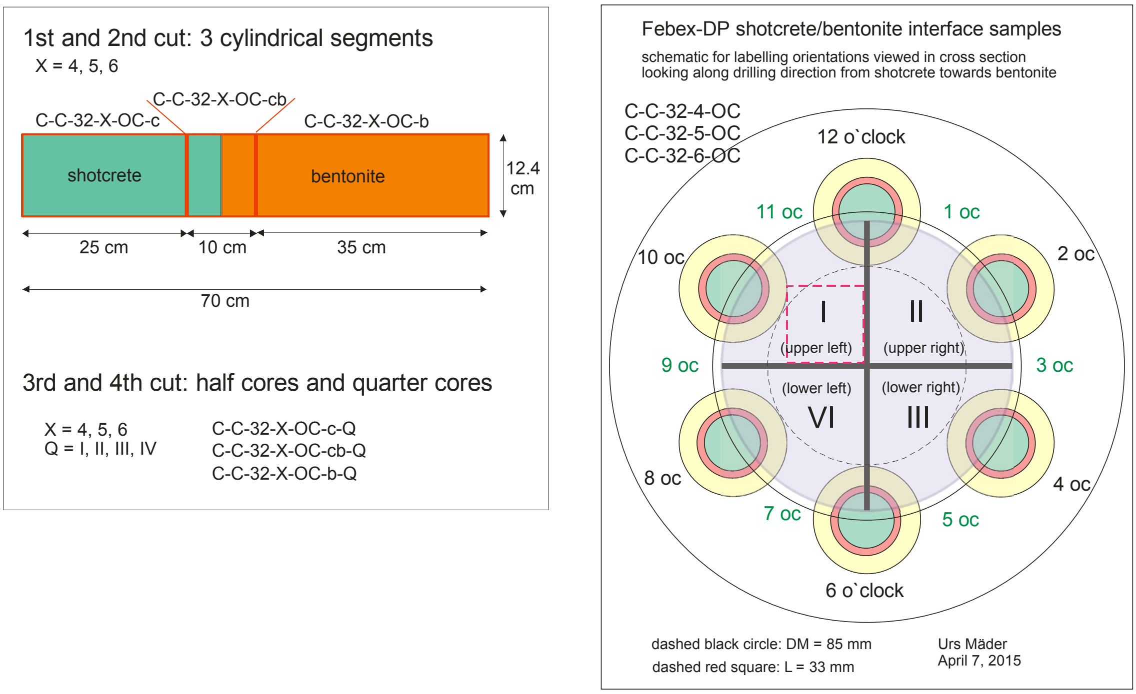
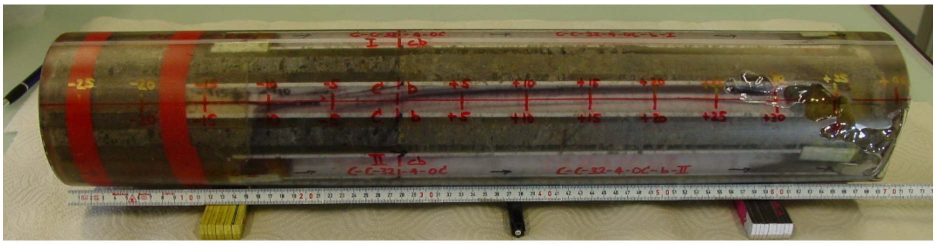
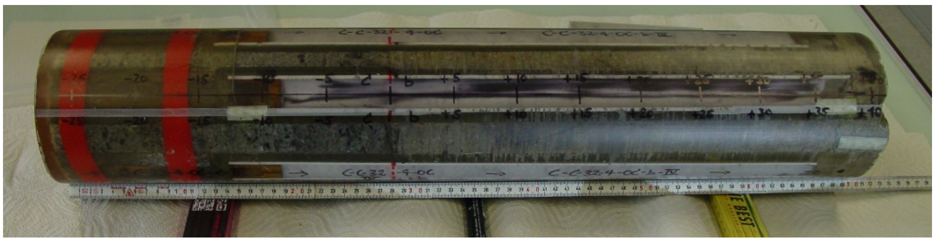


Fig. A-7 Cutting schematic for subsampling overcores

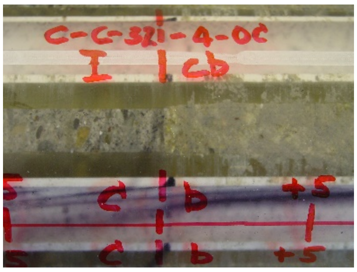


C-C-32-4-OC molded in epoxy resin; top view
(red scale bar marks hinge line, 5 cm intervals). Shotcrete is on the left side.

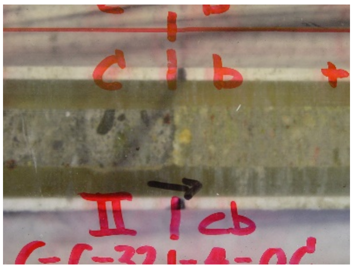


C-C-32-4-OC molded in epoxy resin; base view (black scale bar marks oposite of hinge line, 5 cm intervals). Shotcrete is on the left side.

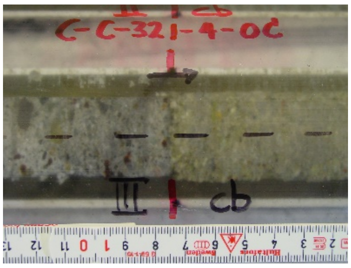
Fig. A-8 Images of samples cut from 132 mm overcore, C-C-32-4-OC



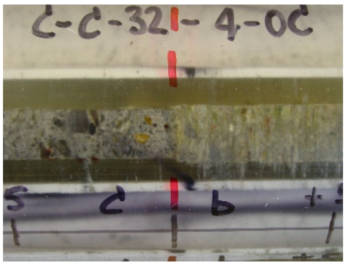
Interface in C-C-32-4-OC-cb, at 11 o'clock orientation



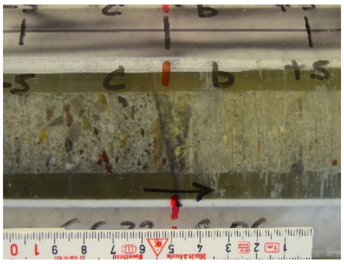
Interface in C-C-32-4-OC-cb, at 1 o'clock orientation.



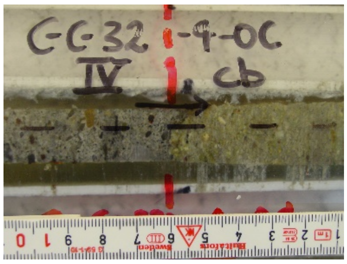
Interface in C-C-32-4-OC-cb, at 3 o'clock orientation.



Interface in C-C-32-4-OC-cb, at 5 o'clock orientation.



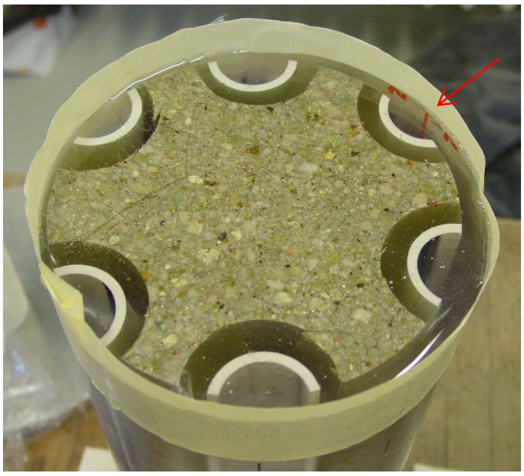
Interface in C-C-32-4-OC-cb, at 7 o'clock orientation.



Interface in C-C-32-4-OC-cb, at 9 o'clock orientation.

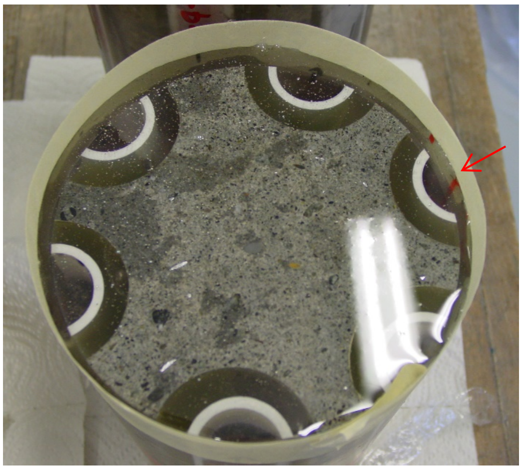
Fig. A-9 Images of interface region from overcore C-C-32-4-OC, viewed through epoxy layer.

Figure A-10 shows cut surfaces just after applying a protective cover of Araldite XW 396 resin. Textures are displayed well through the liquid resin. Steel fibres present in shotcrete have a very fresh and uncorroded appearance.



C-C-32-4-OC-b

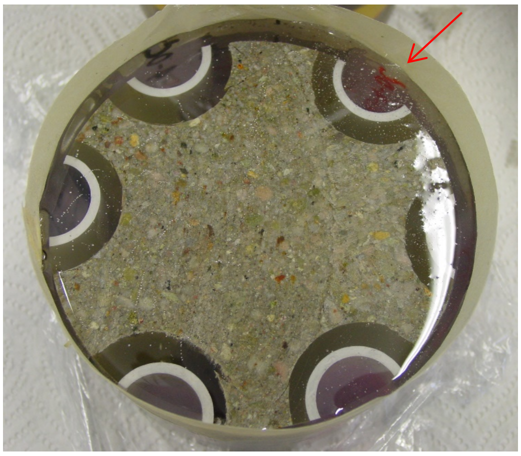
Bentonite surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.



C-C-32-4-OC-c

Shotcrete surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.

The highly reflecting particles are the cut steel fibres contained in the shotcrete.



C-C-32-4-OC-cb

Bentonite surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.

Fig. A-10 Images of cut surfaces from overcore C-C-32-4-OC, viewed through liquid epoxy layer.

No images are available from the cut surfaces of half cores and quarter cores of C-C-32-4-OC. Figure A-11 shows shotcrete/bentonite half cores (C-C-32-5-cb and C-C-32-6-cb) and the uncut segment of C-C-32-4-cb. Subsequent cuts for quarter cores and half cores are marked. The surfaces were not covered in resin after these cuts as requested by the analytical teams. All pieces were immediately vacuum-sealed in plastic. Sharp edges were taped to protect the plastic bags. Protruding steel fibres were snipped off with a pair of pliers. Later, a second layer of plastic was applied, also with vacuum.

Fig. A-11 Images of all sections containing the shotcrete/bentonite interface after resin work

Shotcrete sections were cut in quarter cores and cut surfaces were not covered with resin, but immediately vacuum packed (Fig. A-12). Sharp edges were protected with tape to avoid puncturing plastic bags. Protruding steel fibres were snipped off with a pair of pliers. Later, a second layer of plastic bags was applied, also with vacuum.

Fig. A-12 Quarter cores of shotcrete section from C-C-32-4-c after vacuum sealing

Bentonite sections (ca. 30 cm long) were more difficult to cut because of the limited cutting length and cutting depth that bcould be achieved with the mitre saw. The cores had to be cut from four sides (Fig. A-13) leaving just a small uncut middle section that could be easily separated. The cutting was rapid and drying effects are expected to be minimal. Half cores were further cut into quarter cores and these were immediatley vacuum packed.

Half cores of bentonite section

Quarter cores of bentonite section after vacuum-sealing.

Freshly cut quarter cores of bentonite section.

Fig. A-13 Half cores and quarter cores of bentonite section

Twelve quarter core samples were produced from C-C-32-4-OC (Fig. A-14, Tab. 6-1), vacuum-packed twice in plastic. An additional layer of plasticized aluminium was applied as described in section 5.

Quarter cores of shotcrete section, C-C-32-4-OC-c

Quarter cores of shotcrete/bentonite sections, C-C-32-4-OC-cb

Quarter cores of bentonite sections, C-C-32-4-OC-b

Fig. A-14 Quarter cores cut from C-C-32-4-OC

App. B: Image gallery for C-C-32-5

This appendix contains detailed images of all sample materials recovered from C-C-32-5, including shotcrete from the approach borehole (section B.1), small cores from the 46 mm reinforcement boreholes (section B.2), and the overcore containing the shotcrete/bentonite interface (section B.4, B.5). Also included are images from the borehole wall recorded after extracting the overcore (section B.3).

Below is a summary of coring paramaters and the work schedule associated with C-C-32-5.

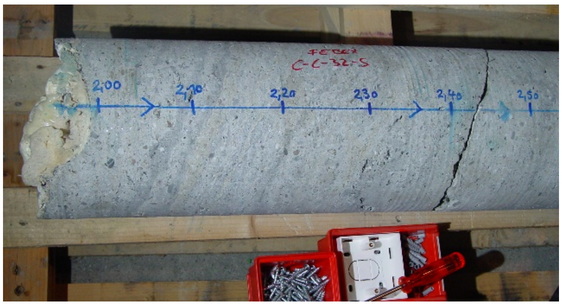
Site preparation, 46 mm pilot borehole:	04.03.2015
Approach borehole, 220 mm OD:	06.03.2015
1st set of boreholes 46 mm OD for reinforcements:	09.03.2015
Emplacement of fibre glass reinforcements (resin):	09.03.2015
2nd set of boreholes 46 mm OD for reinforcements:	10.03.2015
Emplacement of fibre glass reinforcements (resin):	10.03.2015
Overcoring, extraction of overcore:	11.03.2015
Depth location of overcore (from plug front):	270 – 341 cm
Depth location of interface shotcrete/bentonite:	300 cm

B.1 Shotcrete samples from the 220 mm approach borehole (C-C-32-5)

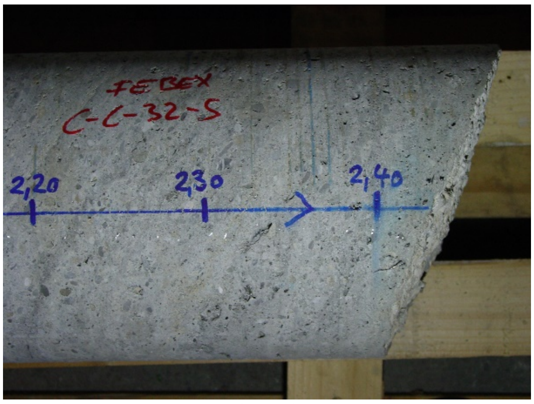
Core segments extracted from drilling the 220 mm OD approach borhole in the shotcrete plug (Fig. B-1) are compact, displaying the usual macro-porosity common to shotcrete. While the 2nd plug section (0-1.95 m) is textureless, the 1st section (1.95 – 2.70 m) displays a layered texture arising from shotcreting. The white sealing layer that separates the two plug sections is extremely well-bonded to the shotcrete, and did not separate during core wedging and extraction. Details of the flat-end steel fibres (Fig. B-1, lower right) explain why core separation was difficult: the wedge-shaped ends are firmly held in concrete, and fibres bridging a fractured core still provide a lot of strength. All fibres have a fresh, uncorroded appearance.

Shotcrete core from 0-270 cm. Arrow points to deep end of borehole. The white sealing layer separates the two plug sections at 195 cm. The scale is drawn along the hinge line.

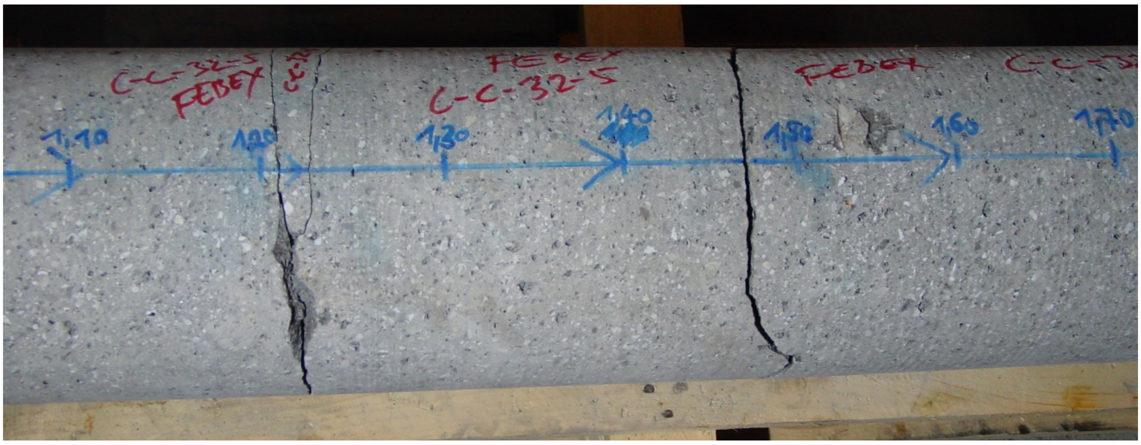
Detail of deep end of shotcrete core. Steel fibres are well visible, and are causing difficulties to pry and retrieve core segments.



Detail of 1st plug section, starting at sealing layer at 195 cm. Layering from shotcreting is well visible.



Detail of image on right side.



Detail of 2nd plug section with massive texture, from 105-170 cm. Scale marks hinge line.

Fig. B-1 Images of samples from 220 mm approach borehole, C-C-32-5

B.2 Samples from the 46 mm reinforcement boreholes (C-C-32-5)

The schematic for positioning and labelling the 46 mm reinforcement boreholes is shown in Figure B-2. A complete sample list is provided in section 6.

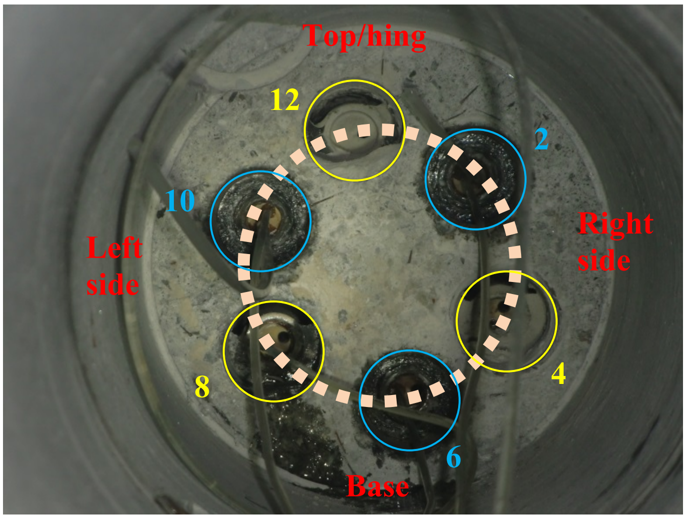
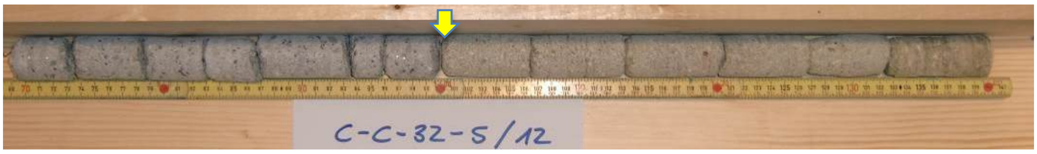


Fig. B-2 Schematic for labelling reinforcement boreholes. View direction is downhole. Approach boreholes is 220 mm OD. Reinforcement boreholes of 46 mm OD: 1st set of three (yellow) and 2nd set of three (blue). Orientations are labelled according to clock position. Overcoring diameter is indicated (132/124 mm).

Cores from all six 46 mm diameter reinforcement boreholes were vacuum-sealed in plastic bags. Cores separated at the shotcrete/bentonite interface in all boreholes during drilling. All sections were drilled dry with compressed air as coolant. Core loss was rather small for all boreholes.

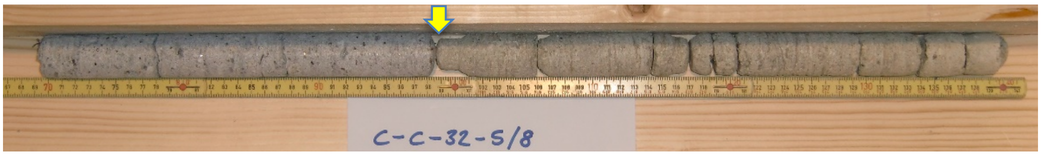
Some details of core material from C-C-32-5/12, 5/4 and 5/8 are shown (Fig. B-3). The colour change from shotcrete to bentonite is quite subtle at first sight. A thin alteration zone is generally visible at the interface in shotcrete samples. The alteration zone is much more subdued in bentonite samples adjacent to the interface (Fig. B.3)

Moisture content is not preserved in these samples. Bentonite tends to dry out already during dry-drilling. Packaging of samples was therefore not done on a rigorous schedule, but rather when time permitted. Observations on the position of block boundaries relative to core segmentation are included in the report on results from bentonite studies (Villar et al. 2016).



Shotcrete/bentonite core, C-C-32-5/12. Interface is marked by arrow. Bentonite is on right side.

Shotcrete/bentonite core, C-C-32-5/4. Interface is marked by arrow. Bentonite is on right side.



Shotcrete/bentonite core, C-C-32-5/8. Interface is marked by arrow. Bentonite is on right side.

Shotcrete core adjacent to interface (white crust)

Same as image on left

Matching bentonite core with interface at top

Fig. B-3 Images of samples from the 46 mm reinforcement boreholes, C-C-32-5

B.3 Borehole wall after overcoring C-C-32-5-OC

The borehole walls after extraction of the overcore were inspected by a borehole camera. The leftover fibre glass and resin reinforcements are well visible and also stabilise the borehole walls, and thus inhibit convergence and deformation of adjacent bentonite regions. No images were taken.

B.4 Sample from 132 mm overcoring C-C-32-5-OC

The core quality appears to be excellent. There is no mechanical disturbance visible at the shotcrete/bentonite interface. The features seen on a fibre glass and resin reinforced core are explained in Figure B-4 for clarity. Depicted is the shotcrete part, right side of core, with hinge line along top (black scale marks). Visible are reinforcements positioned at 12 o'clock (upper fibre glass tube, from 1st set of drilling) and at 2 o'clock (lower fibre glass tube, from the 2nd set drilling). Numbers in Figure B-4 refer to packer seats, with some grease on shotcrete surface

(1), fibre glass rods (2), adapter made of HGW (3) with threading that was connected to the packer and with remnants of resin flow lines, injected resin (4), and shotcrete (6).

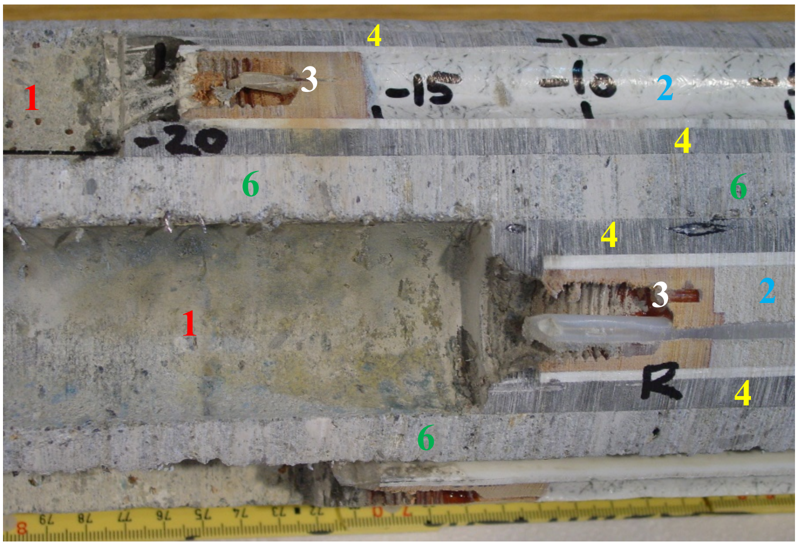


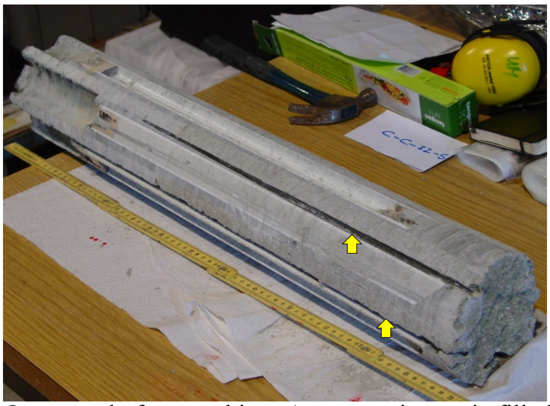
Fig. B-4 Images of shotcrete section of overcore C-C-32-5-OC with different materials numbered (see text). Hinge is along black scale (cm) marks

One issue is that 4 of the 6 reinforcement fibre glass rods were not completely embedded in epoxy resin. This led to a gas-filled open space along the top of four fibre glass rods (at 2, 4, 6 and 8 o'clock position, Figs. B-5, B-6). It may be advisable that fabric analysis, density measurements and water-content measurements should not be done right in contact with these void areas. These voids were filled with resin after encasing the entire cores in epoxy resin (section 4, and images below).

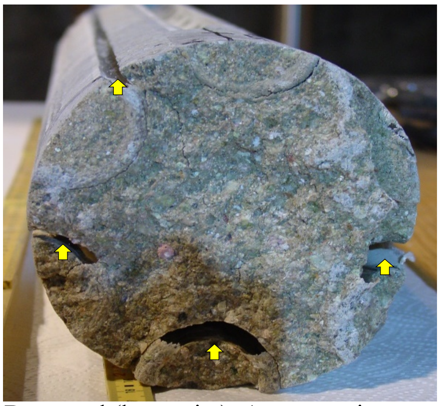
It was observed that parting did occur on occasion between bentonite and the resin reinforcement shortly after recovering the cores. This is thought to be related to thermal shrinkage induced by cooling of the cores. An example is shown in Figure B-6.

Images taken from four different sides (rotations) from the concrete part and the bentonite part are compiled in Figure B-5. Also shown are the front end (shotcrete) and rear end (bentonite, Fig. B-6) of the core. See explanations with Figure B-4 for materials and features.

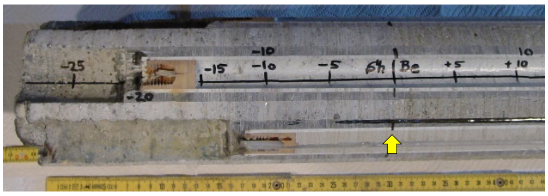
The scale marked in cm along the hinge line and along the base line is set to 0 at the location of the shotcrete/bentonite interface. Negative numbers refer to the shotcrete side, positive ones to the bentonite side. These photographs were taken just before wrapping and vacuum-sealing the core samples.



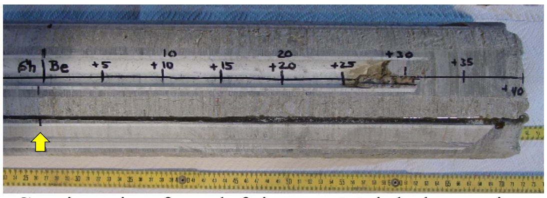
Overcore before marking. Arrows point at air-filled gaps that were not properly filled with resin. Deep end is towards the lower right.



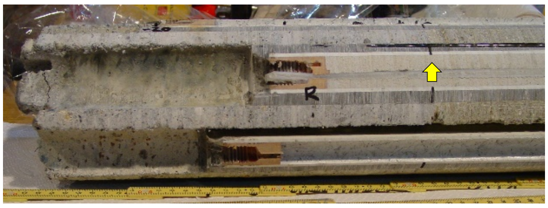
Deep end (bentonite). Arrows point at air-filled gaps that were not properly filled with resin.



View of top (hinge, scale) of overcore. Deep end towards the right. 0-mark is placed at interface position. Shotcrete on left, and bentonite on right (positive length scale).

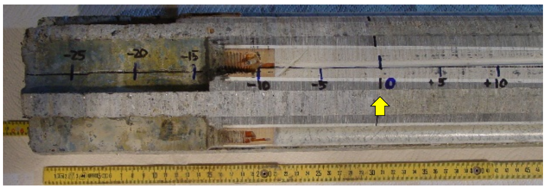


Continuation from left image. Mainly bentonite.



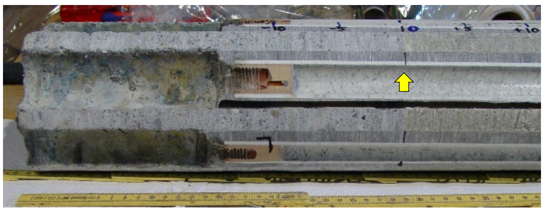
View of right side of overcore (hinge at top). Deep end towards the right.

Continuation from left image. Mainly bentonite.

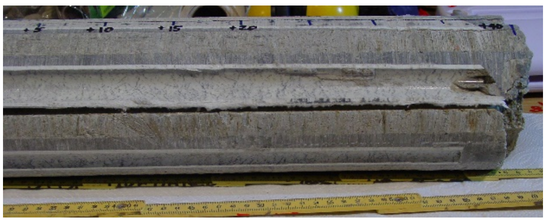


View of base of overcore. Deep end towards the right. 0-mark is placed at interface position.

Continuation from left image. Mainly bentonite.

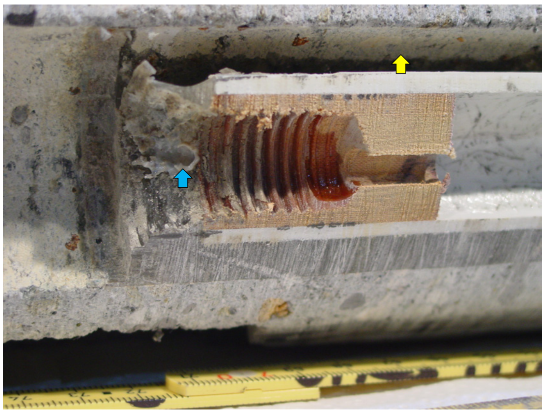


View of left side of overcore (hinge at base). Deep end towards the right.

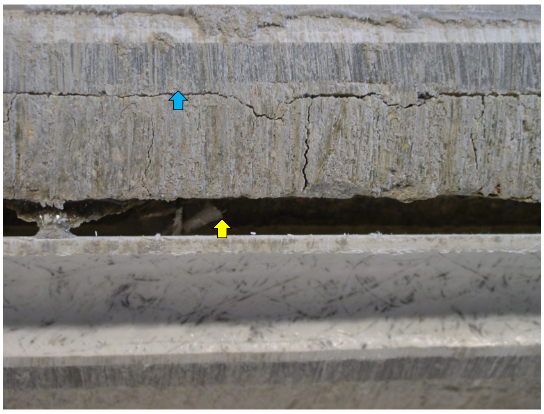


Continuation from left image. Mainly bentonite.

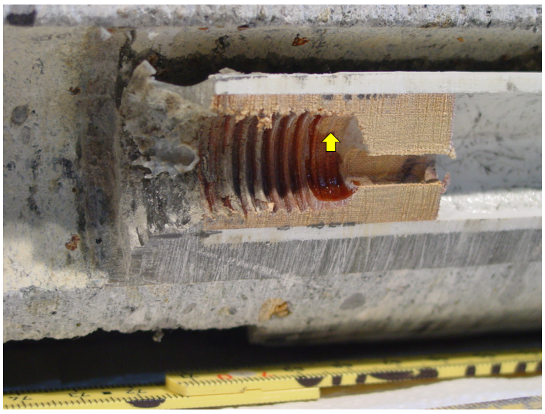
Fig. B-5 Images of overcore C-C-32-5-OC. Arrow marks position of shotcrete/bentonite interface



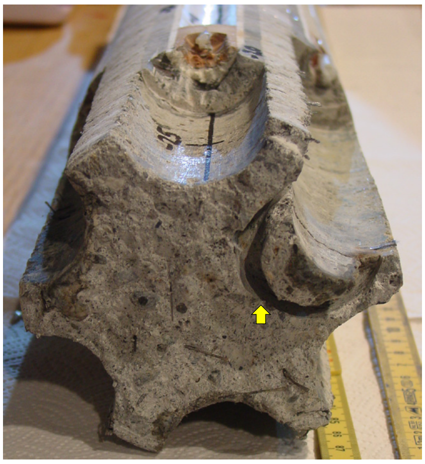
Detail of reinforcement at 4 o'clock position with air gap (yellow arrow) and position of resin back-flow line (blue arrow).



Air gap of reinforcement at 4 o'clock position (yellow arrow). Parting of bentonite along resin of reinforcement at 2 o'clock position (blue arrow).



Air gap (yellow arrow) of reinforcement at 2 o'clock position. Note resin skin covering all surfaces of air gap.



Shotcrete base (steel fibres) with 6 packer seats and trace of pilot borehole (yellow arrow). Hinge along top.

Fig. B-6 Detailed images of overcore C-C-32-5-OC

B.5 Subsamples from overcore C-C-32-5-OC

The cutting scheme is reproduced in Figure B-7 for clarity. Figure B-8 shows the entire overcore after encasing it in epoyxy resin. Details of the interface region are shown in Figure B-9.

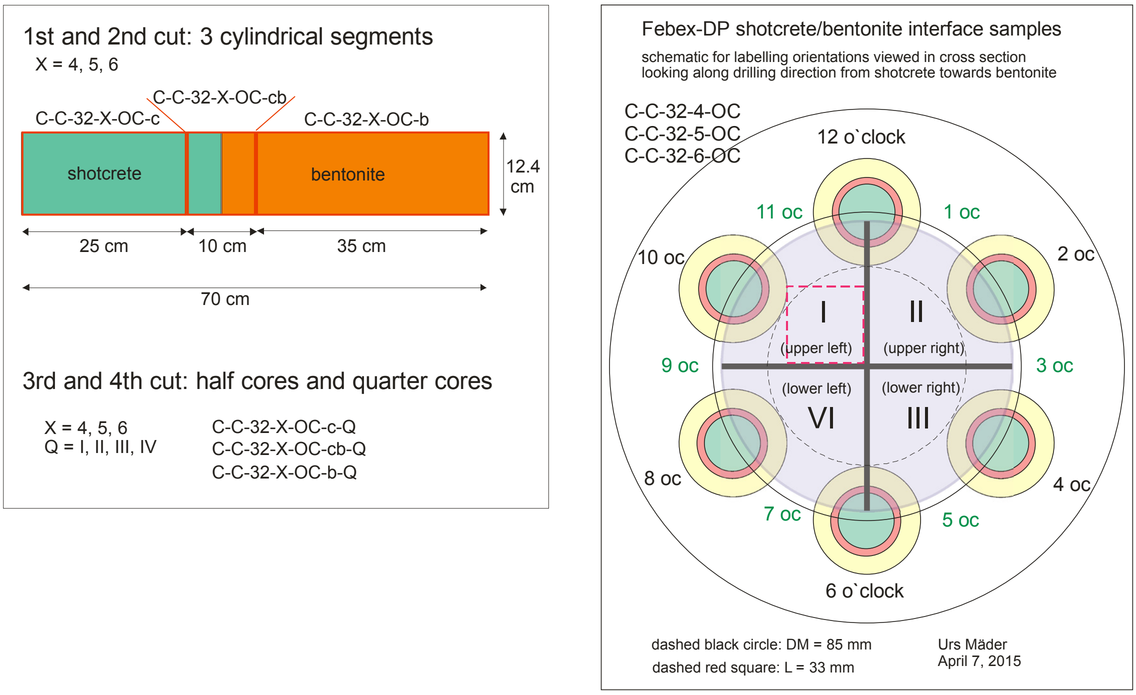
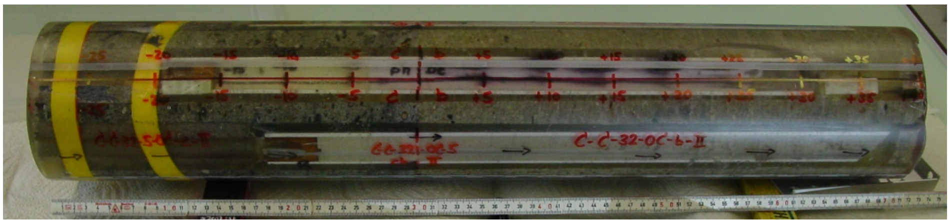
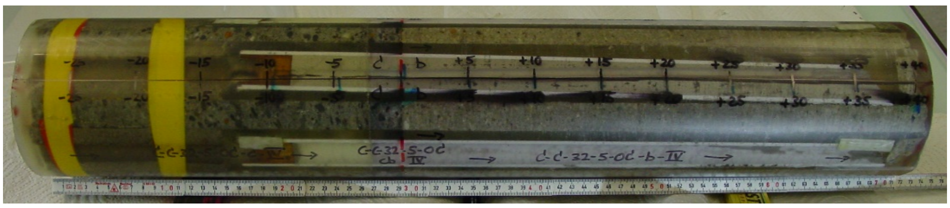


Fig. B-7 Cutting schematic for subsampling overcores

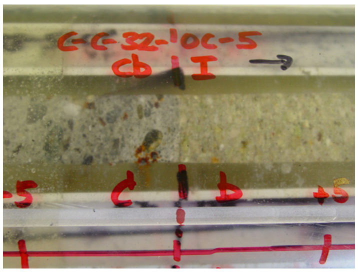


C-C-32-5-OC molded in epoxy resin; top view (red scale bar marks hinge line, 5 cm intervals). Shotcrete is on the left side.

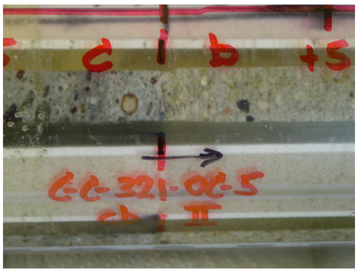


C-C-32-5-OC molded in epoxy resin; base view (black scale bar marks oposite of hinge line, 5 cm intervals). Shotcrete is on the left side.

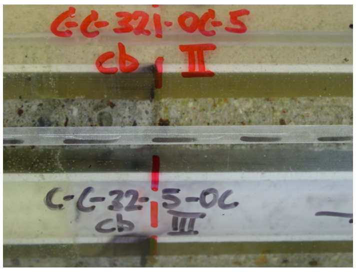
Fig. B-8 Images of samples cut from 132 mm overcore, C-C-32-5-OC



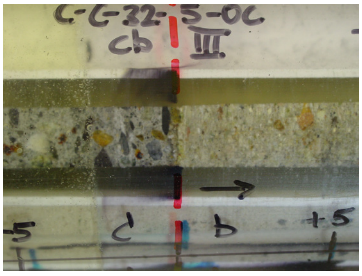
Interface in C-C-32-5-OC-cb, at 11 o'clock orientation



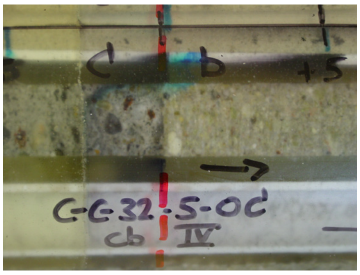
Interface in C-C-32-5-OC-cb, at 1 o'clock orientation



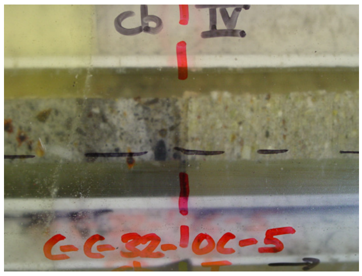
Interface in C-C-32-5-OC-cb at 3 o'clock orientation



Interface in C-C-32-5-OC-cb, at 5 o'clock orientation



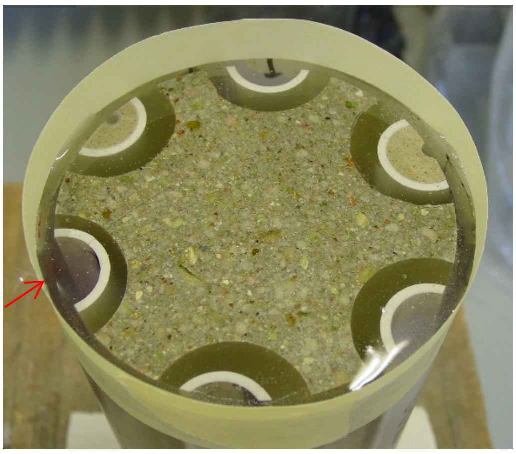
Interface in C-C-32-5-OC-cb, at 7 o'clock orientation



Interface in C-C-32-5-OC-cb, at 9 o'clock orientation

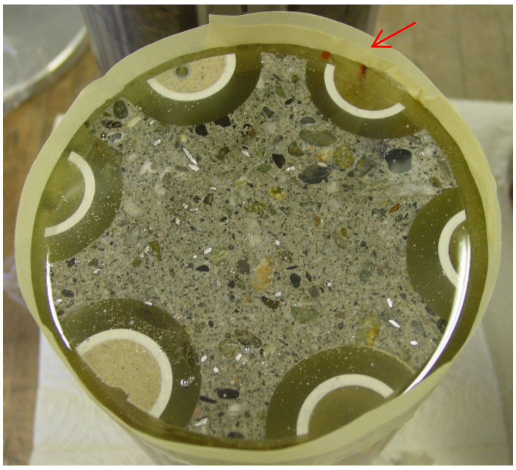
Fig. B-9 Images of interface region from overcore C-C-32-5-OC, viewed through the epoxy layer

Figure B-10 shows cut surfaces just after applying a protective covering of Araldite XW 396 resin. Textures are displayed well through the liquid resin.



C-C-32-5-OC-b

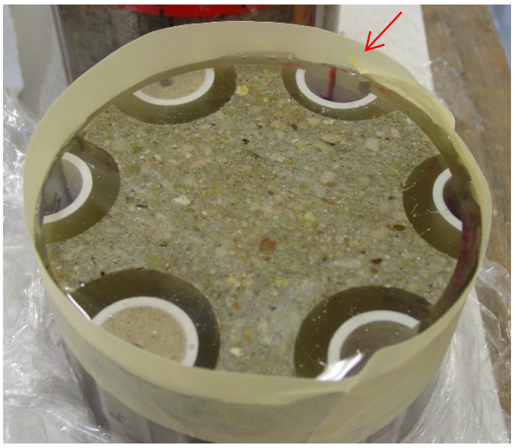
Bentonite surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.



C-C-32-5-OC-c

Shotcrete surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.

The highly reflecting particles are the cut steel fibres contained in the shotcrete.



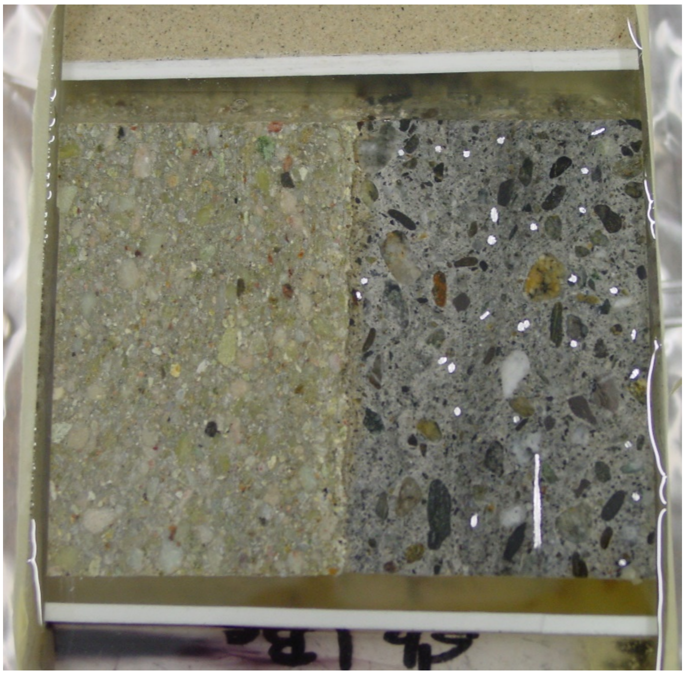
C-C-32-5-OC-cb

Bentonite surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.

Fig. B-10 Images of cut surfaces from overcore C-C-32-5-OC, viewed through the liquid epoxy layer

Figure B-11 shows the surfaces of cuts after producing half cores, just after applying a protective covering of Araldite XW 396 resin. Textures are displayed extremely well through the liquid resin. Steel fibres are not corroded. Some faint alteration zones are visible in both shotcrete and bentonite. An overview of all resin-embedded half cores is shown in Figure A-11.

Half cores of the shotcrete/bentonite section were cut in quarter cores and the cut surfaces were not covered in resin. All cut pieces were immediately vacuum-sealed in plastic. Sharp edges were taped to protect the plastic bags. Protruding steel fibres were snipped off with a pair of pliers. Later, a second layer of plastic was applied, also with vacuum



C-C-32-5-OC-cb-III&IV

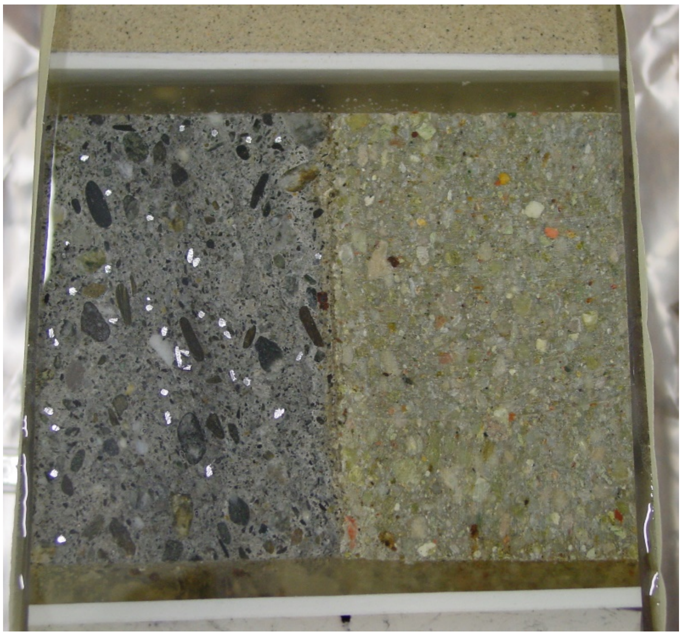
Surface of half-core after cutting and covering with resin.

Sample width is 10 cm. Shotcrete is on the right side, bentonite on the left. Glossy components are the steel fibres.

Quarter core III will contain the upper half of the image, and quarter core IV the lower half.

C-C-32-5-OC-cb-III&IV

Close-up of the image above.

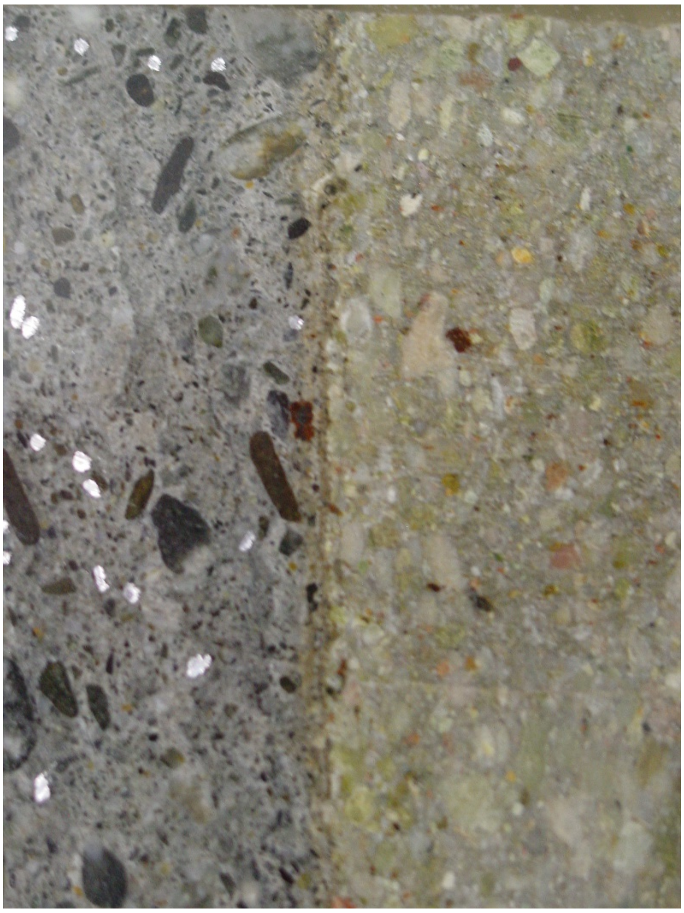


C-C-32-5-OC-cb-I&II

Surface of half-core after cutting and covering with resin.

Sample width is 10 cm. Shotcrete is on the left side, bentonite on the right. Glossy components are the steel fibres.

Quarter core I will contain the lower half of the image, and quarter core II the upper half.



C-C-32-5-OC-cb-I&II

Close-up of the image above.

Fig. B-11 Images of cut surfaces from overcore C-C-32-5-OC, viewed through a liquid epoxy layer

Shotcrete half cores were cut in quarter cores and cut surfaces were not covered with resin, but immediately vacuum packed (Fig. B-12). Sharp edges were protected with tape to avoid puncturing plastic bags. Protruding steel fibres were snipped off with a pair of pliers. Later, a second layer of plastic bags was applied, also with a vacuum.

Fig. B-12 Two quarter cores of shotcrete section from C-C-32-5-c after vacuum sealing

Bentonite sections (ca. 30 cm long) were more difficult to cut because of the limited cutting length and cutting depth that could be achieved with the mitre saw. The cores had to be cut from four sides (Fig. B-13) leaving just a small uncut middle section that could be easily separated. The cutting was rapid and drying effects are expected to be minimal. One half core was further cut into quarter cores and these were immediatley vacuum packed. The other half core (C-C-32-5-OC-b-III&IV) was vacuum-packed and remained in storage as back-up sample.

Fig. B-13 Half cores of the bentonite section from C-C-32-5-OC-b

Ten quarter core samples and one bentonite half core were produced from C-C-32-5-OC (Tab. 6-1) and vacuum-packed twice in plastic. An additional layer of plasticised aluminium was applied as described in section 5.

App. C: Image gallery for C-C-32-6

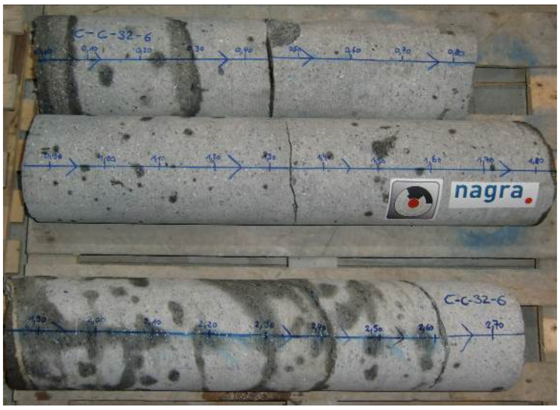
This appendix contains detailed images of all sample materials recovered from C-C-32-6, including shotcrete from the approach borehole (section C.1), small cores from the 46 mm reinforcement boreholes (section C.2), and the overcore containing the shotcrete/bentonite interface (section C.4, B.5). Also included are images from the borehole wall recorded after extracting the overcore (section C.3).

Below is a list of summary paramaters and work schedule for work associated with C-C-32-6.

Site preparation, 46 mm pilot borehole:	16.03.2015
Approach borehole, 220 mm OD:	17.03.2015
1st set of boreholes 46 mm OD for reinforcements:	19.03.2015
Emplacement of fibre glass reinforcements (resin):	19.03.2015
2nd set of boreholes 46 mm OD for reinforcements:	24.03.2015
Emplacement of fibre glass reinforcements (resin):	25.03.2015
Overcoring, extraction of overcore:	26.03.2015
Depth location of overcore (from plug front):	275 – 341 cm
Depth location of interface shotcrete/bentonite:	301 cm

C.1 Shotcrete samples from the 220 mm approach borehole (C-C-32-6)

Core segments extracted from drilling the 220 mm OD approach borhole in the shotcrete plug (Fig. C-1) are compact, displaying the usual macro-porosity common to shotcrete. While the 2nd plug section (0-1.85 m) is nearly textureless, the 1st section (1.85 – 2.75 m) displays a layered texture arising from shotcreting. The white sealing layer that separates the two plug sections is extremely well-bonded to the shotcrete. Details of the flat-end steel fibres (Fig. C-1, lower right) explain why core separation was difficult: the wedge-shaped ends are firmly held in concrete, and fibres bridging a fractured core still provide a lot of strength. All fibres have a fresh, uncorroded appearance.



Shotcrete core from 0-275 cm. Arrow points to deep end of borehole. The white sealing layer separates the two plug sections at 185 cm. The scale is drawn along the hinge line.

Detail of deep end of shotcrete core. Steel fibres are well visible. White surface represents a parting surface, freshly broken surface is grey.

Detail of region at interface between 1st (on right side) and 2nd plug section, with a sealing layer at 185 cm. Layering from shotcreting is well visible.

Detail from 1st plug setion. Layering from shotcreting is well visible. Scale is marked Along hinge.

Fig. C-1 Images of samples from the 220 mm approach borehole, C-C-32-6

C.2 Samples from the 46 mm reinforcement boreholes (C-C-32-6)

The schematic for positioning and labelling the 46 mm reinforcement boreholes is shown in Figure C-2. A complete sample list is provided in section 6.

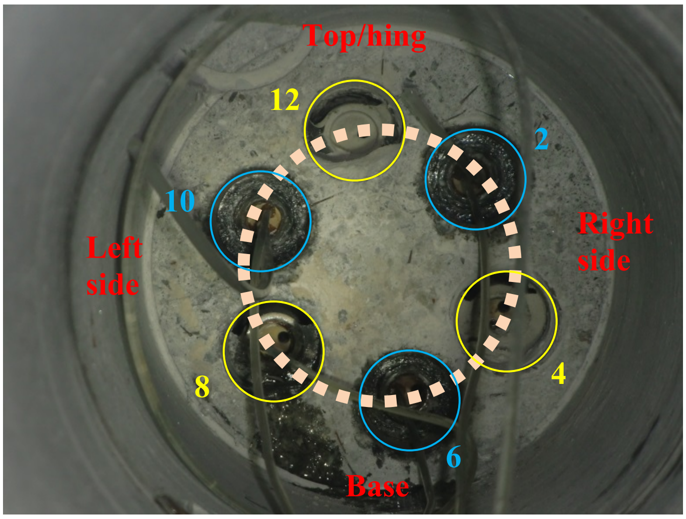
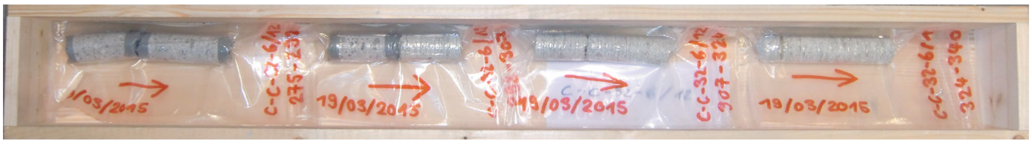


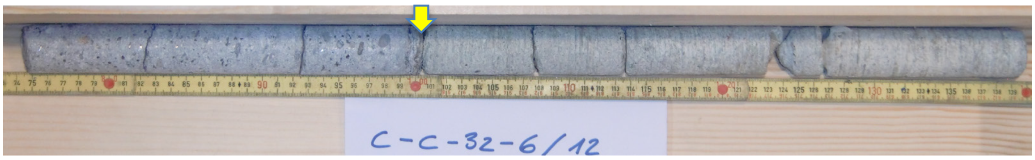
Fig. C-2 Schematic for labelling reinforcement boreholes. View direction is downhole. Approach boreholes is 220 mm OD. Reinforcement boreholes of 46 mm OD: 1st set of three (yellow) and 2nd set of three (blue). Orientations are labelled according to clock position. Overcoring diameter is indicated (132/124 mm).

Cores from all six 46 mm diameter reinforcement boreholes were vacuum-sealed in plastic bags. Cores separated at the shotcrete/bentonite interface in all boreholes during drilling. All sections were drilled dry with compressed air as coolant. Core loss was rather small for all boreholes. Images of all drill cores are shown in Figure C-3.

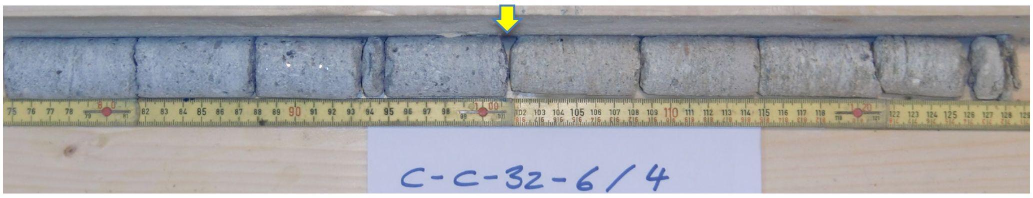
Moisture content is not preserved in these samples. Bentonite tends to dry out already during dry-drilling. Packaging of samples was therefore not done on a rigorous schedule, but rather when time permitted. Observations on the position of block boundaries relative to core segmentation are included in the report on results from bentonite studies (Villar et al. 2016).



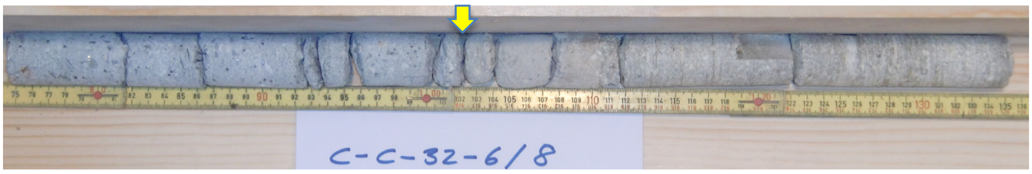
Shotcrete/bentonite core, C-C-32-6/12 vacuum packed. Bentonite is on right side.



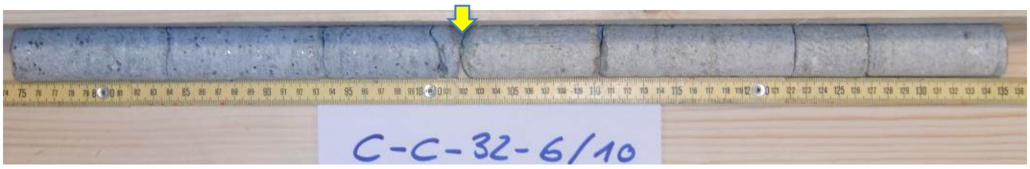
Shotcrete/bentonite core, C-C-32-6/12. Interface is marked by arrow. Bentonite is on right side.



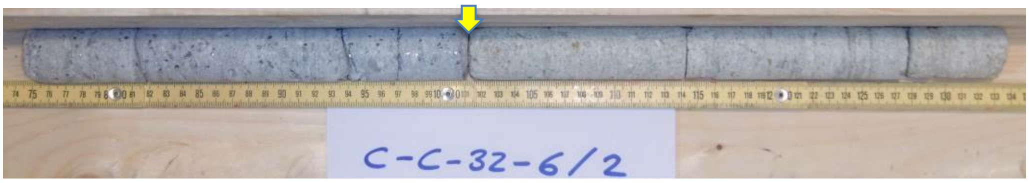
Shotcrete/bentonite core, C-C-32-6/4. Interface is marked by arrow. Bentonite is on right side.



Shotcrete/bentonite core, C-C-32-6/8. Interface is marked by arrow. Bentonite is on right side.



Shotcrete/bentonite core, C-C-32-6/10. Interface is marked by arrow. Bentonite is on right side.



Shotcrete/bentonite core, C-C-32-6/2. Interface is marked by arrow. Bentonite is on right side.

Fig. C-3 Images of samples from all six 46 mm reinforcement boreholes, C-C-32-6

C.3 Borehole wall after overcoring C-C-32-6-OC

The borehole walls after extraction of the overcore were inspected by a borehole camera (Fig C-4). The leftover fibre glass and resin reinforcements are well visible and also stabilise the borehole walls, and thus inhibit convergence and deformation of adjacent bentonite regions

The interface between shotcrete and bentonite is difficult to detect. It is seldom marked by visible discontinuities. This is in agreement with observations during sample cutting that the interface region was always physically intact.

View of the bentonite section of the 132 mm DM borehole after extracting the overcore, and with a temperature probe inserted (yellow). The white fibre glass "lamellae" are well visible (1), with mortar in-fill (2), resin (3) and bentonite (4). The fish-eye effect of the borehole camera is distorting the arrangement of the reinforcements a bit. The quality of the borehole walls is excellent, and drilling performed expertly.

Fig. C-4 Images of the borehole wall, associated with C-C-32-6-OC

C.4 Sample from 132 mm overcoring C-C-32-6-OC

The core quality appears to be excellent. There is no mechanical disturbance visible at the shotcrete/bentonite interface. The features seen on a fibre glass and resin reinforced core are explained in Figure C-5 for clarity. Depicted is the shotcrete part with two fibre glass reinforcements. Numbers in Figure C-5 refer to packer seats, with some grease on shotcrete surface (1), fibre glass rods (2), adapter made of HGW (3) with threading that was connected to the packer, injected resin (4), and shotcrete (6).

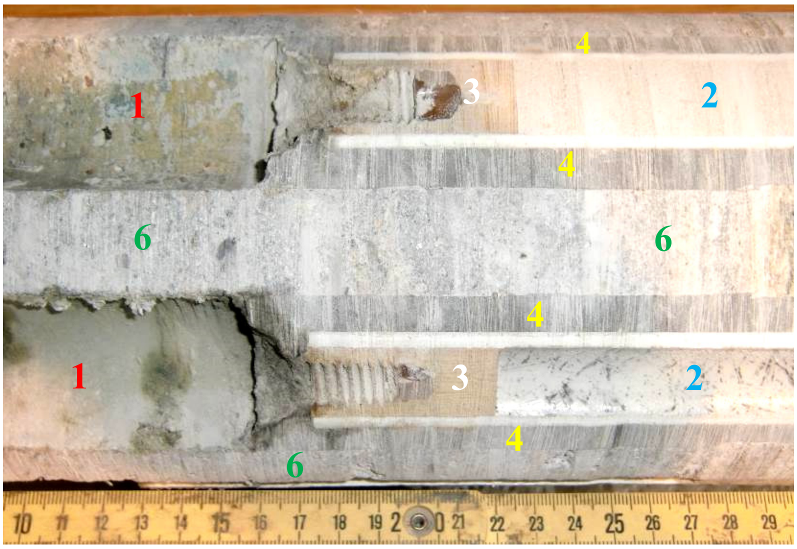


Fig. C-5 Images of shotcrete section of overcore C-C-32-6-OC with different materials numbered (see text)

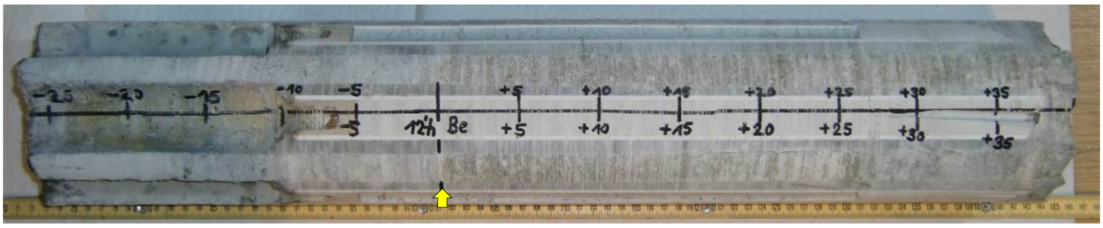
The degree of completeness of resin fill was much improved compared to C-C-32-5. An air-filled gap was only observed in one reinforcement boreholes (Fig. C-6). This void was filled with resin after encasing the entire cores in epoxy resin (section 4, and images below).

Images taken from four different sides (rotations) from the concrete part and the bentonite part are compiled in Figur C-6. Also shown is the deep end (bentonite). See explanations with Figure C-5 for materials and features.

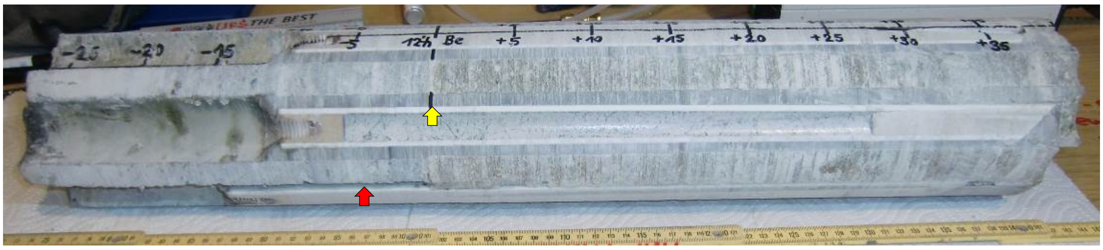
The scale marked in cm along the hinge line (black) and along the base line (green) are set to 0 at the location of the shotcrete/bentonite interface. Negative numbers refer to the shotcrete side, positive ones to the bentonite side. These photographs were taken just before wrapping and vacuum-sealing the core amples.

Detail of shotcrete/bentonite interface (arrow). Black scale is marked along hinge line. Bentonite is on right side. See Fig. C-5 for explanation of different materials.

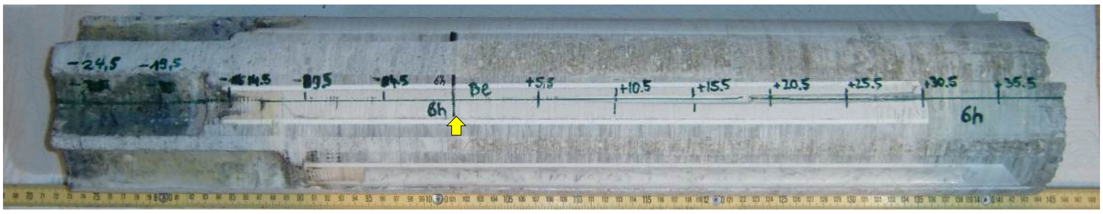
Deep end (bentonite). Arrows point at air-filled gap that was not properly filled with resin.



View of top (hinge, black scale) of overcore. Deep end towards the right. 0-mark is placed at interface position. Shotcrete on left, and bentonite on right (positive length scale).



View of right side of overcore (hinge at top). Deep end towards the right. Red arrow points at air-filled gap from incomplete resin injection.



View of base of overcore (green scale). Deep end towards the right. 0-mark is placed at interface position.

View of left side of overcore (hinge at base). Deep end towards the right. Red arrow points at air-filled gap from incomplete resin injection.

Fig. C-6 Images of overcore C-C-32-6-OC. The yellow arrow marks position of the shotcrete/bentonite interface.

C.5 Subsamples from overcore C-C-32-6-OC

The cutting scheme is reproduced in Figure C-7 for clarity. Figure C-8 shows the entire overcore after encasing it in epoyxy resin. Details of the interface region are shown in Figure C-9.

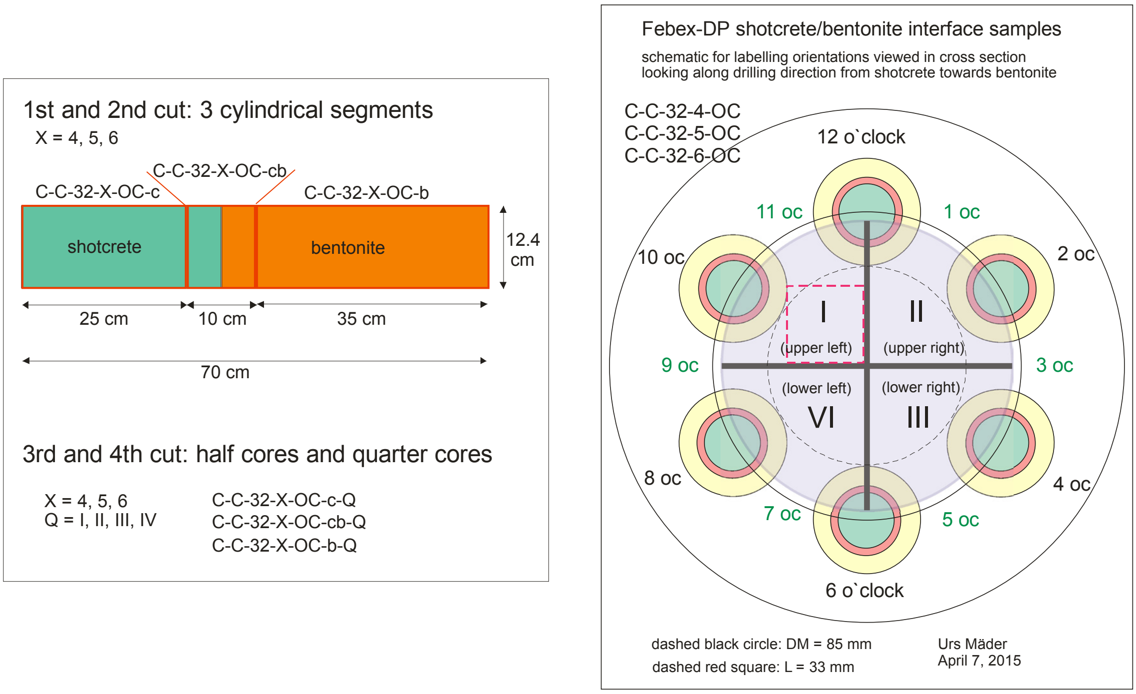
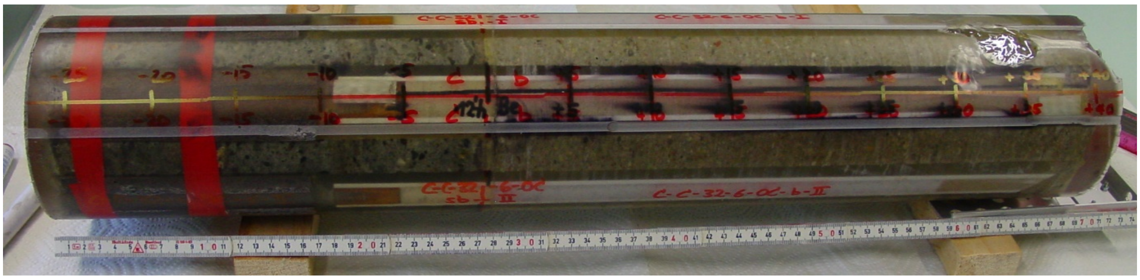
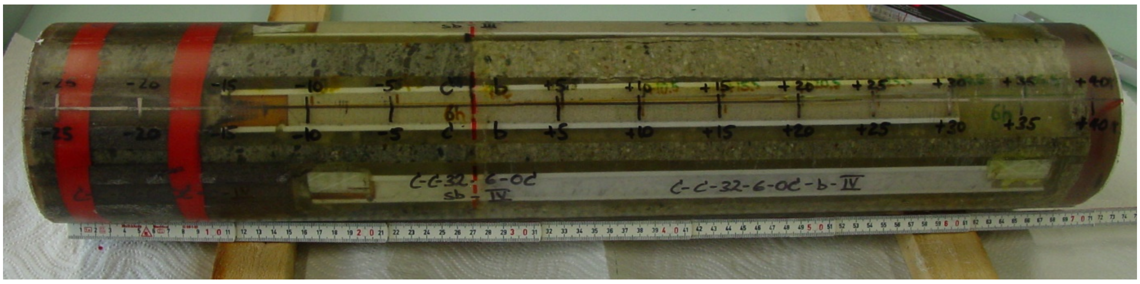


Fig. C-7 Cutting schematic for subsampling overcores

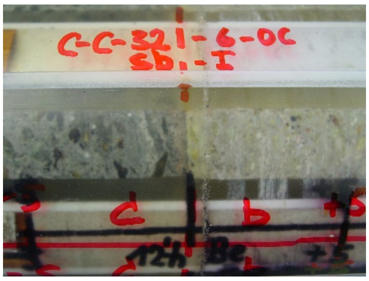


C-C-32-6-OC molded in epoxy resin; top view (red scale bar marks hinge line, 5 cm intervals). Shotcrete is on the left side.

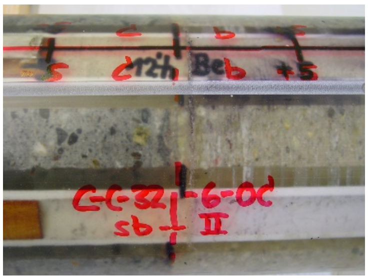


C-C-32-6-OC molded in epoxy resin; base view (black scale bar marks oposite of hinge line, 5 cm intervals). Shotcrete is on the left side.

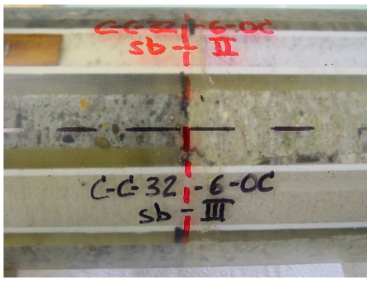
Fig. C-8 Images of samples cut from 132 mm overcore, C-C-32-6-OC



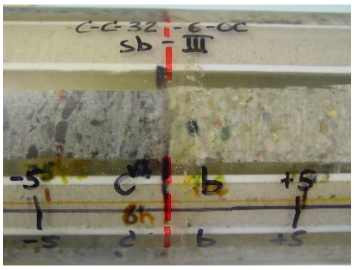
Interface in C-C-32-6-OC-cb, at 11 o'clock orientation



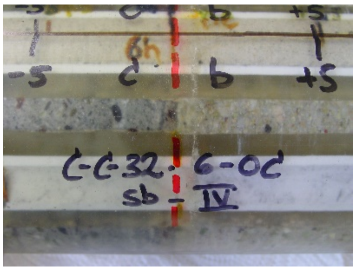
Interface in C-C-32-6-OC-cb, at 1 o'clock orientation



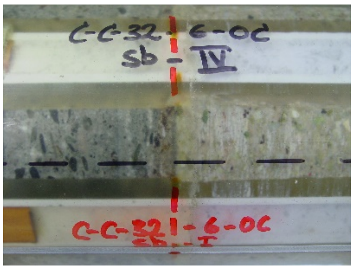
Interface in C-C-32-6-OC-cb, at 3 o'clock orientation



Interface in C-C-32-6-OC-cb, at 5 o'clock orientation



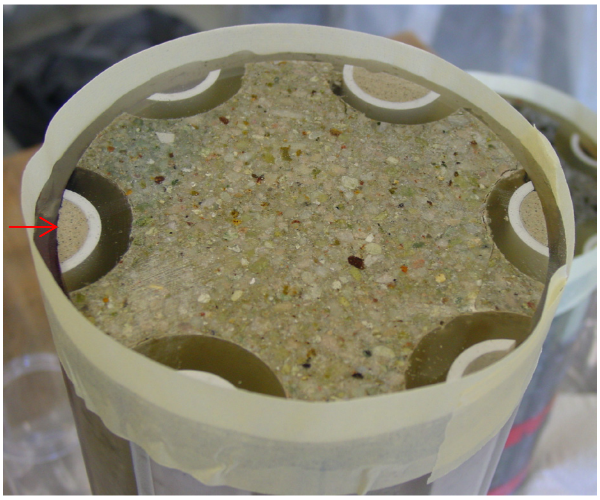
Interface in C-C-32-6-OC-cb, at 7 o'clock orientation



Interface in C-C-32-6-OC-cb, at 9 o'clock orientation

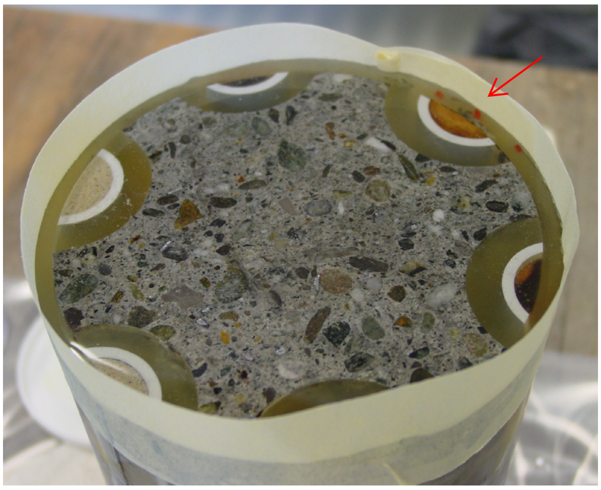
Fig. C-9 Images of interface region from overcore C-C-32-6-OC, viewed through the epoxy layer

Figure C-10 shows cut surfaces just after applying a protective covering of Araldite XW 396 resin. Textures are displayed well through the liquid resin.



C-C-32-6-OC-b

Bentonite surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.



C-C-32-6-OC-c

Shotcrete surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.

The highly reflecting particles are the cut steel fibres contained in the shotcrete.

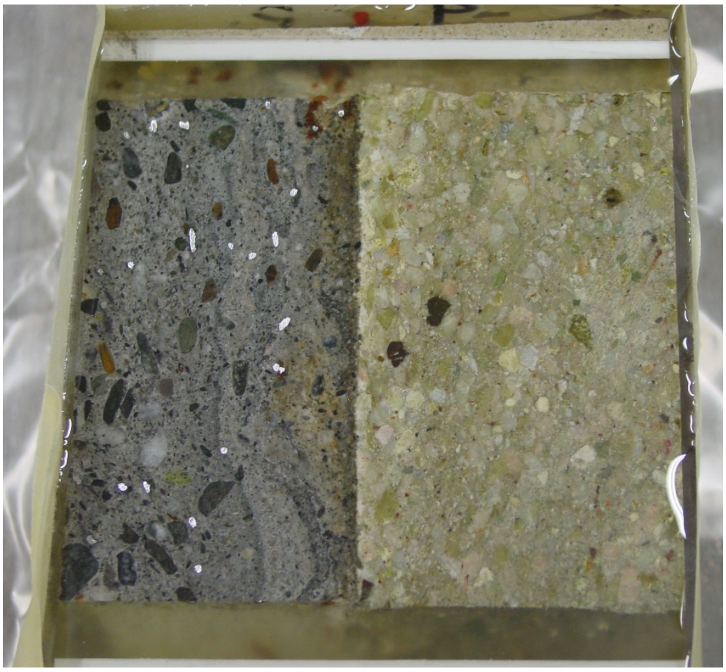
C-C-32-6-OC-cb

Bentonite surface after cutting and covering with resin. Hinge line (12 o'clock) is marked by red arrow.

Fig. C-10 Images of cut surfaces from overcore C-C-32-6-OC, viewed through a liquid epoxy layer

Figure C-11 shows cut surfaces after producing half cores, just after applying a protective covering of Araldite XW 396 resin. Textures are displayed extremely well through the liquid resin. Steel fibres are not corroded. Some faint alteration zones are visible in both shotcrete and bentonite. An overview of all resin-embedded half cores is shown in Figure A-11.

Half cores of the shotcrete/bentonite section were cut in quarter cores and the cut surfaces were not covered in resin. All cut pieces were immediately vacuum-sealed in plastic. Sharp edges were taped to protect the plastic bags. Protruding steel fibres were snipped off with a pair of pliers. Later, a second layer of plastic was applied, also with a vacuum



C-C-32-6-OC-cb-I&II

Surface of half-core after cutting and covering with resin.

Sample width is 10 cm. Shotcrete is on the left side, bentonite on the right. Glossy components are the steel fibres.

Quarter core I will contain the lower half of the image, and quarter core II the upper half.

C-C-32-6-OC-cb-I&II

Close-up of the image above.

C-C-32-6-OC-cb-III&IV

Surface of half-core after cutting and covering with resin.

Sample width is 10 cm. Shotcrete is on the left side, bentonite on the right. Glossy components are the steel fibres.

Quarter core IV will contain the upper half of the image, and quarter core III the lower half.

C-C-32-6-OC-cb-III&IV

Close-up of the image above.

Fig. C-11 Images of cut surfaces from overcore C-C-32-6-OC, viewed through a liquid epoxy layer

Shotcrete half cores were cut in quarter cores and cut surfaces were not covered with resin, but immediately vacuum-packed (Fig. C-12). Sharp edges were protected with tape to avoid puncturing plastic bags. Protruding steel fibres were snipped off with a pair of pliers. Later, a second layer of plastic bags was applied, also with a vacuum.

Fig. C-12 Quarter cores cut from C-C-32-6 after vacuum sealing. Left: shotcrete sections; middle: shotcrete/bentonite sections; right: bentonite sections

Bentonite sections (ca. 30 cm long) were more difficult to cut because of the limited cutting length and cutting depth that could be achieved with the mitre saw. The cores had to be cut from four sides (Fig. C-12, C-13) leaving just a small uncut middle section that could be easily separated. The cutting was rapid and drying effects are expected to be minimal. Both half cores were further cut into quarter cores and these were immediatley vacuum-packed.

Half cores of bentonite section

Half cores of bentonite section

Fig. C-13 Half cores and quarter cores of bentonite section from C-C-32-6-OC-b

Twelve quarter core samples were produced from C-C-32-6-OC (Tab. 6-1) and vacuum-packed twice in plastic. An additional layer of plasticised aluminium was applied as described in section 5.