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Module 4 (Temporary Sealing Technology)

Final report

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Overview of ESDRED Project

The Integrated Project known as ESDRED (Engineering Studies and Demonstrations of Repository Designs) was part of the European Union's 6th Euratom Framework Programme for Nuclear Research and Training. It has been a five years joint research and development effort by major national radioactive waste management agencies (or subsidiaries of those agencies) and by research organisations.

Radioactive Waste Management Agencies:
ANDRA, France (Co-ordinator)
ENRESA, Spain
NAGRA, Switzerland
NDA (Originally NIREX), United Kingdom
ONDRAF/NIRAS, Belgium
POSIVA, Finland
SKB, Sweden

Technological R&D Organisations:
AITEMIN, Spain
CSIC, Spain
DBE TECHNOLOGY, Germany
ESV EURIDICE EIG, Belgium
GRS, Germany
NRG, the Netherlands

ESDRED was mainly focused on technology issues. The first objective was to demonstrate, at an industrial scale, the technical feasibility of some very specific activities related to the construction, operation and closure of a deep geological repository for high level radioactive waste. This part of the work was organised inside four (4) Technical Modules and essentially involved the conception, design, fabrication and demonstration of specific equipment or products for which relevant proven industrial counterparts (mainly in the nuclear and mining industry) do not exist today.

Module # 4, Temporary Sealing

Module # 4, Temporary Sealing (using low pH cement) Technology**,** was focused on designing and demonstrating low pH cement formulations for the construction of sealing plugs and for rock support using shotcrete techniques. The partners involved were, ENRESA (Co-ordinator), NAGRA, POSIVA, SKB, CSIC & AITEMIN.

The construction of underground repositories for the disposal of high activity wastes (high level vitrified waste and spent fuel) will require the use cementitious materials for ground structural support and for the construction of auxiliary structures needed for the operation of the repository. Besides other applications, most underground repository concepts consider the use of cementitious materials for the construction of temporary or permanent plugs and rock support. The plugs are used to provide temporary mechanical (and sometimes hydraulic) confinement to buffer and seal materials arranged around the waste containers; other plugs provide the same functions for the seals placed at different locations in the underground disposal facilities. Specifically the use of concrete for rock support will be a key issue for repository concepts in clayey rock to guarantee the stability of the excavations (shafts, main tunnels and deposition drifts), but they may also be necessary in repositories built in crystalline rock as well.

For some applications the concrete will be in contact with the bentonite buffer materials and the host rock. Over time, concretes based on Ordinary Portland Cement (OPC), leached by the ground waters, will give rise to the release of significant quantities of ions, mainly OH^-, K^+, Na^+ and Ca^{2+}. The resulting leachate could have a pH as high as 13.5. This leaching water might perturb other repository materials such as the engineered barriers (bentonite buffer and backfill material) and the near-field host rock. In literature this phenomenon is known as the hyper alkaline plume.

Several studies have been performed on the reactivity of cement pore waters towards minerals, and bentonite in particular. In several experimental and modelling studies it has been shown that compacted bentonite is not stable in contact with cement pore waters. It has also been shown that cement pore waters of low-alkali cement with pH ≈ 11 are much less reactive towards compacted bentonite. In addition, models of spent fuel leaching are uncertain in the high pH range, but the intrinsic solubility of spent fuel is believed to increase drastically above pH ≈ 11.

From the point of view of creating a robust safety case for a nuclear waste repository, a prediction on how fast and where cement pore waters may travel during the long periods of time involved is uncertain, as well as the extent and nature of the physical and chemical changes produced. The hyper alkaline plume can last for a very long time (up to thousands of years) and therefore cause physicochemical transformations that could modify the radionuclide confinement properties of the disposal components. For preventing the development of the hyper alkaline plume effects it is proposed to develop low-pH cements (pore waters with pH ≤ 11) as an alternative to OPC for concrete formulation.

The concrete for rock support is commonly emplaced by shotcreting. Besides, previous experiments showed that the shotcrete method could significantly optimise plug construction costs, as well as achieve as closer contact between plug and host rock.

The most common shotcrete method is the wet one. By this method a wet concrete mix is fed into the shotcrete gun and sprayed onto the rock surface using compressed air. A set accelerator is fed into the air stream and mixed with the concrete during shotcreting to provide a “false-setting”, which helps to hold the concrete in place on the rock surface while hydration is occurring.

Although the utilization and performance of standard shotcrete in conventional construction works is well known, there is no experience with either the workability or the performance of shotcrete formulated to obtain a final low-pH product. Therefore, testing of this specific material under realistic conditions is needed.

The research activity of this Module, intended for the development of solutions for the use of low-pH shotcrete, was divided in two sub-modules running in parallel: one for the construction of plugs in crystalline rock, and another for rock support in both crystalline and clayey rock.

Low-pH shotcrete plugs

Plugs are required for confining backfills in underground repository drifts. The principal design criterion is that the plug sustains the mechanical loads in the different conditions to which it is subjected during the evolving conditions: during the operating phase one of the sides of the plug is essentially at atmospheric pressure, whereas the other is progressively loaded with the pressure imposed by the backfill materials (due to the mechanical pressure of a swelling clay and to the hydraulic pressure imposed by the rock formation as resaturation of the confined volume progresses). The plug itself is not a safety barrier of the repository; nevertheless it is considered as a functional requirement that it as far as possible provides the same degree of groundwater containment as the surrounding rock.

The construction material for the plugs differs in the national concepts. Most concepts favour the use of concrete but in some cases (e.g. Switzerland) alternative materials are under discussion. Depending on the design of the drifts, the plugs may be keyed in recesses in rock to provide mechanical stability and to project through the EDZ. Seal sections may require the removal of liners and partial (slots) or full re-excavation of the EDZ in weak rocks to avoid preferential flow along or through the EDZ and/or engineered structures which will degrade with time.

The basic objective of this Module 4 research activity was to develop solutions for the use of low-pH shotcrete for the construction of plugs intended for the confinement of buffer and seal materials installed in disposal drifts in crystalline rock.

According to available data, the development of low pH cements can be performed in different ways. Two approaches were pursued within the project, using conventional construction cements as the basic constituent: 1) Using Calcium Silicate Cements, based on Ordinary Portland Cement (OPC), plus significant amounts of blended mineral additions as the binding matrix and 2) Using Calcium Aluminates Cements (CAC) plus mineral additions. The types of blended material considered were mainly Low-calcium Fly Ash (FA) and Silica Fume (SiF).

The work was developed as follows:

- The first step of the project was focused on the definition of the design criteria applicable for the construction of low-pH shotcrete plugs in underground repositories.
- The next step involved the design of low-pH cement formulations, which are responsible for the pH of the system and the design of concrete mixes (basic mix) that would be placed using the wet-mix shotcrete technique. Concrete mix design involved the optimisation of aggregates grading and the selection of suitable chemical admixtures. Both cement pastes and concrete samples were characterized and tested in the laboratory.
- Before proceeding with the demonstration activities, the elaborated low-pH concrete designs were tested and verified, regarding the compliance with the specific functional requirements, in realistic field spraying tests. The industrial production of the low-pH concretes in combination with the shotcreting equipment and techniques available was evaluated in conditions similar to those expected in the underground repository.
- For determining the feasibility of the obtained solution and the bearing capacity of a plug of this type, needed for the design of the demonstrator, a short low-pH shotcrete plug was constructed and tested up to failure in a horizontal gallery in the Äspö Hard Rock Laboratory (HRL, Sweden).
- Finally, using the results from the short plug test a full scale low-pH long shotcrete plug was designed and constructed in the Grimsel underground research laboratory (Switzerland), to be tested under realistic conditions for demonstration purposes.

The viability of the obtained low-pH concrete recipes and the seal/plug construction methods and equipment were demonstrated at an industrial scale, and the obtained results show that in competent rock formations such as granite shotcrete plugs can be built without recesses excavated in the rock. It also showed that this method is much faster than cast in place concrete, that the emplacement method can be easily automated, and that it is almost possible to construct the plugs on a continuous basis due to the low heat release of the low-pH shotcrete during hardening. However, the needed curing time for achieving necessary strength must be considered

Low-pH shotcrete for rock support

In spite of the fact that recipes exist for low-pH concrete mixtures, the application for use as shotcrete for rock support required further testing. The work with the recipe of the low pH concrete for rock support was based on previous work with low-pH concrete, for instance within Module # 4 for plug construction or for construction concrete, and other work done in Canada and France.

The main objective for the work has been to demonstrate the feasibility of using low pH shotcrete for rock support in both crystalline and clayey rock.

Low-pH shotcrete recipes for rock support were developed for testing in Sweden (crystalline rock) and Switzerland (clayey rock). The recipe for the low-pH shotcrete was based on previous development work for low-pH concrete but specific laboratory work was needed to develop the mixture for the shotcrete. This included the selection of superplasticizers and accelerators. Finally the low-pH shotcrete recipes so developed needed to be adjusted for local conditions, just as they had been adjusted before being used for plug construction.

The development for conditions in Sweden was done in two steps:

- Step 1, small laboratory experiments with cement paste (low-pH binder and with shotcrete mortar) to get an understanding about suitable recipes with special investigation on the effect of set accelerators and superplasticizers.
- Step 2, petrographical analyses of the aggregates to be used and the final modification of the recipe to be used for the pilot scale testing and later also for the field test at the Äspö HRL. The aggregate was a mixture of natural sand (0 – 5 mm) and crushed rock

from Äspö HRL (5 – 11 mm). Filler material was also needed as the natural sand contains very little fine material.

The development for conditions in Switzerland was done at the Hagerbach facility:

- Laboratory analyses were carried out as well. Based on the results from Äspö HRL, the recipe used in Sweden was modified to suit standard concrete and local aggregate instead. Due to differences in the compositions of the cement and silica fume, preliminary testing of for e.g. workability was required.
- Opalinus clay samples were excavated and transported to the Hagerbach site to test the concrete. To allow a direct comparison with industrial standards, after preliminary feasibility tests, normal panel tests with a routine laboratory programme were carried out.

The results from the investigation show that it is possible to design a low-pH shotcrete for rock support and that the mechanical properties of the hardened shotcrete meet the requirements. The bonding to the rock at the Äspö HRL was insufficient due to a lack of homogeneity provoked by bad mixing at the shotcrete nozzle.

The work done is preliminary and further work will be needed before this low-pH shotcrete can be accepted for use as rock support in a future deep repository, for instance:

- The pH of hardened low pH shotcrete should be determined on cores taken from sprayed linings to ascertain the actual low pH.
- Suitable superplasticizers and accelerators should be selected with regard to long term safety.
- The field test was done without reinforcement however corrosion rates of wire mesh and steel fibre within sprayed concrete structures should be tested and compared with common shotcrete. The possibility to use other material for reinforcement should also be investigated.
- Reliable data should be collected regarding the durability of low pH shotcrete.
- The low-pH concrete requires good mixing, so suitable mixers and equipment for pumping should be investigated and tested in underground conditions.
- Large scale tests under real construction work conditions (e.g. in Opalinus Clay at the rock laboratory at Mont Terri) are required in order to demonstrate its competitiveness as compared to common shotcrete.

1 Chapter 1: Introduction

1.1 Summary of ESDRED Project

The Integrated Project known as ESDRED (Engineering Studies and Demonstrations of Repository Designs) has been a joint research and development effort by major national radioactive waste management agencies (or subsidiaries of those agencies) and by research organisations. ESDRED was co-ordinated by the French National Radioactive Waste Management Agency (ANDRA) and was part of the European Union's 6th Euratom Framework Programme for Nuclear Research and Training. The five year Project started with a total budget of EURO 18.4 million, of which 7.3 million was provided by the EU's Framework Programme. Many of the participants elected to do more, or more elaborate, work than originally envisaged so that a conservative estimate of the total final expenditure (including other increased costs) is 23 million euros.

The 13 participants (Contractors) in this project, from 9 European countries, were:

Radioactive Waste Management Agencies:	Technological R&D Organisations:
ANDRA, France	AITEMIN, Spain
ENRESA, Spain	CSIC, Spain
NAGRA, Switzerland	DBE TECHNOLOGY, Germany
NDA (Originally NIREX), United Kingdom	ESV EURIDICE EIG, Belgium
ONDRAF/NIRAS, Belgium	GRS, Germany
POSIVA, Finland	NRG, the Netherlands
SKB, Sweden	

ESDRED was mainly focused on technology issues and had **THREE MAIN OBJECTIVES**.

The **FIRST ESDRED OBJECTIVE** was to demonstrate, at an industrial scale, the technical feasibility of some very specific activities related to the construction, operation and closure of a deep geological repository for high level radioactive waste. This part of the work was organised inside four (4) Technical Modules (and numerous work packages) and essentially involved the conception, design, fabrication and demonstration (and further evaluation) of specific equipment or products for which relevant proven industrial counterparts (mainly in the nuclear and mining industry) do not exist today. Execution of the work was often by third party sub-contractors (especially the detailed design, fabrication and testing of new equipment) although, depending on the participant, some of the work was done in-house. Each of the four technical Modules involved from 3 to 7 participants thus always bringing the know-how and experience from several different national disposal concepts to the work. The programmes within these Technical Modules are provided below.

- Within **Module # 1, Buffer Construction Technologies for Horizontal Disposal Concepts,** certain participants were able to successfully design the necessary formulation and thereafter produce 4 ton bentonite rings to be used as an engineered barrier. Other participants demonstrated backfilling of the annular gap between a waste canister and the disposal drift wall using a variety of wet and dry products. Still others developed the product and the technique for backfilling disposal drifts with granular bentonite. The evolution over time and the performance of bentonite based seals, particularly in relation to gas permeability, was also assessed and is in fact on-going beyond ESDRED. Finally non- intrusive monitoring techniques based on seismology were also developed and demonstrated paving the way for additional experiments and cooperation between some of the partners beyond the end of the ESDRED Project.

- In **Module # 2** the 2 main participants were able to design, fabricate and demonstrate the equipment needed for the **Transfer and Emplacement of Waste Canisters** weighing between 2 and 5.2 tonne, in both horizontal and vertical disposal boreholes. A critical review type desk study related to retrievability of emplaced canisters was produced by a third partner.

- **Heavy Load Emplacement Technology** for horizontal disposal concepts was the only focus of **Module # 3.** In this Module two machines were successfully produced, each capable of emplacing 43 to 45 ton waste canisters in bored disposal tunnels while maintaining only a very small annular gap between the canister and the walls of the tunnel. One machine was based on water cushion technology while the other used air cushions. The latter machine was subsequently adapted to demonstrate the emplacement of sets of 4 pre-assembled bentonite rings (produced in Module 1), weighing 17 tons.

- The work in **Module # 4, Temporary Sealing (using low pH cement) Technology,** consisted first of designing a low pH cement formulation and then of preparing several concrete designs suitable for the construction of sealing plugs and for rock support using shotcrete techniques. A short plug was constructed at Äspö in Sweden and it was very quickly loaded to failure i.e. slippage by applying water pressure to one face. A second, much longer full scale plug was subsequently constructed at Grimsel test site in Switzerland. It was loaded using the swelling pressure created by bentonite blocks which were artificially hydrated. At time of writing the long plug had not started to slip. As the saturation of the bentonite is taking longer than expected the partners involved agreed to continue with the saturation of the bentonite blocks and the related data monitoring. The results of the test will be followed under the EURATOM's 7th Framework Programme, **MoDeRn** Project.

A **SECOND** and equally important **ESDRED OBJECTIVE** was to promote a shared European vision in the field of radioactive waste disposal technology. This was accomplished through the **INTEGRATION** process, which is the essence of **Module 6** and which is one of the key objectives that identify EURATOM's 6th Framework Programme. Among other things **INTEGRATION** resulted from working together, from sharing information, from comparing input data and functional requirements, from learning about one another's difficulties, from developing common or similar tender documents and bidder lists, from jointly developing courses and workshops and from coordinating demonstration activities whenever possible

Generally at least 2 **INTEGRATION** meetings were convened annually so that all ESDRED participants were updated on the progress of the work in all the Modules. Whenever practical these meetings were combined with the demonstration of a particular piece of new equipment, process or construction.

The **THIRD ESDRED OBJECTIVE** was entirely focused on training and communication which is the essence of the work in **Module 5** of the Project. Over the life of the project the participants wrote articles, presented technical papers at international conferences, held workshops, produced videos, developed and presented university lectures. The Project finished up by organising an international conference on the operational aspects of deep geological disposal in June 2008 and by contributing significantly to the EURADWASTE '08 Conference in Luxembourg/Bure in October 2008. A web site (www.esdred.info) was created and maintained over the life of the project with more than 16 000 visitors by Q3 2008. This site will be kept on line until 2010.

1.2 Module # 4, Temporary Sealing

The construction of underground repositories for the disposal of high activity wastes (high level vitrified waste and spent fuel) will in most cases require the use of large amounts (up to thousands of tons) of cementitious materials for ground structural support and for the construction of auxiliary structures needed for the operation of the repository. Besides other applications, most underground repository concepts consider the use of cementitious materials for the construction of temporary or permanent plugs and rock support. The plugs are used to provide temporary mechanical (and sometimes hydraulic) confinement to buffer and seal materials arranged around the waste containers; other plugs provide the same functions for the seals placed at different locations in the underground disposal facilities. Specifically the use of concrete for rock support will be a key issue for repository concepts in clayey rock to guarantee the stability of the excavations (shafts, main tunnels and deposition drifts), but they may also be necessary in repositories built in crystalline rock as well.

For some applications the concrete will be in contact with the bentonite buffer materials and the host rock. Therefore the interactions between these different materials and their potential deleterious effects have to be addressed. Over time, concretes based on Ordinary Portland Cement (OPC), leached by the ground waters, will give rise to the release of significant quantities of ions, mainly OH^-, K^+, Na^+ and Ca^{2+}. The resulting leachate could have a pH as high as 13.5. This leaching water might perturb other repository materials such as the engineered barriers (bentonite buffer and backfill material) and the near-field host rock. In literature this phenomenon is known as the hyper alkaline plume.

From the point of view of creating a robust safety case for a nuclear waste repository, a prediction on how fast and where cement pore waters may travel during the long periods of time involved is uncertain, as well as the extent and nature of the physical and chemical changes produced. The hyper alkaline plume can last for a very long time (up to thousands of years) and therefore cause physicochemical transformations that could modify the radionuclide confinement properties of the disposal components. For preventing the development of the hyper alkaline plume effects it is proposed to develop low-pH cements as an alternative to OPC for concrete formulation. It should also be in the interest of the international nuclear waste management community to obtain and test recipes for low-pH cement to be used in general construction in the underground areas of a high-level waste repository.

Very little knowledge has been developed so far in the areas of low-pH cement applications for underground construction; therefore the issues being addressed are both challenging and innovative.

The research activity of this Module, intended for the development of solutions for the use of low-pH shotcrete, was divided in two sub-modules running in parallel: one for the construction of plugs in crystalline rock, and another for rock support in both crystalline and clayey rock.

1.2.1 Background

Plugs are required for confining backfills in underground repository drifts. The principal design criterion is that the plug sustains the mechanical loads in the different conditions to which it is subjected during the evolving conditions: during the operating phase one of the sides of the plug is essentially at atmospheric pressure, whereas the other is progressively loaded with the pressure imposed by the backfill materials (due to the mechanical pressure of a swelling clay and to the hydraulic pressure imposed by the rock formation as resaturation of the confined volume progresses). The plug itself is not a safety barrier of the repository; nevertheless it is considered as a functional requirement that it as far possible provides the same degree of groundwater containment as the surrounding rock.

The construction material for the plugs differs in the national concepts. Most concepts favour the use of concrete but in some cases (e.g. Switzerland) alternative materials are under discussion for the final seals to ensure that the degradation of the cement with time does not influence the function of the seal. Frictional gravel supports or constructions including specially designed rock blocks are being considered.

Concrete plugs are also proposed for salt rock and the creep potential of the salt rock means that the contact with the plug will become increasingly tight.

Seals may consist of two mechanical abutments (e.g., plugs constructed from low-pH cement and rock blocks) on either side of a sealing section to provide mechanical stability for the bentonite seal in between. Depending on the design of the drifts, the abutments may be keyed in recesses in rock to provide mechanical stability and to project through the EDZ. Seal sections may require the removal of liners and partial (slots) or full re-excavation of the EDZ in weak rocks to avoid preferential flow along or through the EDZ and/or engineered structures which will degrade with time.

Since concrete is not considered to be chemically stable due to the dissolution of the cement and, in reinforced concrete, the corrosion of some types of reinforcement, and because the hydrogen gas production associated with this corrosion can cause piping of adjacent backfills, therefore the operational lifetime of such plugs is estimated to be on the order of one or a few hundred years. Besides, installed concrete may have a degrading effect on other EBS components it may have to be removed and replaced by backfills or masonries of compacted clay blocks in conjunction with permanent closure of the repository [1].

Several studies have been performed on the reactivity of cement pore waters towards minerals, and bentonite in particular. In several experimental and modelling studies it has been shown that compacted bentonite is not stable in contact with cement pore waters. It has also been shown that cement pore waters of low-alkali cement with pH ≈ 11 are much less reactive towards compacted bentonite [2, 3]. In addition, models of spent fuel leaching are uncertain in the high pH range, but the intrinsic solubility of spent fuel is believed to increase drastically above pH ≈ 11 [4].

According to available data, the development of low pH cements can be performed in different ways and two approaches were pursued within the project, using conventional construction cements as the basic constituent: 1) Using Calcium Silicate Cements, based on Ordinary Portland Cement (OPC) plus significant amounts of blended mineral additions as the binding matrix and 2) Using Calcium Aluminates cements (CAC) plus mineral additions. The types of blended material mainly considered were Low-calcium Fly Ash (FA) and Silica Fume (SiF).

Previous experiments such as the second concrete plug constructed as part of FEBEX [5], showed that the shotcrete construction method could significantly optimise costs, as well as achieve as closer contact between plug and host rock

On the other hand, although the utilization and performance of standard shotcrete in conventional construction works is well known, there is no experience regarding either the workability or the performance of shotcrete formulated to obtain a final low-pH product and, therefore, testing of this specific material under realistic conditions is needed. Also the bearing capacity of this type of plug requires a specific load test to demonstrate its possibilities, and the same may be said concerning the hydraulic properties.

1.2.2 Objectives

The basic objective of this research activity was to develop solutions for the use of low-pH shotcrete for the construction of plugs intended for the sealing of disposal galleries in crystalline rock.

In this sense, the specific objectives of the proposed activities were:

- Definition of the design criteria applicable for the construction of low-pH shotcrete plugs in underground repositories.
- Development of low-pH cement formulations for industrial shotcrete application in repository construction.
- Design of low-pH shotcretes, compliant with some pre-established functional requirements, to be used in the construction of repository plugs
- Adaptation and optimisation of the wet-mix shotcrete technique to the construction of concrete plugs in real underground drifts using the low pH concrete formulation designed
- Full scale demonstration of a low-pH shotcrete plug construction and operation.

1.2.3 Project technical evolution

The work performed in this sub-module was developed as follows:

- The first step of the project was focused on the definition of the design criteria applicable for the construction of low-pH shotcrete plugs in underground repositories.
- The next step involved the design of low-pH cement formulations, which are responsible for the pH of the system and the design of concrete mixes (basic mix) that would be placed using the wet-mix shotcrete technique. Concrete mix design involved the optimisation of aggregates grading and the selection of suitable chemical admixtures. Both cement pastes and concrete samples were characterized and tested in the laboratory.
- Before proceeding with the demonstration activities, the elaborated low-pH concrete designs were tested and verified, regarding the compliance with the specific functional requirements, in realistic field spraying tests. The industrial production of the low-pH

concretes in combination with the shotcreting equipment and techniques available was evaluated in conditions similar to those expected in the underground repository.

- For determining the feasibility of the obtained solution and the bearing capacity of a plug of this type, needed for the design of the demonstrator, a short low-pH shotcrete plug was constructed and tested up to failure in a horizontal gallery in the Äspö HRL (Sweden).
- Finally, using the results from the short plug test a full scale low-pH long shotcrete plug was designed and constructed in the Grimsel underground research laboratory (Switzerland), to be tested under realistic conditions for demonstration purposes.

1.2.4 Results

The design criteria applicable for low-pH concrete plugs have been established at the beginning of the project by the major national radioactive waste management agencies participating in this Module: ENRESA, NAGRA, SKB, POSIVA and ANDRA.

Different low-pH cement formulations were developed using conventional cement components and their key properties were characterised. According to the characterisation results, the most suitable low-pH cements were selected to design the basic concrete composition for shotcreting.

Results from preliminary field tests confirmed that the concrete materials selected and the proportions used were suitable to fulfil design criteria and that the conventional wet-stream shotcreting technique is appropriate for the construction of plugs with the selected low pH concrete.

Results from a short low-pH short shotcrete plug constructed in a horizontal gallery in the Äspö HRL (Sweden), that was loaded up to failure with a hydraulic pressure provided by a pump, and thereafter dismantled and analysed, confirmed the feasibility of the solution developed and helped to determine the key parameters regarding the bearing capacity of a plug of this type.

Finally, a full scale low-pH long shotcrete plug demonstrator was designed and constructed in the Grimsel underground research laboratory (Switzerland), and is being tested beyond the end of the ESDRED Project under realistic conditions (loaded by the swelling pressure of a bentonite based seal re-saturated under the local hydraulic gradient assisted by an artificial hydration system).

In summary all the objectives of the planned research were fulfilled. Consequently the use of the low-pH concrete is now available as a tool to help increase the long term safety if needed, by achieving a more stable multiple barrier systems (natural and engineered), given the reduction of the hyper alkaline plume effect, and by providing a better compatibility of engineered materials and natural barriers.

Thanks to the research performed the seal/plug design was improved, so that in the future concrete plugs can be built in competent formations (granite) with no reinforcement and without recesses excavated in the rock.

The viability of the obtained low-pH concrete recipes and the seal/plug construction methods and equipment were demonstrated at an industrial scale, and the obtained results show that shotcrete plugs can be built much faster than cast in place ones, and that it is almost possible to construct the plugs on a continuous basis due to the low heat release of the low-pH shotcrete during hardening. However, the needed curing time for achieving necessary strength must also be considered.

1.3 Module # 4, Low-pH Shotcrete Rock Support

1.3.1 Background

In spite of the fact that recipes exist for low-pH concrete mixtures, the application for use as shotcrete for rock support required further testing. The work with the recipe of the low pH concrete for rock support was based on previous work with low-pH concrete, for instance within Module # 4 for plug construction or for construction concrete, and other work done in Canada and France.

The results from the development of low-pH recipes, pilot testing and full scale field tests in Sweden and the results from laboratory and pilot tests in Switzerland are presented herein.

The most common shotcrete method is the wet method. By this method a wet concrete mix is fed into the shotcrete gun and sprayed onto the rock surface using compressed air. A normal concrete will flow easily, however substitution of cement with silica fume in the low-pH concrete makes the concrete more viscous. In the ESDRED work a set accelerator was fed into the air stream and mixed with the concrete during shotcreting. A set accelerator provides a "false-setting", which helps to hold the concrete in place on the rock surface while hydration is occurring.

The selection and testing of suitable reinforcement material, such as wire mesh or short fibres, is outside the scope of this project but requires investigation.

SKB has had the responsibility for recipe development for Swedish conditions, as well as pilot and full scale field tests in Sweden. SKB has also had the overall responsibility for the reporting to the EC on this part of Module 4.

Based on the recipe developed in Sweden, NAGRA has developed its own recipes for rock support using materials available in Switzerland.

1.3.2 Objectives

The main objective for the work has been to demonstrate the feasibility of using low pH shotcrete for rock support. The recipe for the rock support low-pH shotcrete was based on previous development work for plug construction low-pH concrete but specific laboratory work was needed to develop the mixture for the rock support. This included the selection of superplasticizers and accelerators.

1.3.3 Project technical evolution

The development of a low-pH shotcrete recipe for rock support for conditions in Sweden was done in two steps.

Step 1 was executed in 2005 and consisted of small laboratory experiments with cement paste to get an understanding regarding suitable recipes and included special investigations regarding the effect of set accelerators and superplasticizers. This was done at the CBI (The Swedish Cement and Concrete Research Institute) laboratory in Stockholm with low-pH binder and with shotcrete mortar.

The results from Step 1 become the basis for continuation of the work within Step 2, which started with petrographical analyses of the aggregates to be used and the development of a suitable recipe to be used for the pilot scale testing and later also for the field test at the Äspö HRL. All of the crushed rock in the low-pH shotcrete used for the plug construction in the horizontal drift at Äspö HRL, came from Äspö. The recipe for the shotcrete for rock support was modified. Instead of using only crushed rock the aggregate was a mixture of natural sand (0 – 5 mm) and crushed rock from Äspö HRL (5 – 11 mm). Filler material was also needed as the natural sand contains very little fine material.

The work in Sweden with Step 1 and 2 was performed during September 2005 - April 2006.

Development of a low-pH shotcrete recipe for rock support for conditions in Switzerland was done at the Hagerbach facility where all the required equipment and infrastructure to perform shotcrete testing is available. The Hagerbach team carried out the laboratory analyses as well.

The work in Switzerland was performed during September – November 2006 followed by reporting from NAGRA when results were available in early 2007.

1.3.4 Results

1.3.4.1 Results of work done in Sweden

Based on the results of the laboratory work within Step 1 the selected recipes were tested in pilot scale in February 2006 at Vattenfall´s Concrete Research Centre at Älvkarleby, Sweden.

All the ingredients in the recipes were carefully measured and mixed in a small concrete paddle mixer and each mix had a volume of 150 litres. The selected superplasticizer and the air entraining agent were added in the concrete mix. Slump tests as well as measuring the air content in the mix were done before the concrete was transferred to the concrete pump in the test area.

Two types of commercially available filler gave good coherence and workability. These were quartz filler (Öresund sand <0.25mm) and limestone filler (Köping 500 <0.5mm). The Öresund sand, which comes from the seabed and contains well-rounded quartz particles, gives a somewhat lower plastic viscosity than the more angular limestone powder (from crushed crystalline limestone). Further tests were continued with these fillers and rheology was measured with and without entrained air. In fresh concrete entrained air acts as a particle but it will give lower mechanical strength in hardened concrete. In shotcrete, most of the air will be lost during the shooting.

Tests with different amounts of air entraining agent were also done.

The recipe selected (10-2) for pilot and field experiments is based on undensified silica fume and lean natural sand complemented by a filler based on well rounded quartz grains. The rounded grains help to overcome the higher viscosity due to silica fume. To improve the rheology of the concrete, an air entraining agent could be used to increase the air content. Shotcrete recipe 12-2 based on limestone filler was also chosen for further tests to demonstrate the difference between limestone and quarts filler.

The pilot test was performed in February 2006 on two recipes, recipe 10-2 with quartz filler and recipe 12-2 with limestone filler respectively. The amount of plasticizer was adjusted during the test to achieve different workability and spraying properties. The test was performed at ambient temperature.

The field-testing at Äspö HRL was done after the evaluation of the results from the pilot testing., The same contractor and the same equipment that had been used for the construction of the low pH shotcrete plug in the KBS-3H deposition drift (with a diameter of 1.85 m) were employed for the field tests for rock support at the Äspö HRL.

No specific preparation of the rock wall at Äspö HRL was done except that the area was cleaned using pressurised water before starting the work.

Field tests were conducted using recipe 10-2 with 250 kg of quartz filler only because limestone was not used in the shotcrete for the plug. Compressive strength and density were tested on core drilled cylinders according to SS-EN 12504-1 and Young's modulus on core drilled cylinders according to SS 13 72 32. In Table 5 the compressive strength is recalculated to cube strength (Fck.cube). Shrinkage was measured both, according to SS 13 72 15 and in water on sawed beams. The shotcrete was sprayed with water daily for 7 days but not kept continuously wet. At CBI, beams were sawn and put in water for 24 hours before the first measurement. Bonding to rock was determined according to SS 13 72 43.

The compressive strength and Young's modulus were sufficient although the water-binder-ratio had to be increased from 0.45 to 0.50. The beams did swell a little when placed in water. This indicates that the beams had lost some water before the drying started. If this is considered then the drying shrinkage would be higher than for cast in place low-pH concrete as it was the case for the shotcrete from the Älvkarleby experiments.

1.3.4.2 Results of work done in Switzerland

Pre-tests, Phase 1, consisted of spraying tests onto panels. The spraying operation was commenced two hours after mixing the concrete to demonstrate the specified workability time. The wet mix was transported by a ready-mix drum on a lorry. Modern wet-mix spraying equipment with electronically controlled push-over system provided a nearly pulsation-free conveyance of the wet mix from the pump to the nozzle. The concrete had to be pushed through a 30 m long delivery pipe. The nozzle was installed to a remote controlled manipulator. This equipment corresponds to modern sprayed concrete wet-mix equipment and provides homogeneous shotcrete of good quality and minimised rebound.

Dosage of an alkali free set accelerator was varied between 5 and 15 wt % of cement (equals 10.5 to 31.5 kg/m^3).

Numerous tests were carried out either directly on the sprayed concrete (e.g. fresh concrete early strength) or from cores drilled after the placement tests.

Spraying tests on prepared Opalinus clay specimen were carried out as Phase 2, in order to investigate the performance of the low pH shotcrete mix on rock conditions as envisaged for future repositories in Switzerland. The Opalinus clay specimens were excavated 18 months ago from the Mont Terri Rock Laboratory and stored within plastic bags to protect against moisture. There was no visual sign of weathering or disintegration of the Clay stone when prepared for testing.

Spraying performance under realistic underground conditions showed to be satisfactory. Up to 150 mm shotcrete could be sprayed on Opalinus clay in one pass without any problems.

In November 2006, Phase 3, a large-scale field test, was carried out at the Hagerbach test gallery. The objective of this field test was to demonstrate the applicability of low pH shotcrete for underground excavation rock support. In particular it was shown that spraying overhead is feasible within economically reasonable performance rates compared to common wet mix shotcrete work.

2 Chapter 2: Program Implementation

2.1 Low-pH Shotcrete Plug

2.1.1 Introduction

Concrete will be used during the construction of the deep geological repository for high level radioactive waste for different purposes such as grouting, fixing of rock bolts, rock support, lining of tunnels and drifts (galleries) and for sealing plugs at the mouth of the disposal drift or disposal cell, as well as in other specific locations of the underground excavated areas. Concrete will also be used for construction of various auxiliary structures needed for the operation of the repository. Depending on the type of host rock, the amount of concrete will vary. For instance, for a repository constructed in granite as in Sweden and Finland concrete will only be used for grouting, rock bolts, rock support and sealing plugs for disposal drifts. The amount of concrete used that needs to be left in the repository depends on the disposal concept, but it has been estimated, in some cases, to be in the order of 10000 metric tons. Auxiliary structures may be required to be removed, totally or in part, in order to reduce the risk for long term interaction between the concrete, waste, buffer material and the host rock. On the other hand, for a repository constructed in clayey rock, such as could be the Spanish reference formations, the amount of concrete would be much higher as thick supporting lining will be needed for the tunnels, disposal drifts and disposal cells. ENRESA's estimation of the concrete needed for the construction of a HLW repository in clayey rock is about 670000 metric tons. As for some applications the concrete will be in contact with the bentonite buffer materials and the host rock, so the interaction and potential deleterious effects have to be addressed.

Over time, normal concretes based on Ordinary Portland Cement (OPC) will be leached by the ground waters, giving rise to the release of significant quantities of ions, mainly OH^-, K^+, Na^+ and Ca^{2+}. The resulting leachate could have a pH as high as 13.5 for some time. This leaching water might perturb other repository materials such as the engineered barriers (bentonite buffer and backfill material) and the near-field host rock. In literature this phenomenon is known as the hyper alkaline plume.

The radwaste decay heat and the underground water will influence the equilibrium of the physicochemical properties of the bentonite-concrete system. During and after resaturation, highly alkaline interstitial waters from the concrete will diffuse through the clay (bentonite) barrier. The high pH conditions (pH of 12.5 to 13.5) of the concrete pore waters is very much in contrast with the pH of 7 to 9 of the equilibrium pore waters in the bentonite. This will produce a complex geochemical cement-bentonite system, whose evolution with time becomes of great importance to the global performance and safety assessment of the repository. First, radionuclide mobility may be affected by precipitation/adsorption processes at the cement-bentonite interface. Second, the properties of the clay barrier may also be affected by the instability of the clay minerals in a high pH environment.

Several studies have been performed on the reactivity of cement pore waters towards minerals, and bentonite in particular. In several experimental and modelling studies it has been shown that compacted bentonite is not stable in contact with cement pore waters but the maximum expected alteration in repository conditions will be at the cm scale. It has also been shown that cement pore waters of low-alkali cement with pH ≈ 11 are much less reactive towards compacted bentonite, and the potential adverse effects are in practice negligible. In addition, models of spent fuel leaching are uncertain in the high pH range, but the intrinsic solubility of spent fuel is believed to increase drastically above pH ≈ 11.

From the point of view of creating a robust safety case for a nuclear waste repository, a prediction on how fast and where cement pore waters may travel during the long periods of time involved is uncertain. Furthermore the hyper alkaline plume can last for a very long time (up to thousands of years) and therefore cause physicochemical transformations that could modify the radionuclide confinement properties of the disposal components. For preventing the development of the hyper alkaline plume effects it is proposed to develop low-pH cements as an alternative to OPC for concrete formulation. It should also be in the interest of the international nuclear waste management community to obtain and test recipes for low-pH cement to be used in construction in the underground areas of a high-level waste repository.

Hence, the basic objective of this research activity was to develop solutions for the use of low-pH shotcrete for the construction of plugs, for the sealing of disposal galleries.

In this sense, the specific objectives of the proposed activities were:

- Development of low-pH shotcrete formulations for industrial application in repository construction.
- Development or adjustment of the required low-pH shotcreting techniques for construction of repository plugs.
- Full scale demonstration of a low-pH shotcrete plug.

2.1.2 Input data and Functional Requirements

The input data and functional requirements applicable for low-pH concrete plugs, listed hereafter, were agreed by the major national radioactive waste management agencies participating in this Module: ENRESA, NAGRA, SKB, POSIVA and ANDRA.

2.1.2.1 Definitions

Within ESDRED IP the term ***input data*** refers to criteria or elements that, as a rule, are unavoidable and are not negotiable or open to discussion even though there will be differences between the various partners in any given Module. These could also be described as *fixed design criteria*. The term ***functional requirements*** refer to those criteria or elements that are open to discussion or negotiation. In other words these may also be described as *flexible design criteria or flexible input data.*

Therefore, the *input data* and *functional requirements* applicable for low-pH concrete applications had to be explicitly indicated, but in order to be applicable those requirements had to be connected to measurable parameters. If limitations on a precise determination for a requirement existed, the need and difficulty for its characterisation had to be justified.

2.1.2.2 Input data and functional requirements

The considered *input data* were:

- Shotcrete as emplacement method: the use of shotcreting has proven to be an efficient and cost saving method for rock support in underground construction, and can be also applied to plug construction with several advantages.

- pH equal or below 11: a pH value ≤ 11 was considered acceptable for the shotcrete formulation. The squeezing technique (pore pressing extraction) was considered within this project as the reference method for measuring the pH.

- Mechanical properties of host rock: the rock properties needed for the designs are: Young's module, Poisson's ratio, tensile strength, friction angle and cohesion. Additionally, some rock-plug interface mechanical properties are needed: friction angle, cohesion and normal and shear stiffness.

- Hydraulic conductivity of host rock: the maximum hydraulic conductivity allowed through the shotcrete plug should be at least that of the host rock (it is an input parameter for the function of the plug).

- Ground water composition: the durability of the shotcrete will depend on the aggressiveness of the underground water, which is a function of salinity and flow. Therefore, these parameters should be known.

The *functional requirements* to comply with are: hydraulic conductivity (site specific – same order of magnitude as that of the EDZ), mechanical properties of concrete, durability (concept specific – linked to the operational life of the repository), workability, pump ability, slump (as per NAGRA), peak hydration temperature, thermal conductivity (concept specific – not below that of the bentonite barrier), construction rate, use of organic components (fibres or admixtures), steel fibres (as per NAGRA), maximum total pressure or pressure at the plug/buffer interface, length of plug (as per SKB), gallery dimensions or diameter, time between start of construction and full function of plug (as per SKB), use of other products (as per SKB), drainage (as per SKB).

The specified values for functional requirements are shown in Table 1. A discussion on some of the functional requirements can be found in Module 4 Deliverable Report [D1].

Table 1: Functional requirements for concrete plugs

Ítem	ENRESA	SKB	ANDRA	POSIVA
Hydraulic conductivity	$k \leq 10^{-10}$ m·s^{-1}	$k \leq 10^{-10}$ m·s^{-1}	Depends on length L: $k / L \leq 10^{-12}$ s^{-1}	$k \leq 10^{-10}$ m·s^{-1}
Final mechanical properties: **- Young modulus** **- Poisson's ratio** **- Tensile strength** **- Friction angle** **- Cohesion** **- Compressive strength**	›20000MPa 0,2 – 0,3 > 1 MPa ≥ 37º ≥ 2 MPa ≥ 10 MPa	›20000MPa 0,2 – 0,3 > 1 MPa ≥ 37º ≥ 2 MPa ≥ 10 MPa	High strength is not required as such, but the requirements on durability lead to prescribe mix compositions corresponding to high performance concrete (≈ 60 MPa at 90 days)	›20000MPa 0,2 – 0,3 > 1 MPa ≥ 37º ≥ 2 MPa ≥ 10 MPa
Durability	≥ 100 years	≥ 100 years	as high as possible (and sulphate resistant)	≥ 100 years
Workability	≥ 2 hours	≥ 2 hours	≥ 2 hours	≥ 2 hours
Pump ability	250m	250 m	> 100 m	250 m
Peak hydration temperature	≤ 40ºC	≤ 40ºC	≤ 30ºC	≤ 40ºC
Thermal conductivity	1,2 W/mºC	1,2 W/mºC	Access drift plugs: not specified Disposal cell plugs: 1,75 W/mºC	1,2 W/mºC
Construction rate	1 m/day		Not specified	
Use of organic components (fibres or admixtures)	To be studied	Not at all but if this is not possible, quantities and types of organic material must be described	Not at all but if this is not possible, quantities and types of organic material must be described	Not at all but if this is not possible, quantities and types of organic material must be described
Estimated pressure at the plug/buffer interface	7 MPa	15 MPa	Access drift plugs: 3 MPa Disposal cell plugs: 4.5 MPa	15 MPa
Length of plug		As short as possible but it must be able to withstand the estimated pressure with a safety factor	Access drift plugs: not defined Disposal cell plugs: 4 to 6 m	As short as possible but it must be able to withstand the estimated pressure with a safety factor
Rock surface		No slot shall be necessary		No slot shall be necessary
Diameter		1860 mm-1840 mm	Access drift plugs: 7 m Disposal cell plugs: 0.7 to 3.5 m	1860 mm-1840 mm
Ground water conditions		Saline (3.5%)		Saline (3.5%)
Time between start of construction and full function of plug		To be studied	Not specified	To be studied
Rest products		It must be possible to describe and quantify the rest products after degradation of the plug	It must be possible to describe and quantify	It must be possible to describe and quantify the rest products after degradation of the plug
Drainage		It must be possible to drain water through the plug during construction (including curing time). It must be possible to seal the drainage hole after the construction of the plug.	Not specified. However, piping might be needed for artificial water supply to buffer (to be eventually grouted)	It must be possible to drain water through the plug during construction (including curing time). It must be possible to seal the drainage hole after the construction of the plug.

NAGRA does not specify requirements for concrete plugs. The Swiss concept for the construction of the seals foresees the use of frictional non-cementitious materials for embankments. Concrete plugs will only be used to protect the seals from accidental flooding during the operational phase. The distance between such concrete plugs and waste packages will be large enough (metres) to rule out any influence of a potential pH-plume in a diffusion dominated system (bentonite and Opalinus Clay). Regular (not low-pH) concrete is therefore planned to be used.

2.1.3 Studies and/or computer simulations and/or Modelling

The main goal of the first part of the project was the development of a low pH concrete to be employed in the construction of shotcrete plugs. This implied the use of low-pH cement formulations in the concrete mixes. The required work was divided in three steps:

1. Development and characterization of low-pH cement formulations.
2. Design of basic concrete mixes to be shotcreted, which includes the evaluation of the compatibility between low-pH cement formulations and chemical admixtures commonly used when shotcreting.
3. Realization of the shotcrete tests in a real scale (see 2.1.4).

2.1.3.1 Development and characterization of low-pH cement formulations

The development of low pH cement formulations implies the use of mineral admixtures with high silica contents which reduce the pore fluid pH of the cementitious materials. In this step only conventional construction materials were use:

1. Base cement matrix: Ordinary Portland Cement (OPC) and Calcium Aluminate Cement (CAC).
2. Mineral admixtures for pH reducers: Silica Fume (SiF), Fly Ash (FA), Blast Furnace Slags (BFS) and bentonite (BN).

Different cement pastes were prepared using the above commented raw materials, employing several water/cement ratios. A standard curing process was employed: 98% Relative Humidity (RH) and 21± 2ºC. The acceptance criteria for the selection of adequate low-pH cement formulations were:

1. Setting time and hardening of the cement paste.
2. Pore water pH of cement paste < 12.5 after 90 days of curing, in order to fulfil the pH ≤ 11 requirement in the final product, i.e. the shotcrete, as defined in [D1]. This criterion was based on the fact that the pH of pore water evolves with cement hydration and that hydration is slower with mineral additions which hydrate at a lower rate.

For the measurement of the pore fluid pH of the cement pastes no standardized method exists, so a methodology was developed, described in [D2.1 & D3.1], and calibrated with the Pore Fluid Extraction technique. This method basically consists of measure the pH of a mix composed of powdered cement paste and deionised water, with a solid/liquid ratio = 1.

The main conclusions for low pH cements formulations were:

- In mixes based on CAC: percentages of mineral admixtures between 20 % and 30 % are enough to achieve a pH near 11.5 at 90 days of curing. The more effective blended agents are firstly SiF and secondly FA.
- In cases of mixes based on OPC: percentages of mineral admixtures above 40% are needed to obtain a suitable pore fluid pH. In binary blends the SiF is the more effective and in ternary blends SiF plus FA in appropriate proportions.

Twelve cement formulations (mixes) were selected in the first step; all of them having a pore fluid pH value near or below 12 at 90 days of hydration and they were considered as the basis for further developments. The cement paste pore fluid compositions including pH are given in Table 2.

Table 2: Pore water composition of the 12 selected cement pastes formulations at 90 days of hydration

Paste composition	PP pH	Chemical composition (ppm)					
		OH^-	Na^+	K^+	Ca^{2+}	SiO_3^{2-}	SO_4^{2-}
100% CAC (reference)	*12.25*	*357*	*285.35*	*626.14*	*22.59*	*ND*	*10.37*
80%CAC+20%SiF	11.78	289	455.00	524.15	13.96	ND	154.17
70%CAC+30%SiF	11.41	17	418.00	468.27	1.99	ND	204.91
50%CAC+50%SiF	11.34	34	282.55	178.62	1.87	ND	48.32
70%CAC+30%FA	12.12	544	496.61	1545.7	1.91	ND	9.03
50%CAC+50%FA	11.95	442	278.30	907.94	15.54	ND	15.14
70%CAC+20%SiF+10%FA	11.56	119	295.86	424.71	2.01	ND	12.60
70%CAC+10%SiF+20%FA	11.91	221	354.43	711.17	1.91	ND	7.59
100% OPC (Reference)	*12.92*	*1734*	*603.27*	*2129.5*	*474.41*	*1.23*	*12.78*
60%OPC+40%SiF	12.22	539	119.7	321.8	612.1	9.82	84.40
50%OPC+50%SiF	11.20	51	165.1	368.6	650.9	60.27	2180.8
80%OPC+10%SiF+10%FA	12.5	816	118.50	459.40	689.86	ND	31.62
35%OPC+35%SiF+30%FA	10.5	21	175.09	387.92	486.10	47.98	1819.3
20%OPC+50%SiF+30%FA	9.8	17	220.75	219.02	1208.0	72.28	3105.0

PP pH: Pore Pressing pH. ND: none detected.

The main ions in the pore solution of pastes based on CAC were alkaline ions, Na^+ and K^+, whereas in the pore fluid of cement pastes based on OPC the alkaline ion content decreased with respect to the reference cement but calcium ions, whose concentration increased with the decrease of the pH below 12.5. The binding of alkaline ions and the disappearance of portlandite are the main responsible of pH decrease for cements based on OPC. Other significant difference was the increase in silica ions in the pore solution with the introduction of high pozzolanic additions; mainly SiF. Additionally, the cementing solid phases generated and their evolution, in the low-pH cement pastes were analysed.

Furthermore, the evolution of pH with hydration was measured in standard mortars prepared using the 12 cement formulations selected and standard siliceous sand as aggregate. The results indicate a decrease of the pH inside the pores of these mortars, near or below 11.5, as compared to the corresponding pastes. This decrease was attributed to a dilution in the pore water fluid caused by the aggregate. The decrease in the pore water pH due to the presence of aggregates was at least 0.5 units below that of the cement paste alone, which allow predicting that the requirement of a pore fluid pH ≤ 11 would be reached in the concrete.

The mechanical performance of low pH cement formulations was also analysed using standard mortars (w/c: 0.5; c:s = 1:3).Two considerations were started out with respect to the properties measured in the fresh state of the fabricated mortars:
Initial setting times > 1 hour and/or final ones < 5 hours were considered as limit conditions for their practical use in shotcrete.
Consistency values (flow) > 10 cm were established as minimum.

For mechanical properties development, compressive strengths values above 20 MPa at 28 days of curing were considered acceptable and a flexural strength > 2 MPa. All the 12 low-pH cements formulations selected showed a compressive strength > 20 MPa after 28 days of curing, complying with the selection criterion.

2.1.3.2 *Design of low-pH concretes for plug construction*

The low-pH cement formulations selected in the previous step were used to design concrete mixes suitable to build the low-pH shotcrete plugs. Mix design procedure was developed in two phases:

1. The selection of the proportions of concrete constituents: low-pH cement formulations, coarse aggregate, fine aggregate, water and chemical admixtures.
2. The assessment of actual performance by means of suitable tests aimed at verifying the compliance with the functional requirements, defined in 2.1.2.2. These requirements were related to the fresh state (workability, pumpability and projectability) and to the properties in the hardened state (compressive strength, modulus of elasticity and hydraulic conductivity) of the concrete.

With regard to the procedure followed to verify the compliance with the determined functional requirements, the selection of the concrete components was divided in two stages: 1) paste components (including chemical admixtures) and 2) aggregates proportioning. The flow chart in Figure 1 shows the selection process followed for the paste components to study the compatibility with admixtures, and Table 3 summarises the materials used in this step.

Table 3: Materials used in the study of the compatibility between low-pH cements and chemical admixtures

Component material	Alternatives
Cement (low pH)	7 formulations based on CAC
	4 formulations based on OPC
Superplasticizer	Sika ViscoCrete SC-305 : Policarboxilate, (pH = 4,3)
	Sikament TN-100: Naphtalene formaldehyde. (pH = 7,5) Solids content: 38-40 %
Accelerating admixture	Sigunita L-22 R: Liquid formed by special inorganic substances (pH = 12)
	Sigunita L-53 AF S: Liquid, non-alkali, formed by inorganic substances (pH = 3)
Air-entraining admixture	Sika Aer 5: Liquid based on organic resin (pH = 11)

Accelerating admixtures, which are based on inorganic compounds, must be added to ensure that the concrete will adhere to the surface without slipping or collapsing. Air-entraining are also inorganic admixtures that are used to improve workability (overcome the harshness) of the mixes in the fresh state as a result of the shape and texture of the sand.

On the other hand, superplasticizers are composed of organic substances in solution. Although the use of organic components should be avoided in the repositories, the use of superplasticizers is essential when utilizing ultra fine mineral additions (such as silica fume) to properly disperse the particles and to allow an adequate pumpability of the concrete mix, and all this kind of chemical admixtures are based on organic substances. However, their use in the concretes is quite limited due to they usually represent less than a 0.15% of the mix.

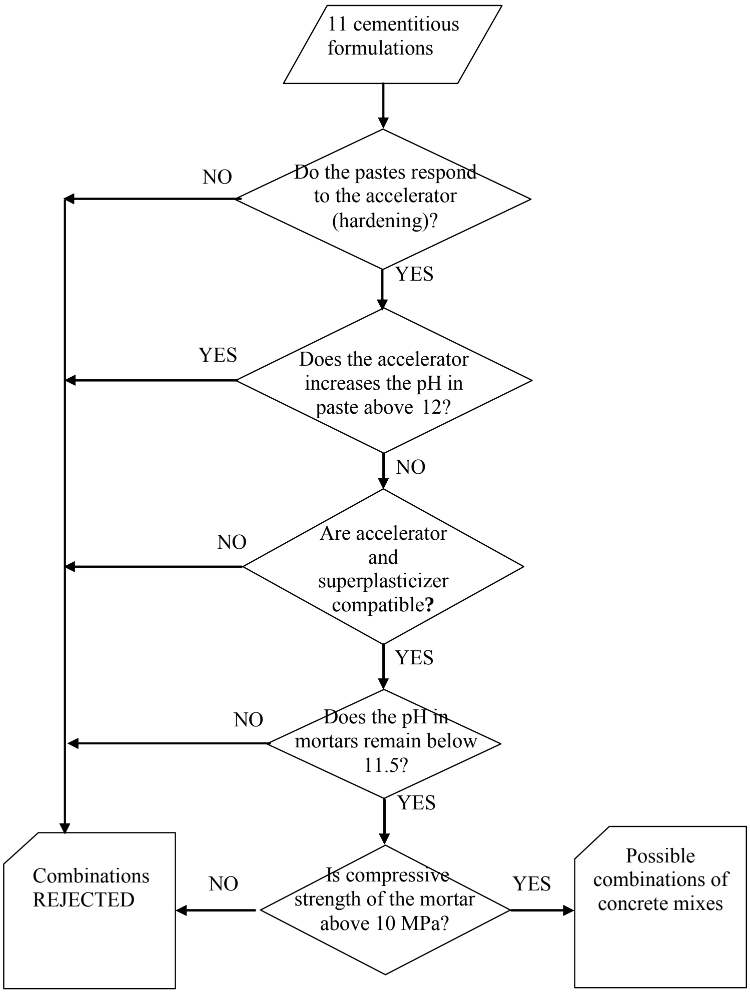

Figure 1: Diagram of the selection process for the paste components

According to this selection process, using the appropriate selection criteria in each step, four mixes of cement formulation+ accelerator + superplasticizer were chosen and compiled in Table 4:

Table 4: Paste components selected for basic concrete designs

Cement formulation	Accelerator	Superplasticizer	w/c	pH (90 days of curing)	CS (28 days of curing)
70%CAC-20%SiF-10%FA	L53	Sikament TN-100	0.52	11.1	15 MPa
70%CAC-10%SiF-20%FA	L53	Sikament TN-100	0.49	11.5	17.5 MPa
60%OPC-40%SiF	L53	Sikament TN-100	0.77	11.1	20.6 MPa
35%OPC-35%SiF-30%FA	L53	Sikament TN-100	0.67	10.9	11.4 MPa

CS: Compressive Strength measured on mortars of equivalent consistency.

Four low-pH cement formulations were finally selected for the preparation of the concrete mixes, two based on CAC and two on OPC. The w/c ratio to achieve a certain consistency was higher in the mixes based on OPC, which can be attributed to a larger percentage of mineral addition than those based on CAC.

Two types of aggregates were considered in the design of the concrete mixes for the shotcrete plugs (both short and long) built in the project (see 1.2.3). For the plug constructed in Äspö HRL, (Sweden), the so called short plug, granitic rock from the excavation was crushed and sieved to produce both fine and coarse aggregate. The shape of these aggregate was flacky and texture was harsh. For the case of the plug elaborated in Grimsel, (Switzerland) more suitable aggregate were used, made of natural siliceous gravel and river sand. Limestone filler was also incorporated in the mix to improve cohesion and pumpability of the concrete.

To determine the relative proportions of each aggregate fraction, the reference grading limits of the Sprayed Concrete Association (SCA) were used, slightly adapted to the actual maximum size of the coarse fraction selected. The aggregate grading used at the short plug in Äspö HRL is displayed in graphs of Figure 2 while Figure 3 shows the grading of the aggregates used for the long plug at Grimsel.

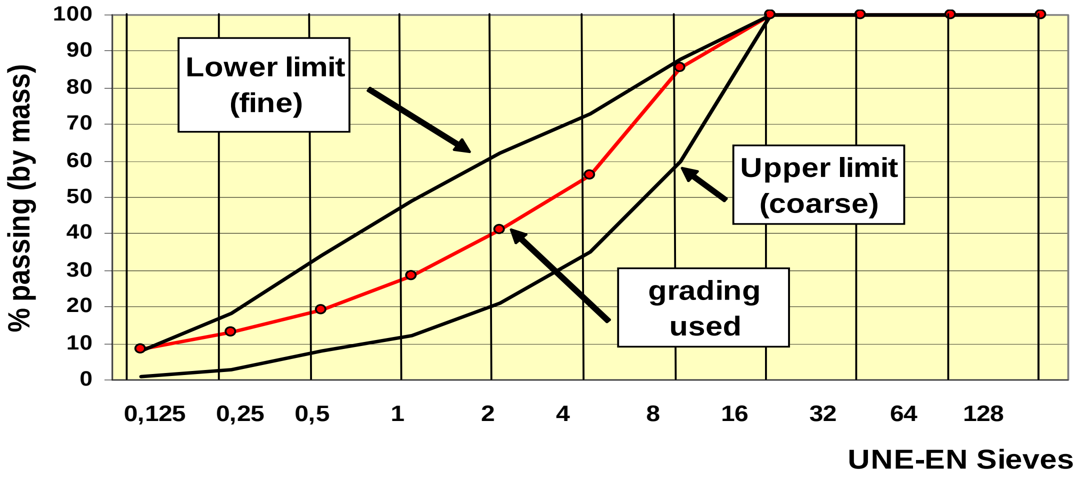

Figure 2: Aggregate grading selected for the concrete mix used in the short plug construction

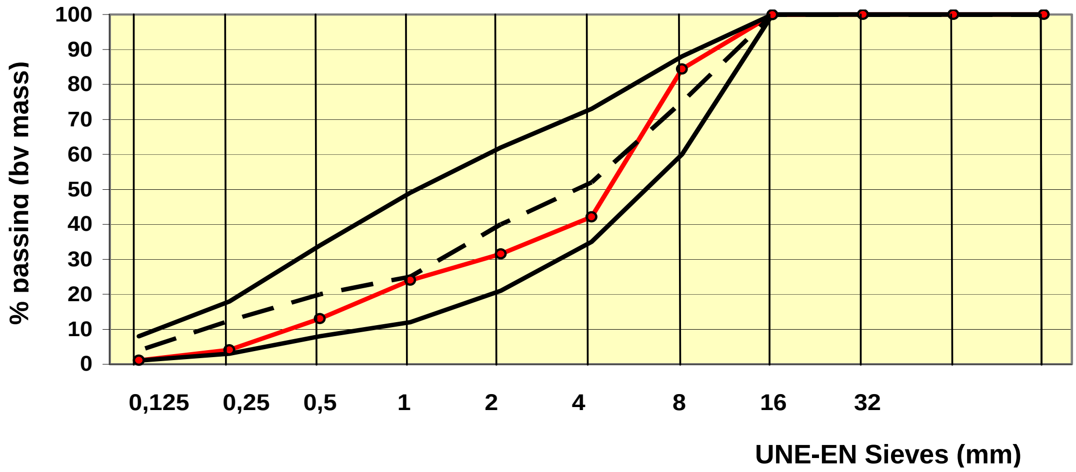

Figure 3: Aggregate grading selected for the concrete mix used in the long plug construction

The integration of concrete components was made by means of the absolute volume method using the aggregates and the paste components selected. A cement content of approximately 300 kg/m^3 was determined and the water was adjusted in trial mixes for a slump in the range 12–17 cm. During experimental trials, a formulation based on CAC (70%CAC-10%SiF-20%FA) showed variations and instability (strong thyxotropic behaviour) at the fresh state, and thus it was rejected for further studies. The nominal compositions of the low pH concretes used for pumping and shotcreting tests are given in Table 5 (the three remaining formulations developed in step 2 were firstly tested for the short plug while only the finally selected formulation, adapted to the right aggregates, was employed for the long plug tests, see 2.1.4).

Table 5: Nominal composition of basic concrete types

	Short Plug (aggregate from the excavation)			**Long Plug (conventional aggregates)**
Cement formulation	**70%CAC+20%SiF+ 10%FA**	**60%OPC+40%SiF**	**35%OPC+35%SiF +30%FA**	**60%OPC+40%SiF**
Water (kg/m^3)	262	277	237	230
Binder (kg/m^3)	310	307	316	275
Water/binder	0.85	0.9	0.75	0.84
Filler (kg/m^3)	-	-	-	70
Gravel (kg/m^3)	621	615	635	-
Fine Gravel (kg/m^3)	201	200	205	588
Sand (kg/m^3)	825	818	843	1045
Superplasticizer (kg/m^3)	5.58	5.5	5.7	5.7
Air-entraining admixture (kg/m^3)	-	0.6	0.6	

The properties of fresh concretes evaluated were: unit weight (kg/m^3), consistency (slump), cohesion and aspect (qualitative assessment). The relevant properties at the hardened state were: compressive strength, elastic modulus and pH, determined at different ages (time of curing). The main results are summarized in Table 6 and 7, and Figures 4 and 5.

Table 6: Properties of basic concretes at the fresh state

Properties	**Short Plug (aggregate from the excavation)**			**Long Plug (conventional aggregates)**
	70%CAC+20%SiF +10%FA	**60%OPC+40%SiF**	**35%OPC+35%SiF+ 30%FA**	**60%OPC+40%SiF**
Unit weight (t/m^3)	2.23	2.23	2.25	2.27
Slump (cm)	17	12	13	15
Cohesion	Good	Good	Good	Good
Aspect	Good	Good	Good	Good

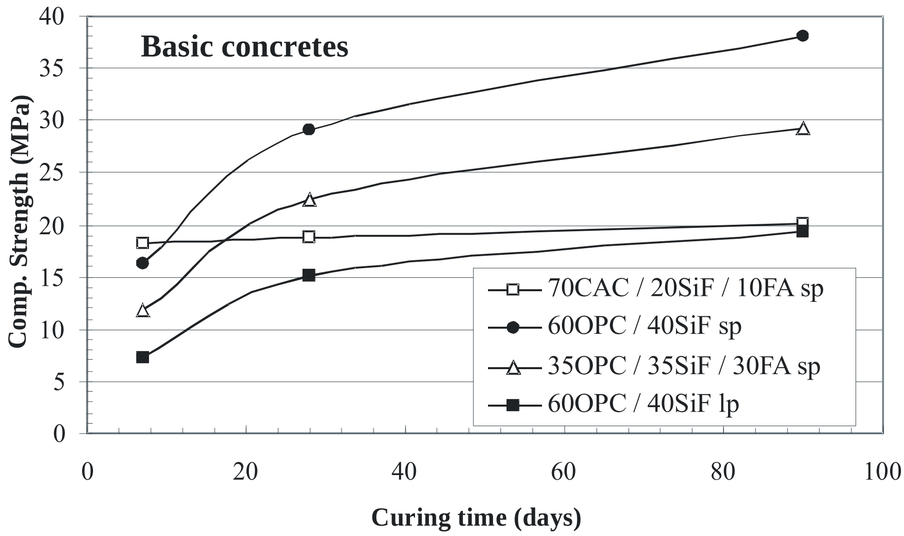

Figure 4: Evolution of compressive strength over curing time in basic concretes with superplasticizer (sp: short plug; lp: long plug)

Table 7: Modulus of elasticity of basic concretes at 90 days of curing time

	Short Plug (aggregate from the excavation)			**Long Plug (conventional aggregates)**
	70%CAC+20%SiF +10%FA	**60%OPC+40%SiF**	**35%OPC+35%SiF+ 30%FA**	**60%OPC+40%SiF**
Static Modulus of elasticity (GPa)	15.5	21.7	17.2	14.2

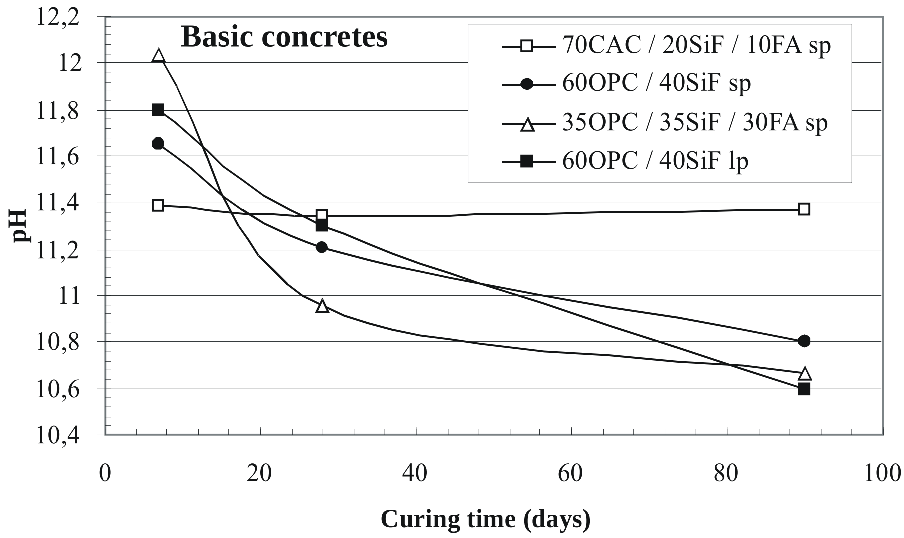

Figure 5: Evolution of pH against curing time in basic concretes with superplasticizer. (sp: short plug; lp: long plug)

2.1.4 Laboratory Test Work

The concrete elaborated for the construction of the shotcrete plugs (both short and long) were expected to comply with the specific functional requirements at 90 days of curing, taking into account that shotcreting technique would cause a decrease of the compressive strength and elastic modulus.

The three concrete formulations firstly designed for the shot plug were evaluated with respect to pumping and projection performance. The suitability of the low pH concrete formulations selected was verified in realistic spraying tests. The industrial production of the low-pH concretes were evaluated in conditions similar to those expected in the real field of the repository. The robustness of the mix was confirmed in combination with the equipment and techniques available, under equivalent conditions to those expected for the underground repository. The low-pH basic concrete mixes made at industrial scale showed similar performance than those prepared at laboratory level, as can be seen by comparing Table 7 and Table 8.

Table 8: Modulus of elasticity and compressive strength (at 90 days of curing) of basic concretes made at industrial scale using aggregate from Äspö excavation

Parameter	70%CAC+20%SiF+10%FA	60%OPC+40%SiF	35%OPC+35%SiF+30%FA
Static Elasticity Modulus (GPa)	15.8 ± 0.5	21.7 ± 2.5	18.3 ± 1.6
Compressive strength (MPa)	18.7±0.3	37.5± 0.3	29.3 ± 0.2

2.1.4.1 Definition of Pumpability Shotcreting procedure

The shotcrete trials were carried out according to the following work process:

1. Definition of conditioning and preparation of the trial zone
2. Procedure for spraying and quality control:
   - Preparation of basic low pH concrete in the concrete plant or in a mixer truck
   - Quality test of fresh concrete and further adjustment (if required)
   - Sampling basic low pH concrete
   - Pump and/or spray trials in the trial zone
   - Fast-set behaviour assessment (Proctor needles)
   - Check on level of rejection during spraying

3. Modification of formulations if needed (proportion of the different fractions of aggregates, water/cement ratio, proportions of admixtures…) and/or of the spraying equipment/technique relative to the results obtained.

Series of spraying trials on panel with the objective of verifying the pumpability of the concrete over short and long distances as well as the viability of spraying under realistic conditions were carried out. During the trials over short distance, of around 30 m between the pump and the robot, (Figure 6) no difficulties were observed for pumping and spraying. For greater distances, around 100 m, tests showed that although the concrete mix was pumpable and sprayable, obstructions could occur in the conveying pipe if curved sections exist or if the transitions in the diameter changes were not sufficiently graded. Figure 7 shows a panoramic of the trial for long distance pumping.

Figure 6: Spraying with robot on panel

Figure 7: Long pumping trial

Spray trials on panels were also carried out for the three possible formulations with the objective of reproducing as far as possible the working conditions during the construction of the short plug in the Äspö HRL with regard to some parameters as distance and elevation of pumping, temperature, humidity, etc. A trial zone was created in a tunnel with a distance between the pump and the spray panel of approximately 20 m and a difference in elevation of some 2 m. In this case a pump with lower output was used, in order to allow spraying by hand, given that the size of the demonstration gallery in Äspö HRL did not allow a conventional spray robot to be used (Figure 8).

Figure 8: Spraying trial on panel reproducing conditions at Äspö HRL

The trials were fully satisfactory: the pump managed the difference in height without any difficulty, and spraying by hand could be carried out without problems for the three formulations, resulting in regular surfaces of sprayed concrete. The concrete temperatures measured after each spraying were low, reaching a maximum of 26 ºC after one hour, which remained at this level for about six hours before starting to drop again. The three low-pH concrete formulations proved to be suitable for shotcrete plug construction. After evaluating the preparation conditions, toughness of the mix, and the pumpability and sprayability of all three, the binary mix 60%OPC+40%SiF was selected as the most suitable to carry out the mock-up and the demonstration test too.

The influence of the cylindrical geometry was also evaluated using the selected concrete formulation for plug construction. The trial consisted of spraying two layers of concrete inside a prefabricated tube of reinforced concrete, with a diameter similar to the gallery in Äspö HRL (1.85 m). Spraying was carried out without problems (Figure 9) and an overall thickness of concrete of half a meter was achieved. The feasibility of the operation and the good behaviour of the low-pH shotcrete formulation selected for the plug shotcrete construction confirmed good adhesion of the sprayed concrete with the surface and very little rebound.

Figure 9: Shotcreting in concrete tube

Table 9 and Table 10, show the properties measured in cores from the shotcreted panels which confirm that the shotcrete fully complied with the functional requirements: pH < 11, compressive strength > 10 MPa and static elasticity modulus < 20 GPa, hydraulic conductivity ≤ 1E-10 m/s). It is also remarkable that there was not significant difference between spraying in cylindrical or panel geometry

Table 9: Comparison of results at 90 days for formula 60%OPC+40%SiF sprayed on the panel and in the pipe (aggregate from Äspö HRL excavation, short plug formulation)

Parameter	Shotcrete from panel	Shotcrete from tube
Compressive strength (MPa)	27.5	25.0
VC (Std Dev/ Mean value)	10 %	5 %
Elasticity Modulus (GPa)	13.6	14.8
VC (Std Dev/ Mean value)	7 %	7 %
pH	10.4	10.3
Density (Main value and VC) (t/m^3)	2.21 (VC = 2 %)	2.19 (VC = 1 %)

Table 10: Results of the analysis of 60%OPC+40%SiF concrete formula sprayed in prefabricated tube (at 90 days) (mean values) (aggregate from Äspö excavation, short plug formulation)

Parameter	60%OPC+40%SiF
Modulus of elasticity (GPa)	14.8 ± 1.1
Compressive strength (MPa)	25.1 ± 1.2
pH	10.2-10.3
Density (g/cm3)	2.1-2.2
Mean hydraulic conductivity (m/s)	1.03 E-10
Total porosity (PIM)(%)	18.0±3.6

The interface between the low-pH sprayed concrete and the concrete pipe confirmed a very good joint, without holes and with a good distribution of aggregates in the sprayed concrete (Figure 10).

Shotcrete trials were carried out also to test the binary mix 60%OPC+40%SiF adapted to the aggregate used at Grimsel Test site (long plug). The objective of the trials was to check the performance of the adapted mix in terms of pumpability, sprayability, etc. The spraying tests were carried out over a panel resembling the long plug gallery, to check the self-supporting capacity of the fresh shotcrete in such large cross section (Figure 11). The tests were successful, and the adapted formulation proved to be suitable for the construction of the long plug.

Figure 10: Interfacial zone (base: 14 mm)

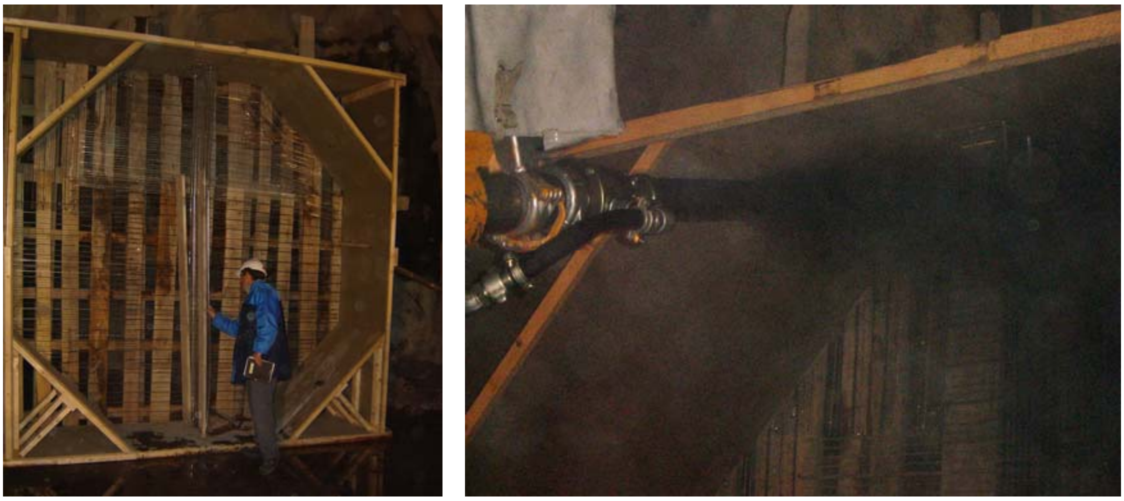

Figure 11: Spraying trial on panel reproducing conditions at Grimsel

2.1.5 Design Work /demonstrator layouts / Test program definition

2.1.5.1 Introduction

As a result of the preliminary design work performed at the initial stages of the project it was clearly established that for designing a plug demonstrator the bearing capacity of this type of plug was a key issue that required being determined, by means of a preliminary specific load test, to investigate and validate, according to established requirements, the feasibility of construction and its performance. The initial project approach was therefore modified to include the construction of a short plug, to be tested up to failure by only hydraulic (not mechanical) loading.

2.1.5.2 *Prototype Test (Short Plug Test)*

Test design

The objectives of the short shotcrete plug test were to demonstrate the construction feasibility and to check its bearing capacity in compliance with the established functional requirements. The test was designed as a parallel 1 meter long shotcrete plug (without keys in the rock) constructed in a horizontal drift measuring 1.85 m in diameter and 15 m in length, excavated by full face push boring technique in the –220 m level of the Äspö HRL (Sweden).

A mechanical pressure had to be applied at one side of the plug, by injecting and pressurising water in a hydraulically sealed water chamber. The high-pressure water injection system had to provide sufficient loading capacity to bring the plug to failure (Figure 12).

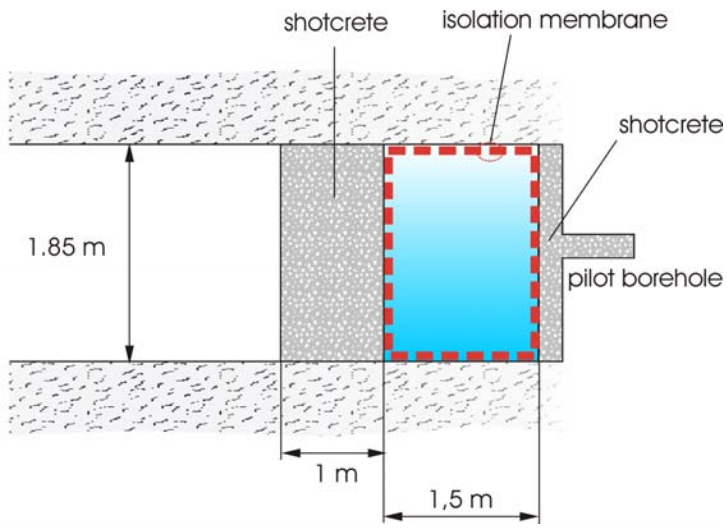

Figure 12: General layout of the Preliminary Short Plug Test

Preliminary mechanical scoping calculations

In order to comply with the objectives of the test and with the functional requirements established for the plug, two-dimensional axisymmetric mechanical calculations were performed using the FLAC code, assuming an elasto-plastic Mohr-Coulomb model with ubiquitous joint (at the granite-shotcrete interface), without hydraulic coupling and on the basis of the information available.

The initial data on the granite rock, the plug and the rock-plug interface used for the calculations are listed in Table 11.

Table 11: Initial parameters for the preliminary scoping calculations of the short plug

	GRANITE	SHOTCRETE	UBIQUITOUS JOINT
Density (γ)	2700 kg/m^3	2250 kg/m^3	-
Porosity (n)	0.003	0.15	-
Young's modulus (E)	55000 MPa	Variable (Table 12)	-
Poisson's ratio (ν)	0.25	0.25	-
Friction angle (ϕ')	41^o	38^o	38^o
Cohesion (c′)	16 MPa	3 MPa	Variable (Table 12)
Tensile strength (T)	14 MPa	1.5 MPa	0.7 MPa
Dilation angle (ψ_j)	-	-	5^o

The obtained results on the basis of rationale assumptions are summarised in Table 12.

Table 12: Results from the preliminary scoping calculations of the short plug

Variable parameters	APPLIED PRESSURE AT FAILURE (MPa) PLUG LENGTH 1.0 m	1.5 m	2.0 m	3.0 m	4.0 m
Es = 10000 MPa c′j = 1.0 MPa	4.0	6.0	9.0	16.5	27.5
Es = 15000 MPa c′j = 0.7 MPa	3.0	4.5	6.5	11.0	18.0
Es = 20000 MPa c′j = 0.7 MPa	3.0	4.5	6.0	10.5	16.5

NOTES:

- The granite-shotcrete interface (ubiquitous joint) was divided in segments of 1 m maximum length. In each segment, when the displacement was greater than 0.5 mm (in all its nodes), the dilation angle value was set equal to zero.

- Pressure applied in 0.5 MPa steps.

The results of the scoping calculations showed that the 1 m long plug could fail for applied pressures of 3 MPa to 4 MPa, the calculated variation depending mainly on the assumed range of the cohesion (0.7 MPa – 1.0 MPa). The Young's modulus of the shotcrete was also ranged between 10000 MPa and 20000 MPa, but this parameter (if greater than 10000 MPa in any case) has little relevance for the plug failure calculation.

Detailed description of the test

The main components of the test were the short plug itself, a water injection system and the sensors and associated Data Acquisition, Display and control System (DADCS).

Plug

A sprayed waterproof membrane was applied on the surface of the water chamber walls and over a wooden support frame closing the entire cross-section of the test drift to obtain a hydraulically sealed water chamber. The plug construction was planned in successive vertical layers of shotcrete, the first one applied over the support frame, with a thickness not exceeding 30 cm each, and a waiting time of several hours between them. The proposed formulation for the shotcrete is shown in Table 13.

Table 13: Proposed formulation for short plug

Component	kg/m^3
Water	277,2
Ordinary Portland Cement: CEM I 42.5 R/SR	184,3
Silica Fume	122,9
Coarse aggregate (5-12)	615,6
Medium aggregate (2-5)	199,7
Fine aggregate (0-2)	818,1
Superplastizer “Sikament TN-100”	5,5
Air entrapper “Sika Aer 5”	0,6
Accelerant "Sigunita L-53 AF S"	18,5

Water injection system

The water injection system provided water to fill the chamber behind the plug and apply the necessary pressure (range 0 MPa to 10 MPa) required for the testing. The test was to be performed with “formation water”. In the case of Äspö HRL this is saline water. According to the initial dimensions of the water chamber a minimum of 4 m^3 - 5 m^3 of water was needed.

The water injection system featured a vacuum pump for purging the air during the filling up of the water chamber, a piston pump for pressurizing the chamber once filled up, a water tank, pressure and water flow gages, and pipes and valves for connection to the water chamber.

Sensors

A number of sensors were installed to monitor the plug performance during the test, namely three total pressure cells installed in the rock, three displacement sensors on the plug face, and four acoustic emission sensors (Figure 13).

The sensors were connected to a DADCS comprising all the electrical components and software packages necessary for the monitoring and control of the test. The acoustic emission sensors were connected to a dedicated signal processing unit for feature extraction and waveform capture.

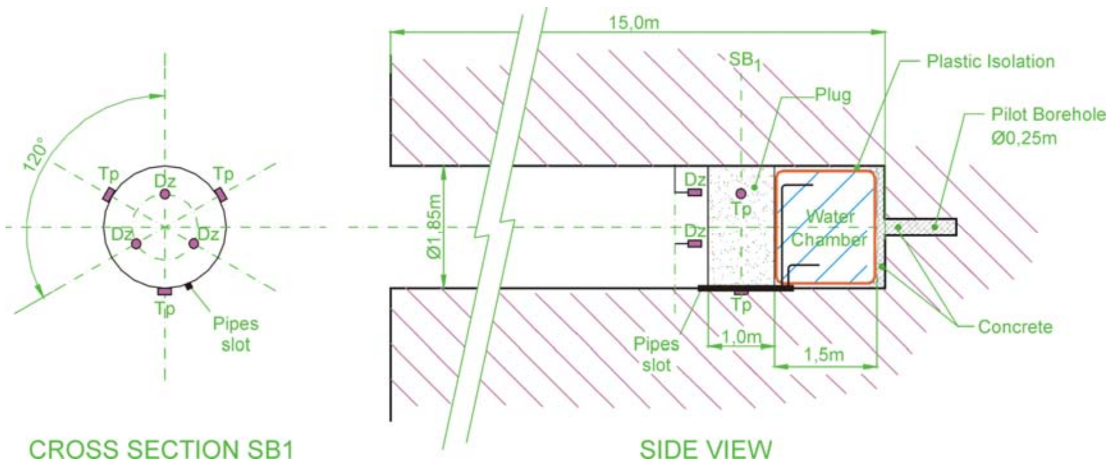

Figure 13: Instrumentation layout

2.1.5.3 *Full Scale In situ Test*

<u>Test design</u>

The objectives of the Full-Scale In situ Test were to demonstrate again the construction feasibility, at a bigger scale and under more difficult construction conditions, and to demonstrate the support capacity of a long low-pH shotcrete plug, in compliance with the established functional requirements, under realistic conditions, i.e. loaded with the swelling pressure of a bentonite buffer applied at one side of the plug.

The basic layout of the test consisted of a 4 m long parallel low-pH shotcrete plug constructed at the back end of a 3.5 m diameter horizontal gallery, excavated in granite with a TBM in the Grimsel URL (Switzerland).

The end of the gallery was filled with 1 m of buffer constructed with blocks of highly compacted bentonite (Figure 14). The bentonite was provided with geotextyle mats for water injection, working as an artificial hydration system to accelerate the saturation process and if required, to impose a pore water pressure in the buffer. Besides, several sensors were installed to follow the evolution of the test. Both the tubing from the hydration system and the cables from the sensors were led, through a pass-through borehole excavated in the rock, to the service area, were they were connected to the water injection system and the data acquisition and control system respectively.

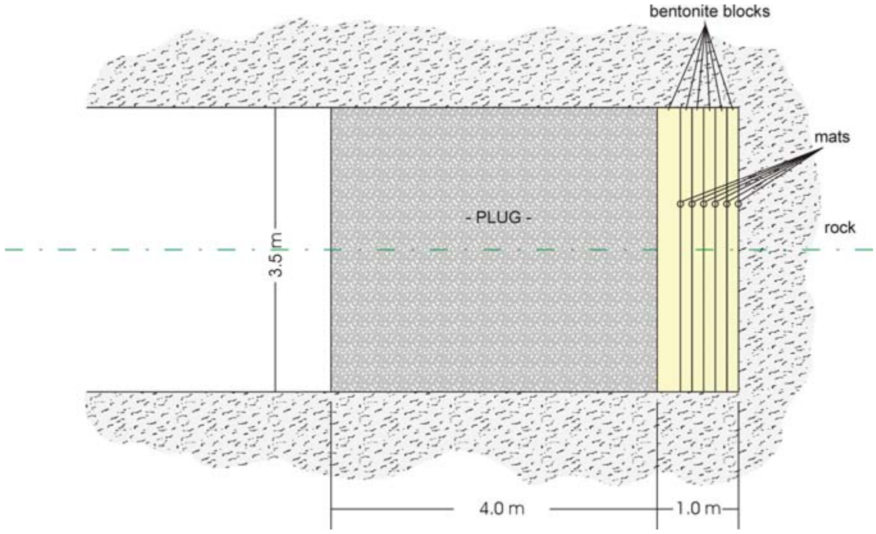

Figure 14: General layout of the Full Scale In situ Test

<u>Preliminary mechanical scoping calculations</u>

Mechanical calculations have been made with FLAC code for a low-pH shotcrete plug measuring 4 m in length and 3.5 m in diameter. An elasto-plastic Mohr-Coulumb model without hydraulic coupling has been assumed, taking into account the experience gained from the Äspö test. The parameters used for the calculation can be found in Table 14.

Table 14: Initial parameters for the preliminary scoping calculations of the long plug

	GRANITE	SHOTCRETE	UBIQUITOUS JOINT
Density (γ)	2600 kg/m^3	2200 kg/m^3	-
Porosity (n)	0.01	0.18	-
Young's modulus (E)	50000 MPa	18000 MPa	-
Poisson's ratio (ν)	0.30	0.25	-
Friction angle (ϕ')	50^o	38^o	38^o
Cohesion (c′)	12 MPa	3 MPa	0.1 MPa
Tensile strength (T)	10 MPa	1.5 MPa	0.1 MPa
Hydraulic conductivity	-	10^{-10} m/s	-
Dilation angle (ψ_j)	-	-	12^o

NOTES:

- Ubiquitous joint parameters estimated from Äspö test.

- If the interface displacement was greater than 1 mm, the dilation angle value was set equal to zero.

According to the calculations, the maximum pressure that the plug can support is estimated to be 5 MPa.

Detailed description of the test

The main components of the test were the long low-pH shotcrete plug, the bentonite buffer comprising a water injection system, and the sensors and associated Data Acquisition, Display and Control System (DADCS).

Plug

The main components of the shotcrete were similar to those used for the short plug construction but the aggregates were local and therefore different from those used for Äspö HRL. Therefore some adjustments in the shotcrete formulation were performed by CSIC-IETcc to adapt it to the new aggregate (see 2.1.3). The proposed formulation can be found in Table 15.

Table 15: Proposed formulation for long plug

Component	kg/m^3
Water	230
Ordinary Portland Cement: CEM I 42.5 R/SR	165
Silica Fume	110
Limestone filler	70
Fine size aggregate (0-4)	1045
Medium size aggregate (4-8)	590
Superplastizer “Sikament TN-100”	2.8
Accelerant "Sigunita L-53 AF S"	16.5

The plug construction was planned in successive vertical layers of shotcrete, the first one applied directly over the face of the bentonite buffer, with a thickness not exceeding 30 cm each, and a waiting time of several hours between them. In order to improve the bonding in the contact between the shotcrete and the rock, it was decided to curve the shape of the layers in the borders, so that the shotcrete could be applied perpendicularly to the rock along the periphery of each layer (see Figure 21 in 2.1.6.2).

Bentonite buffer and water injection system

A one meter thick bentonite buffer was built at the rear end of the test gallery with vertical layers of highly compacted bentonite blocks.

The blocks were manufactured from compacted powder bentonite from the Cortijo de Archidona deposit in the Cabo de Gata region (Almería, Spain), with a water content estimated on 12 % in weight, and a dry density of 1.70 g/cm^3, and planned to obtain a global dry density of 1,595 g/cm^3. The mean swelling pressure of the buffer with this global dry density is 4.5 MPa when fully hydrated. The actual value obtained for the global dry density was slightly lower than the planned one (see 2.1.6.2).

The artificial hydration system consists of 6 hydration mats installed perpendicular to the gallery axis between every three layers of bentonite blocks, with the first mat located at the back end of the bentonite buffer.

The water injection system installed was intended to fill with normal tunnel water (formation water) the mats inside the bentonite chamber at a low pressure to hydrate the bentonite blocks, and afterwards, if needed, to impose a pore water pressure in the buffer. It was composed basically of two pumps fed from a water tank and connected through a distribution panel to each mat individually. The injection pressure and water inflow is controlled by manual pressure regulators and valves. Pressure transducers were installed to register the water pressure.

Sensors

To monitor the plug performance during the test, a number of sensors were installed at different locations in the rock, in the bentonite and in the shotcrete mass, namely 13 total pressure cells, 22 humidity sensors of different types, 12 piezometers and 4 displacement sensors (Figure 15). The sensors are mainly conventional (wired) ones but a number of them were connected to a wireless transmission system. These wireless transmitted sensors were installed as a part of the TEM Project, which is run by NAGRA in the Grimsel URL.

The sensors were connected, through the necessary data acquisition units, to the main DADCS for the monitoring and management of the test, which worked in unattended mode and could be contacted with modem for remote supervision.

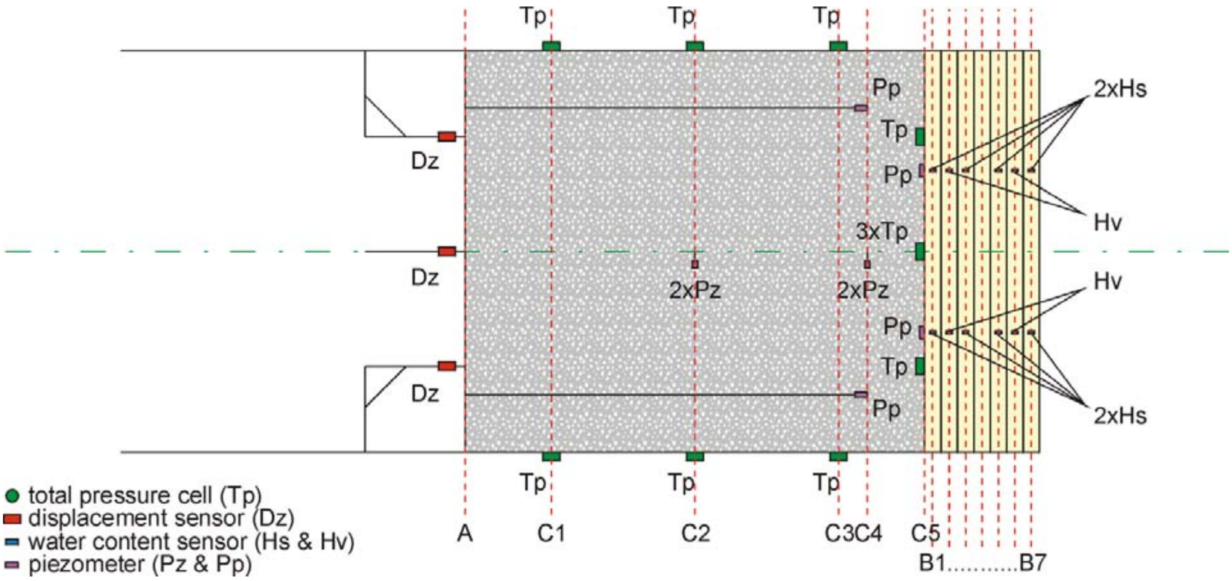

Figure 15: Layout of instrumentation (wired transmitted sensors only)

Finally, NDA (formerly NIREX) installed a non-intrusive monitoring system. It consisted of six linear boreholes (each 25 m long) excavated around the gallery, which captured a series of non-intrusive seismic tomography measurements over the lifetime of the experiment. It also included 25 single-component geophones with a natural frequency of 100 Hz installed at the front face of the concrete plug.

2.1.6 Procurement and set-up of test facilities

2.1.6.1 Prototype (Short Plug) Test

<u>Procurement</u>

The required instrumentation as well as all the elements for the water injection system were selected and ordered between spring and summer 2005. Everything was sent to the Äspö HRL in September 2005.

The materials needed to produce the required amounts of concrete during the plug construction, such as cement, silica fume and additives, had to be exactly the same used during the tests in Spain, so as to avoid any variation in the behaviour of the shotcrete. Therefore, all the materials needed for the final tests in Sweden and the construction of the short plug were ordered, stocked, and sent to Sweden during the summer of 2005.

The required amounts of aggregate fractions were produced from crushed rock from the excavation of the URL in a nearby aggregate plant, and stocked in separate pre/weighed big bags ready to be introduced in the mixer.

<u>Site preparation</u>

The work, carried out by SKB staff, consisted in the geological mapping of the gallery, grouting of the pre-existing boreholes at the end of the gallery, construction of the access to the gallery, and the supply of the electrical power, light and ventilation to the test gallery.

Given the short duration foreseen for the operational phase of the test, the monitoring was conducted with personnel on site and therefore, no permanent computer building was installed nor was a telephone line required for remote monitoring.

Preliminary shotcreting tests in Sweden

The low-pH short shotcrete plug and ancillary structures were constructed in the -220 m level niche of the Äspö HRL during the months of September, October and November 2005. BYGGS was the Swedish company selected to construct the plug under the supervision of AITEMIN and with the attendance of SKB.

A preliminary test for checking the shotcrete equipment and the mixing procedure with the concrete formulation provided was successfully performed on September 14, 2005 at some surface facilities that BYGGS has in Tumba (Sweden). The dry spraying of the water chamber isolation membrane was also successfully tested.

Final outdoors shotcrete test

A final outdoors shotcreting test at Äspö HRL was scheduled for October 11, 2005, the day before the start of the plug construction. The concrete was mixed as initially planned using a mixer truck. The test was carried out successfully although it was necessary to set the pump at full pressure.

Installation of instrumentation in rock

The three total pressure cells were installed in the rock at mid section of the designed plug, embedded into high strength resin based concrete, for measuring the pressure transmitted by the plug to the rock.

Conditioning of the water chamber

The water injection pipes were installed in a slot in the rock floor and the watertight membrane was then applied all along the water chamber rock wall. The construction of the water chamber was completed by installing the wooden panel needed to construct the plug and spraying the watertight membrane over it.

Plug construction

An attempt to construct the short plug was made on October 12, 2005 using the same equipment as the day before but with a 90º curve at the concrete pump outlet, due to lack of space in the niche. Several attempts were unsuccessfully made to pump the concrete, which due to that curve got stuck at different points along the pump line

After analysing the problems encountered, a second attempt was carried out on November 2, 2005 using this time the same stand-alone concrete pump and arrangement used in the preliminary test in Tumba, and a mixer truck with a higher rotation speed, to improve the mixing of the concrete. In this occasion the plug was successfully constructed in four steps. Three layers of 21, 22 and 35 cm were constructed on that day, followed the next day by the last layer to complete the 1 m long plug (Figure 16).

Figure 16: Short plug construction at Äspö HRL

<u>Auxiliary system installation</u>

After a hardening period of more than 90 days, up to the end of January 2006, the auxiliary systems required to perform the test were installed the first week of February 2006, namely the remaining sensors in the plug face (displacement and acoustic emission, plus a survey webcam), and the water injection system and data acquisition and control system, installed close to the gallery entry (Figure 17).

Figure 17: Test set-up at Äspö HRL

2.1.6.2 Full Scale In situ Test

Procurement

The procurement phase was carried out during the second half of 2006. As for the short plug, the materials needed to produce the concrete for the long plug construction were ordered and stocked in Spain, and sent to the Grimsel URL in December 2006, along with the geotextyle mats and the water injection system, the instrumentation and the DADCS.

The bentonite blocks were produced in a workshop in Spain with proven experience in similar manufacturing. The bentonite amount was estimated in 15.46 Tons for the 20 layers of blocks. A 20% surplus of blocks was considered as a safety margin, so a total of 11500 blocks were constructed, controlled statistically, packed with full mechanical and moisture protection, and transported to the Grimsel URL between December 2007 and January 2008.

Site preparation

The site preparation work was carried out by NAGRA staff. Initially all the remains from previous projects carried out at the site were removed to leave the gallery clear, and the back-end of the gallery was flattened with mass concrete to obtain a vertical wall. The service area for the DADCS was cleared too.

The necessary utilities were provided to the site, including electrical power, telephone lines and normal tunnel water supply.

The necessary slots for the installation of rock instrumentation were excavated, as well as the borehole for passthrough of cables and tubings, and the six inclined boreholes for seismic tomography measurements.

Final shotcreting tests in Switzerland

The low-pH long shotcrete plug including bentonite buffer and ancillary structures were constructed in the VE gallery of the Grimsel URL from December 2006 to February 2007. HAGERBACH was the Swiss company selected to construct the plug under the supervision of AITEMIN and with the assistance of NAGRA.

A preliminary test was performed on December 12, 2006 at the VSH Hagerbach Test Gallery in Flums Hochwiese (Switzerland), in order to test the correct behaviour of the equipment with the same set-up to be used during the plug construction (mixing procedure, pumping length, spraying section, etc). The test was successful, and one metre of plug could be constructed without problems in one day. The shotcrete layers were constructed with a curved shape in the borders, which allowed the application of shotcrete perpendicular to the rock, improving the shotcrete-rock bonding. This technique was later used during the long plug construction (see 2.1.6.2).

Installation of instrumentation in rock

The instrumentation in rock was installed between December 2006 and mid January 2007. Six total pressure cells and four piezometres were installed into slots excavated by NAGRA.

Bentonite buffer construction

The construction of the buffer was carried out from January 15, 2007 to February 14, 2007.

The lower part of the buffer up to the middle of the gallery was first completed in its full one metre of length and secured with a wooden support, and then the upper part was completed. The six hydration mats were installed as planned starting with a mat hung at the back of the chamber a hydration mat was thereafter placed after every 3 rows of bentonite bricks, except that there were 5 rows of bricks between the last mat and the face of the shotcrete plug (Figure 18). The global dry density obtained for the bentonite buffer was 1,55 g/cm^3 and therefore the expected mean swelling pressure of the buffer when fully hydrated, is 4.15 MPa, instead of 4.5 MPa. Nevertheless, the natural variability of the bentonite should be taken into account for such value (±25 %, that is, ± 1 MPa approximately).

Figure 18: Bentonite buffer construction

The instrumentation was installed as planned in each central layer of bentonite bricks between hydration mats. In total 22 humidity sensors were installed in the bentonite, plus 2 total pressure cells and 2 piezometers.

All cables and tubings from the instrumentation and hydration mats were led to cable connection boxes lodged in the hole excavated at the right hand side of the gallery, and from those boxes to the service area through a connecting borehole running parallel to the gallery.

All the bricks installed were weighed to control the amount of bentonite installed. A total of 16588 kg of bentonite were installed.

Once the bentonite buffer was finished, 5 total pressure cells and 4 piezometers were installed in the buffer front, right before the start of the plug construction (Figure 19).

Figure 19: Bentonite buffer finished

<u>Plug construction</u>

The construction of the plug was carried out from February 15 to 21, 2007. The concrete mixer and pump were installed in the VE cavern, located at some 80 m from the construction point (Figure 20). The shotcreting was done with a spraying robot.

Figure 20: Shotcreting of long plug at Grimsel

The plug was constructed in 7 curved layers (Figure 21). After the spraying of each layer, the hardening was controlled with a penetrometer.

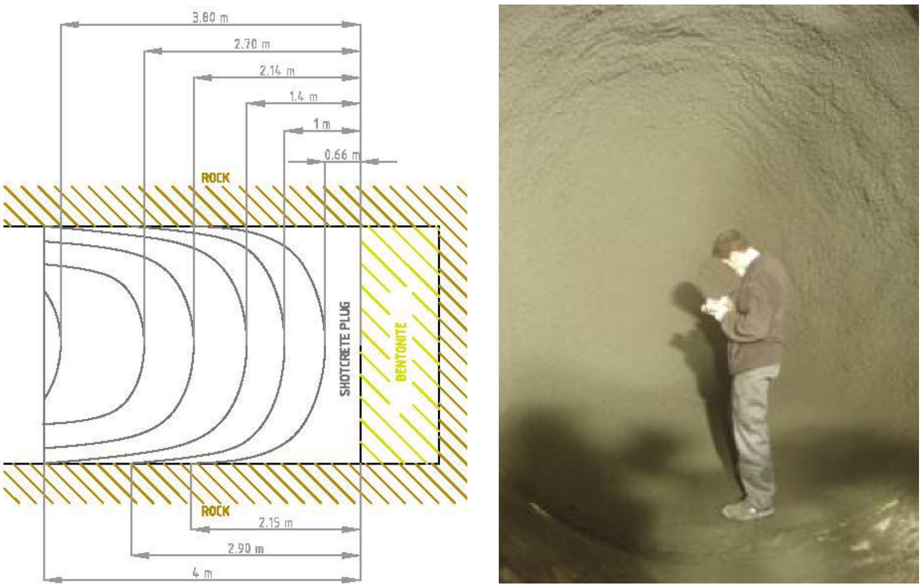

Figure 21: Curved layers of plug

<u>Installation of DADCS and gallery instrumentation on the plug face</u>

The Water Injection System, the Data Acquisition, Display and Control System and the gallery instrumentation were installed from March 19 to 29, 2007.

The instrumentation on the plug face comprised four extensometers and 25 geophones.

The DADCS comprised the data reading units and the dedicated computer. The wireless receptor and associated DADCS for the wireless system were also installed.

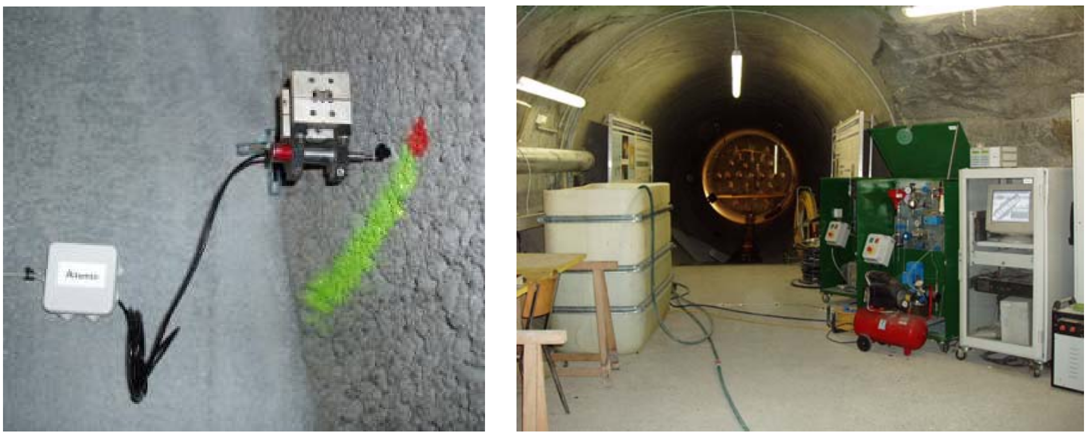

Figure 22: Gallery instrumentation and DADCS

2.1.7 Implementation of Prototype (Short plug) Test

2.1.7.1 Short plug test

<u>First test series (February 2006)</u>

On February 8, 2006, the test was started up. The water chamber was filled up, and a checking test was carried out without problems up to a pressure of 6 bars, but the water chamber was not water tight. It was very difficult to increase the pressure over 9 bars of pressure, so it was decided to stop the test until a more powerful pump was available.

<u>Second test series (March 2006)</u>

On March 2, two new pumps were installed and the test was resumed (Figure 23). Given the difficulties found to increase the pressure during the first test series, the objective was to reach at least 20 bars.

The pressure was increased in three steps to 10 bars, 15 bars and up to 17 bars without problems, and then the injection was stopped. The plug deformation registered during the increase of pressure was of almost 2 tenths of millimetre. It was an elastic deformation, as no increase was registered at constant pressure.

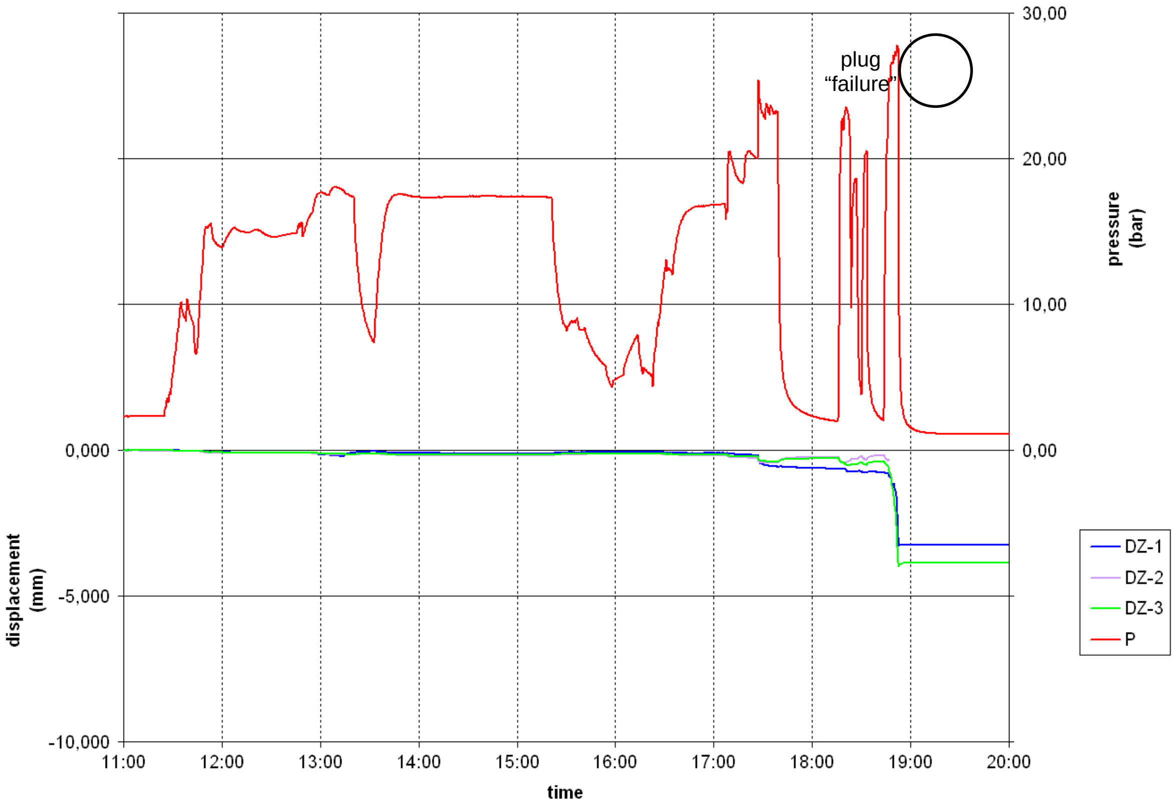

Figure 23: Loading test, March 2, 2006

A red colour tracer was introduced in the water, to identify the water flow path (through the plug, through the rock or both?). Then the injection was resumed up to reach first 20.5 bars, and then 24 bars. The water leakage increased significantly and the elastic deformation registered was four tenths of millimetre.

A final pressurisation was carried out, up to 26.6 bars, and then to 27.09 bars. At this pressure, slightly lower than the minimum calculated “failure” pressure of 30 bars (see 2.1.5.2), it was considered that the plug had “failed”, given the sudden increase in the rate of displacement and in the number of acoustic hits per second. The plug continued moving at constant pressure during a few minutes, eventually registering a total displacement of 3.8 mm. At that point, the test was stopped. A visual inspection of the plug face revealed no cracks in the plug mass.

Third test series (March 2006)

On March 3, 2006 a new test series was planned to further understand the plug “failure” event. More tracers were added to the water chamber for checking the water leakages. At a pressure of 25 bars the plug moved again, so that the displacement was increased from 3.8 mm to 8.4 mm (Figure 24).

A final test was done at 24.9 bars, and the plug moved up to a total displacement of 16.1 mm from the start of the tests. Manual measurements taken along the perimeter of the plug confirmed that the movement of the plug had been uniform.

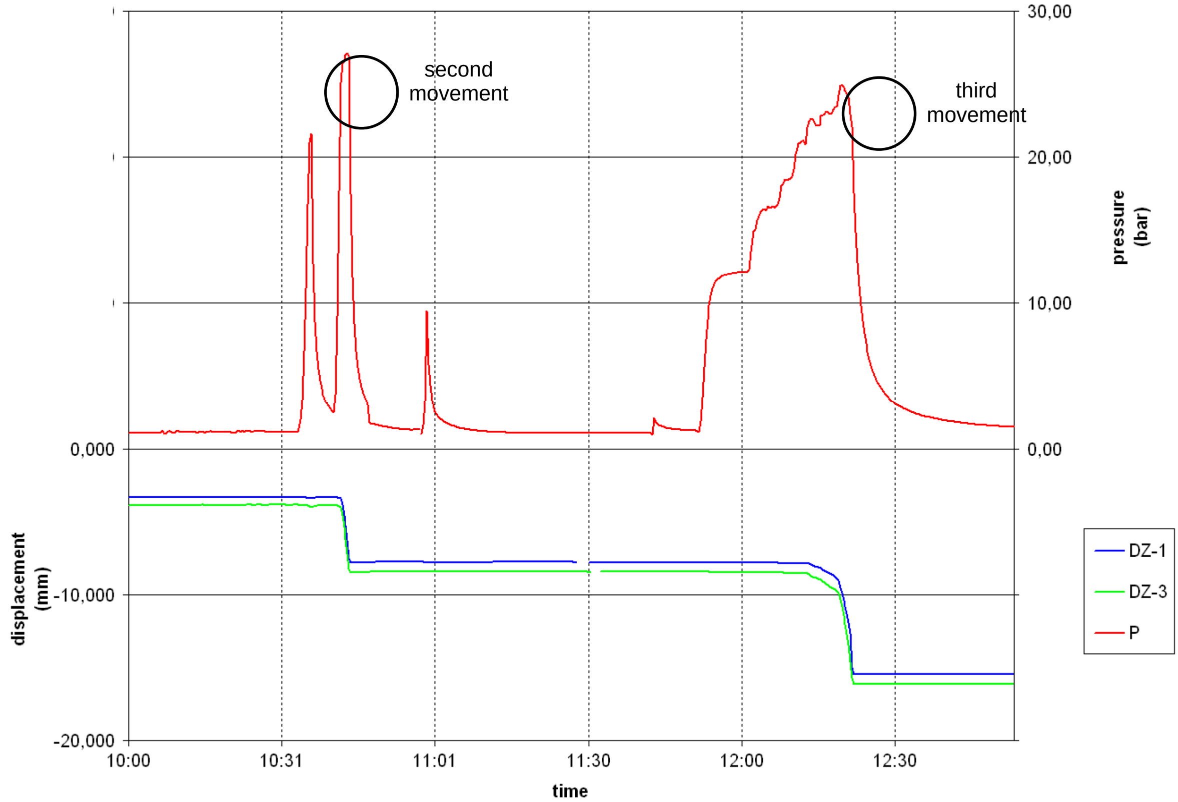

Figure 24: Loading and displacements during March 3, 2006

Test results

The test results indicated that after breaking the “true” cohesion between the concrete and the rock at an applied pressure of 27.09 bars, the plug remained intact, functioning like a rigid body, at least in most of its mass, and still withstanding pressures of about 25 bars.

No water leakage was detected at the rock-plug interface even after the plug “failure” with the exception of the bottom part of the plug, so it can be stated that no significant retraction of the concrete had taken place.

The information provided by the acoustic emission sensors correlated well with the plug movement but did not anticipate the “failure” episode.

The noisy signals and unexpected overpressures recorded by the total pressure cells could be caused by installation problems (cells working under anomalously high shear stresses). However, the pressure increase applied to the rock registered by the cells correlated quite well with the pressure applied in the water chamber, even after the plug displacement events.

2.1.7.2 Short Plug dismantling and sampling

The detailed dismantling of the plug sought to gain information on the plug properties (fabric, bounding between concrete batches and with the rock, mechanical and hydraulic properties, etc) and look for any signatures left by the induced failure that could help in the test interpretation and in future design and construction processes.

After the removal of the sensors installed in the plug front, the water injection system and the Data Acquisition and Display System, a detailed inspection of the plug face was done, finding no evidence, nor sign of any gap between the shotcrete and the rock along the plug perimeter.

Four boreholes were drilled from the plug surface at an angle to intercept the concrete/rock interface at different points. The core extracted from the top of the plug showed slickensides both in the concrete and in the rock, indicating a tight contact between them (Figure 25). A rectangular piece of the concrete in contact with the rock on top of the plug was cut out. Its entire surface showed slickensides too. Nine horizontal boreholes were drilled for studying the concrete fabric and properties.

Figure 25: Detail of inclined from the top of the plug; rock core (left) and concrete core (right) both with slickensides

A pass-through was excavated through the plug by drilling two large horizontal boreholes. This opening allowed a detailed inspection of the water chamber and a detail mapping of the inner part of the plug along its entire length.

The contact between the four layers of concrete used for the construction of the plug could be clearly observed. In particular, the first and second layers were separated by a gap between 2 and 4 centimetres wide that extended throughout the whole cross section of the plug, created most likely during the pressurising of the chamber, as this corresponds to the total displacement withstood by the plug after the different test series [D8.1].

The watertight membrane lining the water chamber seemed to be intact except in some points in the contact with the wooden support. The concrete showed a long crack along the perimeter, due to the displacement of the plug towards the entrance.

The rest of the plug was carefully demolished with hydraulic splitter. Six vertical borehole cores were extracted from the lower half of the plug. In general no significant variation could be observed between bottom and top parts of the extracted cores.

After removing the concrete numerous slickenside surfaces were observed in the granite in contact with the concrete, again indicating a tight concrete-rock contact.

2.1.8 Implementation of Full Scale In situ Tests

2.1.8.1 Operational phase

The initially planned test operation comprised four phases:

1. Hydration through mat S6 only (the one at the rear end of the buffer) at a maximum injection pressure of 3 bars until registering a peak of swelling pressure, during three months maximum.
2. Hydration through mats S2, S4 and S6 at a maximum pressure of 3 bars, again during three months maximum.

3. Hydration through all six mats S1 to S6 at a maximum pressure of 3 bars, until reaching the target swelling pressure of 4.5 MPa or until registering a plug "movement" or break (plug failure).
4. Hydraulic pulses of increasing pressure in steps of 0.5 MPa, to be performed after reaching the target swelling pressure and until achieving the plug failure.

The operational phase started on March 29, 2007 with the injection of water at a pressure of 2 bars through mat No. 6, located at the back end of the bentonite buffer

The following day a water leakage was detected through the contact of the rock with the bottom of the plug, and the injection was stopped. Successive injections lasting between 24 and 48 hours were carried out in April and June, and the water leakage appeared every time. The instrumentation did not give any indication of progress in the saturation of the bentonite buffer.

On September 19, 2007 a retaining dam was constructed close to the plug front up to mid height of the gallery, so to allow the retention of water and favour the swelling of bentonite. The water injection was resumed on November 8, 2007. Total pressure and humidity started rising after a few weeks (Figure 26).

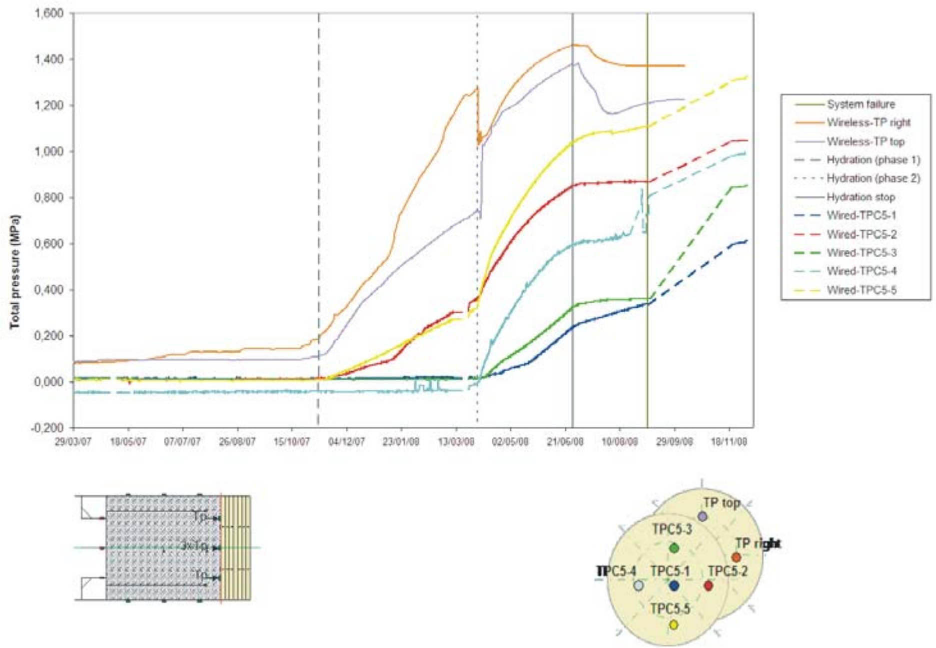

Figure 26: Total pressure cells at the back end of the gallery and at the contact bentonite-plug

2.1.9 Summary and Analysis of main achievements

2.1.9.1 Short Plug test

The main findings obtained from the Short Plug test are as follows:
1. Concrete with a pH equal to or lower than 11 may be formulated and successfully used for the construction of plugs with the desired mechanical properties in underground

galleries with a diameter down to 1.85 m at least, using the shotcrete technique, in compliance with the functional requirements.
2. The shrinkage of the concrete has been negligible, given that the force needed to move the plug was over 700 t, versus 6 t of plug weight. Besides, no water flow along the plug/rock interface at any time, but only through the bottom of the plug. Furthermore, slickensides were found throughout the interface plug/rock.
3. The “failure” (sudden plug movement of several millimetres behaving as a rigid body) of the plug is governed by the mechanical characteristics of the confined rock-shotcrete interface. The loading test has allowed a better estimation of these characteristics to be obtained. The interlocking effect (represented in the calculation model by a dilation angle) plays a very important role in the shear strength of the confined interface. A better calibration of the mechanical parameters of the interface plug/rock was obtained.
4. Valuable experience was obtained on how to construct parallel plugs in difficult working conditions.

2.1.9.2 Long Plug test

The main achievement in this test is the feasibility of the construction of a full scale shotcrete plug under restrictive working conditions and in a short period of time, which adds up an extra value to the realistic conditions of this test resembling a full scale plug as incorporated in a typical disposal concept. The obtained results show that shotcrete plugs could be built much faster than cast in place concrete ones, with an emplacement method that can be easily automated, and almost carried out on a continuous basis due to the low heat release of the low-pH shotcrete during hardening. However, the needed curing time for achieving necessary strength must also be considered.

This test is still on-going so no results for the bearing capacity of the plug are still available. Nevertheless valuable data are being obtained from the different sensors installed, and the comparison between wired and wireless data acquisition systems yields consistent results. The MoDeRn project, within the EURATOM’s 7th Framework Programme will follow the performance of the long plug beyond the ESDRED project.

2.1.10 Possible improvements of the designs developed

Further improvements might be introduced in the plug construction process to avoid or minimise the discontinuities between concrete layers and potential heterogeneities in the bottom part of the plug caused by shotcrete rebound, which is considered responsible for the leaks which appeared in the two plugs built in the project. The potential contribution of the shrinkage of the shotcrete to the leakage of the plug has not been studied. The improvements might be convenient for situations in which significant amounts of water are expected to interact directly over the plug. In conventional repository conditions, highly compacted bentonite plugs, interposed between the waste and the shotcrete plug, act as hydraulic sealants, as a result of which the shotcrete plugs will never be exposed to significant amounts of free water.

2.2 Low-pH Shotcrete Rock Support

2.2.1 Introduction

The studies on low-pH shotcrete for rock support were based on available recipes of low-pH concrete mixtures for use in a repository. Tests were carried out in Sweden and in Switzerland.

SKB has had the responsibility for recipe development for Swedish conditions, as well as pilot and full scale field tests in Sweden. SKB has also had the overall responsibility for the reporting to the EC.

The Swedish Cement and Concrete Research Institute (CBI) in Stockholm and shotcrete experts at the Royal Institute of Technology (KTH) in Stockholm were responsible for the development of the recipe and the demonstration of the shotcrete in Sweden, at Vattenfall´s Concrete Research Centre at Älvkarleby for the pilot tests and at Äspö HRL for the full scale field tests.

Based on the recipe developed by CBI/KTH in Sweden, NAGRA has developed recipes using materials available in Switzerland. NAGRA has performed pilot tests to apply low-pH shotcrete on clay samples from Mont Terri, Switzerland at the Hagerbach Test Facility.

Posiva has followed and reviewed the work and documentation on development of the low-pH shotcrete for rock support and the results from the pilot and field tests.

2.2.2 Input data and Functional Requirements

See also Chapter 2.1.2.

The functional requirements for the shotcrete for rock support have been revised relative to what was reported in Deliverable D1 of Module 4, mainly due to the slow increase of the compressive strength of the shotcrete. Consequently a 90 day value has been added. The mechanical properties of the final shotcrete product were also measured including pumpability, compressive strength, Young's modulus, shrinkage, and bonding to the rock wall.

The yellow column in Table 16 shows the new specification used for this development work as well as the original specification shown in the first Module 4, Deliverable D1.

2.2.3 Studies and/or computer simulations and/or Modelling

Step 1 in Sweden was executed during September – December 2005 and consisted of small laboratory experiments with cement paste to get an understanding about suitable recipes with special investigation on the effect of set accelerators and superplasticizers. This was done in the CBI laboratory in Stockholm with low-pH binder and with shotcrete mortar. The first candidate as set accelerator was water glass (alkali silicate) as this component does not contain any organic constituents and is compatible with the long term safety requirements for deep repositories for spent fuel. Following this, test specimens were made and tested for both drying and autogeneous shrinkage.

The recipe development was done in steps, starting with laboratory tests and ending in pilot-scale tests.

2.2.4 Laboratory Test Work

The aim was to determine the compability between superplasticizers, set accelerators and low-pH grout and also to determine the basic parameters for formulating low-pH shotcrete.

Table 16: Specification of mechanical properties for low-pH shotcrete.

Ítem	Previous NAGRA	Previous SKB/Posiva	New specification
Hydraulic conductivity	$k \leq 10^{-10}$ m·s^{-1}	Not relevant	Not applicable
Mechanical properties: • **Compressive Strength**	≈ 10 MPa (8 hours) ≈ 25 MPa (7 days) ≈ 35 MPa (28 days)	≈ 10 MPa (8 hours) ≈ 25 MPa (7 days) ≈ 35 MPa (28 days)	≈ 10 MPa (36 hours) ≈ 20 MPa (7 days) ≈ 30 MPa (28 days) ≈ 40 MPa (90 days)
• **Young modulus**		≈ 15 GPa (7 days) ≈ 20 GPa (28 days)	≈ 15 GPa (7 days) ≈ 20 GPa (28 days)
• **Bonding**	≈ 0.5 MPa (28 days, rock/clay) ≈ 1.0 MPa (28 days, concrete)	≈ 0.9 MPa (7 days) ≈ 1.5 MPa (28 days)	≈ 0.5 MPa (7 days) ≈ 0.9 MPa (28 days)
Durability	≥ 2 years (sulphate resistant)	≥2 years (sulphate resistant)	(sulphate resistant)
Workability	≥ 2 hours	> 2 hours	≥ 2 hours
Pump ability	> 100m	~ 15m	> 15m
Slump	15 – 20 cm	15 – 20 cm	15 – 20 cm
Peak hydration temperature	Not relevant (< 100°C)	~ 40ºC-	Not relevant (< 100°C)
Thermal conductivity	Dry: > 0.5 W/m°C Saturated: >1.2 W/m°C	Not applicable	Not relevant
Use of organic components (fibres or admixtures)	Compatible with PA, needs to be studied	Compatible with PA, needs to be studied	Compatible with PA, needs to be studied
Steel fibres	Steel (or plastic) fibres compatible with PA, needs to be studied	No steel fibres	Steel (or glass) fibres compatible with PA, needs to be studied in a later phase.

The tests included laboratory shotcrete (paste) experiments. Apart from analyzing the compability between the additives, it also included a series of experiments to find out how the set accelerators influence the shrinkage of the low-pH paste, which in turn will influence the function of the hardened concrete. The results show that both set accelerators and superplasticizers are compatible with low-pH concrete, but there is a delay in the hardening process. Low-pH paste with set accelerators seems to develop a larger shrinkage than normal low-pH paste.

In short, the laboratory test work, Step 1, can be summarized as follows:

– The aim of this part was to find out the compability between superplasticizers, set accelerators and low-pH paste (binder) in order to find out the basic premises for the formulation of low-pH shotcrete.

- The compability of the low-pH binder fraction, different superplasticizers and set accelerators in different dosages.
- The effect on binding time.
- The strength development of paste.
- Shrinkage of paste.
- The effect of admixtures on shrinkage of paste.

The results of the work during Step 1 are in short the following:

- The results show that the low-pH binder is compatible with the superplasticizer (SP) and the set accelerators (SA). Both alkali free accelerators and water glass (alkali silicate) can be used as SA with all types of SP but there will be variations as regarding binding time and strength development depending on the combination.
- In general the hydration is somewhat delayed and consequently the strength development is delayed.
- Ther strength of the hardened low-pH shotcrete is similar to that of ordinary paste.
- The fresh shotcrete is sensitive to curing. Water has to be added to avoid plastic shrinkage.
- The basic shrinkage of the low-pH binder is substantially larger than for normal binders. The shotcrete shrinks much more than normal concrete, presumably as a result of the set accelerator.

Step 1, the development of the recipes low-pH shotcrete for rock support is documented in a previous report [D2.2, D3.2 & D4.2].

The laboratory tests in Switzerland were performed at the Hagerbach facility (www.hagerbach.ch), where all the required equipment and infrastructure to perform shotcrete testing is available. The laboratory analyses were carried out by the Hagerbach team as well.

Based on the results from Äspö HRL, NAGRA modified the recipe 10-2 used in Sweden to suit cement available in Switzerland and local aggregate instead. The lists of test mixes at Hagerbach and comparison with some of the mixes tested in Sweden are shown in Table 17.

This suggests that the mixture will need to be adjusted for at any actual repository site and that careful quality control will need to be maintained in production.

Although the recipe was as close as possible to the Äspö one, due differences in the compositions of the cement and silica fume, preliminary testing of e.g. workability was required.

Consequently the first step in the programme was to determine the modifications required on the Äspö recipe to optimise the shotcrete for application on Opalinus clay samples excavated and transported to the Hagerbach site. To allow a direct comparison with industrial standards, after preliminary feasibility tests, normal panel tests with a routine laboratory programme were carried out. The same type of measurements made for the field tests at Äspö HRL, e.g. mechanical properties, were done to allow a direct comparison of results.

In Sweden the coarse aggregates consisted of crushed rock of fraction 5/11, whereas the aggregates at Hagerbach comprised natural rounded river sand, 0 - 8 mm. The grain fraction curve coincides with the standardised base sieving curve of aggregates for concrete according to EN 12620 / 2002. Unlike the Swedish mix 10-2, no filler was added since the natural sand proved to have sufficient amounts of fine fraction material.

Table 17: List of tested mixes at Hagerbach and comparisons with some of the mixes at Äspö HRL.

	Tests in Sweden			**Tests at Hagerbach Test Gallery**					**Common shotcrete**
Mix	10-2	10-2 day 1 (Äspö)	10-2 day 2 (Äspö)	Base Mix	Mix 1	Mix 2	Mix 3	**Mix 4**	*Ref. mix*[1]
Component:	kg/m3								
Water	154.3	175.0	175.0	158.0	179.0	166.0	190.0	**175.0**	*225.0*
CEM I 42.5 N [2]	210.0	210.0	210.0	210.0	210.0	210.0	210.0	**210.0**	*425.0*
Silica Fume (940U/EN 13263)	140.0	140.0	140.0	140.0	140.0	140.0	140.0	**140.0**	*20.0*
- Filler (Quartz Sand)	250.0	250.0	250.0						
- Sand 0/1	1'025.2[3]	996.0	996.0	162.0	184.0	184.0	175.0	**175.0**	*1'079.0*
- Sand 0/4				990.0	1'111.0	1'110.0	1'057.0	**1'057.0**	
- Gravel 4/8	552.1[4]	537.0	537.0	648.0	690.0	692.0	672.0	**672.0**	*626.0*
Aggregates in total	1'827.3	1'783.0	1'783.0	1'800.0	1'985.0	1'986.0	1'904.0	**1'904.0**	*1'705.0*
Superplastizicer „Glenium 51“	3.48	5.67	5.00	3.00	3.50	5.25	7.00	**7.00**	*7.65*
Air entraining Agents “Sika Air S”	2.5	3.0	3.0	2.5	-	-	-	-	-
Water/Binder ratio [%]	0.45	0.50	0.50	0.45	0.51	0.47	0.54	**0.50**	*0.50*
Water/Cement ratio [%]	0.73	0.83	0.83	0.75	0.85	0.79	0.90	**0.83**	*0.53*
Slump (0 min) [mm]	205	175	180		150	130	235	**220**	*?*
Slump (120 min) [mm]							230	**160**	*?*
Flow table (0 min) [mm]					330	400	550	**500**	*420*
Flow table (120min) [mm]							550	**430**	*?*
Air content [%]	13.5	10.3	11.0		4.0	6.1	4.5	**4.7**	*2.6*
Density [kg/m^3]					2’283	2’262	2’268	**2’299**	*2’333*

The equipment to measure out the components and to mix the concrete provided an accurate and good mixing process. The procedures applied to mix the concrete (e.g. mixing time) have been similar to common concrete.

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1 Reference wet mix of common shotcrete (Cornejo-Malm, 1995)

2 Mix 10-2 with Standard Portland “Anläggningscement” from Cementa AB, commonly used in shotcrete in Sweden. According EN 197-1 it is a CEM I 42.5 N/SR/LA (Moderate heat/sulphate resistant/low alkali) cement.

3 Mix 10-2 with fraction 0/5 mm;

4 Mix 10-2 with fraction 5/11 mm;

Based on sieve curve analysis, the amount of fine fraction (<0.125 mm) of the aggregates corresponds approximately with 10 wt % (192.5 kg/m^3). This is within recommended aggregate gradation of 4 to 12 wt % according to the European Specification for Sprayed Concrete (EFNARC, 1996). The total proportion of fine fraction components within the shotcrete recipe equals 540 kg/m^3. Commonly used Portland cement CEM I 42.5 N was taken. Furthermore no air entraining agents was used.

Although the water content of the first mix was 0.51, similar to the mix in Äspö HRL, the wet mix was far too stiff. Since it was aimed not to exceed the water/binder ratio of 0.50 the amount of superplastizicer was increased. With 5.25 kg/m^3 (= 1.5 wt % of binder) of superplastizicer the consistency seemed to be slightly improved but was still insufficient for pumping. Furthermore workability time was substantially less than two hours. By increasing the amount of superplastizicer up to 7 kg/m^3 (corresponds to 2 wt % of binder) the wet mix (Mix 4) eventually showed the envisaged behaviour in terms of consistency to pump, homogeneity, tendency of segregation and workability.

A batch of 2 m^3 wet mix 4 was prepared to carry out spraying tests on panels. The spraying operation was commenced two hours after mixing the concrete to demonstrate the specified workability time. The wet mix was transported by a ready-mix drum on a lorry. Modern wet-mix spraying equipment (MEYCO Suprema®) with electronically controlled push-over system provides a nearly pulsation-free conveyance of the wet mix from the pump to the nozzle. The concrete had to be pushed through a 30 m long pumping pipe. The nozzle was installed to a remote controlled manipulator. This equipment corresponds to modern sprayed concrete wet-mix equipment and provides homogeneous shotcrete of good quality and minimised rebound.

Dosage of alkali free set accelerator was varied between 5 and 15 wt % of cement (equals 10.5 to 31.5 kg/m^3). The concrete was sprayed onto wooden panels (see Figure 27).

Figure 27: Pre-tests on panels (700 mm x 700 mm) using mix 4 and different dosage of set accelerator.

Numerous tests have been carried out either directly on the sprayed concrete (e.g. fresh concrete early strength) or from cores drilled in the placement test panels.

The work in Switzerland was performed during September – November 2006 followed by reporting from Nagra when results were available in early 2007.

A more detailed description and result of the work done in Sweden and Switzerland are presented in Deliverable [D8.2].

2.2.5 Design Work /demonstrator layouts / Test program definition

The development of low-pH shotcrete did not require any specific design work or demonstrator layout as the development of recipes as well as pilot tests and field tests was done in existing laboratories and test facilities.

2.2.6 Procurement and set-up of test facilities

SKB contracted out the work for the development of the recipes in August 2005. The work with the pilot testing at Älvkarelby was contracted in January 2007 and the subcontractor for doing the field test at Äspö was engaged in March 2006. No special set-up of the test facility was required.

NAGRA contracted out the corresponding work at Hagerbach facility in Switzerland in August 2006. No special set-up of the test facility was required for doing the development of the recipes or pilot testing.

2.2.7 Implementation of Reduced Scale mock-up Tests

The results from Step 1 become the basis for continuation of the work within Step 2.

Step 2 started with petrographical analyses of the aggregates to be used and the development of the availability recipe to be used for the pilot scale testing and later also for the field test at the Äspö HRL. All of the crushed rock (fractions 0-2, 2-5 and 5-11 mm) contained in the low-pH shotcrete used for the plug construction in the horizontal drift at Äspö HRL, came from Äspö. The recipe for the shotcrete for rock support was modified. Instead of only crushed rock the aggregate was a mixture of natural sand (0 - 5 mm) and crushed rock from Äspö HRL (5 – 11 mm). Filler material was also needed as the natural sand contains very little fine material.

The functional requirements for the shotcrete for rock support have been revised relative to what was reported in Deliverable D1 of Module 4, mainly due to the slow increase of the compressive strength of the shotcrete. Consequently a 90 day value has been added. The mechanical properties of the final shotcrete product were also measured including pumpability, compressive strength, Young's modulus, shrinkage, and bonding to the rock wall.

Based on the results of the laboratory work the selected recipes were tested in pilot scale at Vattenfall´s Concrete Research Centre at Älvkarleby, in February 2006, some 200 km north of Stockholm.

All the ingredients in the recipes were carefully measured and mixed in a small concrete paddle mixer and each mix had a volume of 150 litres. The selected superplasticizer and the air entraining agent were added in the concrete mix. Slump test as well as measuring of the air content in the mix was done before the concrete was transferred to the concrete pump in the test area.

The results showed that two types of commercial available filler gave good coherence and workability. These were quartz filler (Öresund sand <0.25mm) and limestone filler (Köping 500 <0.5mm). The Öresund sand, which comes from the seabed and contains well-rounded quartz particles, gives a somewhat lower plastic viscosity than the more angular limestone powder (from crushed crystalline limestone). Further tests were continued with these fillers and rheology was measured with and without entrained air. In fresh concrete entrained air acts as a particle but it will give lower mechanical strength in hardened concrete. In shotcrete, however, most of the air will be lost during the shooting.

The recipe selected (10-2) for pilot and field experiments is based on undensified silica fume and lean natural sand complemented by a filler based on well rounded quartz grains. The rounded grains help to overcome the higher viscosity due to silica fume. To improve the rheology of the concrete, an air entraining agent could be used to increase the air content. Shotcrete recipe 12-2 based on limestone filler was also chosen for further tests to demonstrate the difference between limestone and quarts filler.

The pilot test was performed in February 2006 with the two recipes, recipe 10-2 with quartz filler and recipe 12-2 with limestone filler respectively. The amount of plasticizer was adjusted during the test to achieve different workability and spraying properties. The test was performed at ambient temperature; Table 18 shows the comparison of the tested concretes. The variation in aggregate content is a result of a slight difference in density between quartz filler and limestone filler.

Table 18: Recipes for pilots tests at Älvkarleby, February 21, 2006 in kg/m^3.

Component	**Natural filler, Öresund sand. Recipe 10-2**	**Limestone filler Köping 500. Recipe 12-2**
Water	158	158
CEM I 42.5 N SR/LA	210	210
Silica Fume 940 U	140	140
Coarse aggregate (5-11mm)	550	552
Natural sand (0-5mm)	1021	1025
Filler	250	250
Superplasticizer	Adjusted 2.67 – 3.35	3.15
Air entraining	2.5	2.5
Accelerator	4 - 10 %	4 - 10 %
Water/binder ratio	0.45	0.45

The results from the field test at Älvkarleby are shown in Table 19 below. It should be noted that the compressive strengths of the shotcrete exceed the required values specified by ESDRED of 20 MPa after 7 days, 30 MPa at 28 days and 40 MPa at 90 days.

In order to investigate the performance of the low pH shotcrete mix on rock conditions as envisaged for future repositories in Switzerland, spraying tests on prepared Opalinus clay specimen have been carried out. The preparation of the test samples is shown on Figure 28 and the actual test is shown on Figure 29. The Opalinus clay specimens were excavated 18 months earlier from the Mont Terri Rock Laboratory and stored within plastic bags to protect against moisture. There was no visual sign of weathering or disintegration of the Clay stone when prepared for testing. Deliverable [D8.2] presents the details of the preparation and the tests done.

Table 19: Compressive strength, Young's modulus and density of samples from Älvkarleby.

	Recipe 10-2, quartz filler			Recipe 12-2, limestone filler		
Age [days]	**$F_{ck,cube}$ [MPa]**	**Density [kg/m³]**	**E_0/E_c [GPa]**	**$F_{ck,cube}$ [MPa]**	**Density [kg/m³]**	**E_0/E_c [GPa]**
7	32.0	2350	-	35.5	2400	-
28	80.5	2330	30.0 / 33.8	92.0	2390	35.2 / 38.7
91	94.8	2320	-	117.7	2390	-

Figure 28: Preparation of Opalinus Clay test panels (1.5 m x 1.5 m).

Figure 29: Photo of the equipment used for the test for preparation of the test panels.

The specimens were cast in place with low pH concrete according to mix 4 and Figure 29 shows the equipment used during the tests.

Spraying performance under realistic underground condition showed to be satisfactory. A 150 mm layer of shotcrete could be sprayed on Opalinus clay in one pass without any problems.

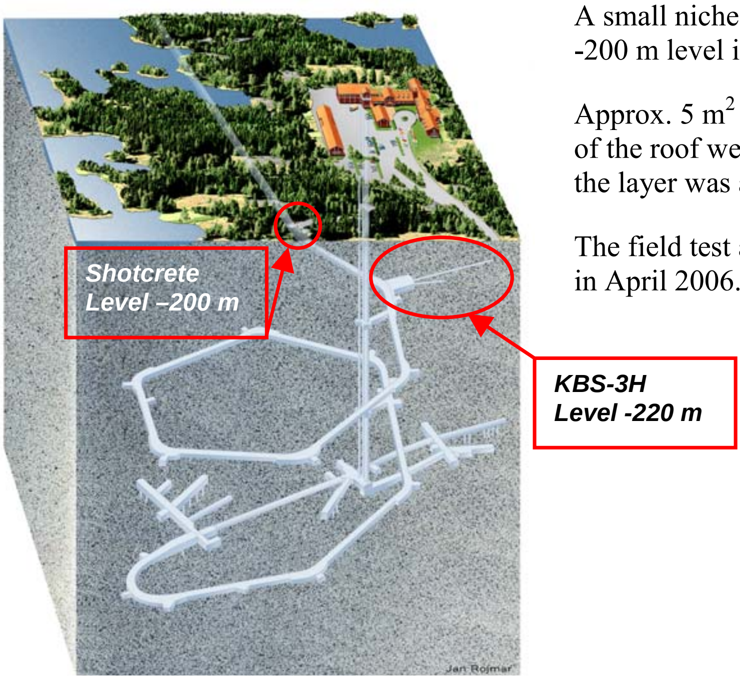
2.2.8 Implementation of Full Scale mock-up Tests

After evaluation of the results from the pilot testing, the field-testing at Äspö HRL was done, using the same contractor and the same equipment as for construction of the shotcrete plug in the KBS-3H deposition drift.

No specific preparation of the rock wall at Äspö HRL was done, except that the area was cleaned using pressurised water before starting the work.

The field test at Äspö HRL was done in April 2006. The location of the test area can be seen on Figure 30 and a photo of the selected area is shown on Figure 31.

Field tests were conducted using recipe 10-2 (see Table 17 and Table 18) with 250 kg of quartz filler only because limestone was not used in the shotcrete for the plug. Compressive strength and density were tested on core drilled cylinders according to SS-EN 12504-1 and Young's modulus on core drilled cylinders according to SS 13 72 32. In Table 20 the compressive strength is recalculated to cube strength (Fck.cube). Shrinkage was measured both, according to SS 13 72 15 and in water on sawed beams. The shotcrete was sprayed with water daily for 7 days but not kept continuously wet. At CBI, beams were sawn and put in water for 24 hours before the first measurement. Bonding to rock was determined according to SS 13 72 43.



A small niche was selected as test site at -200 m level in the ramp.

Approx. 5 m^2 of the wall and approx. 5 m^2 of the roof were shotcreted. The thickness of the layer was about 50 mm.

The field test at Äspö HRL was carried out in April 2006.

Figure 30: Location of the test area at Äspö HRL for the field test with low-pH shotcrete for rock support.

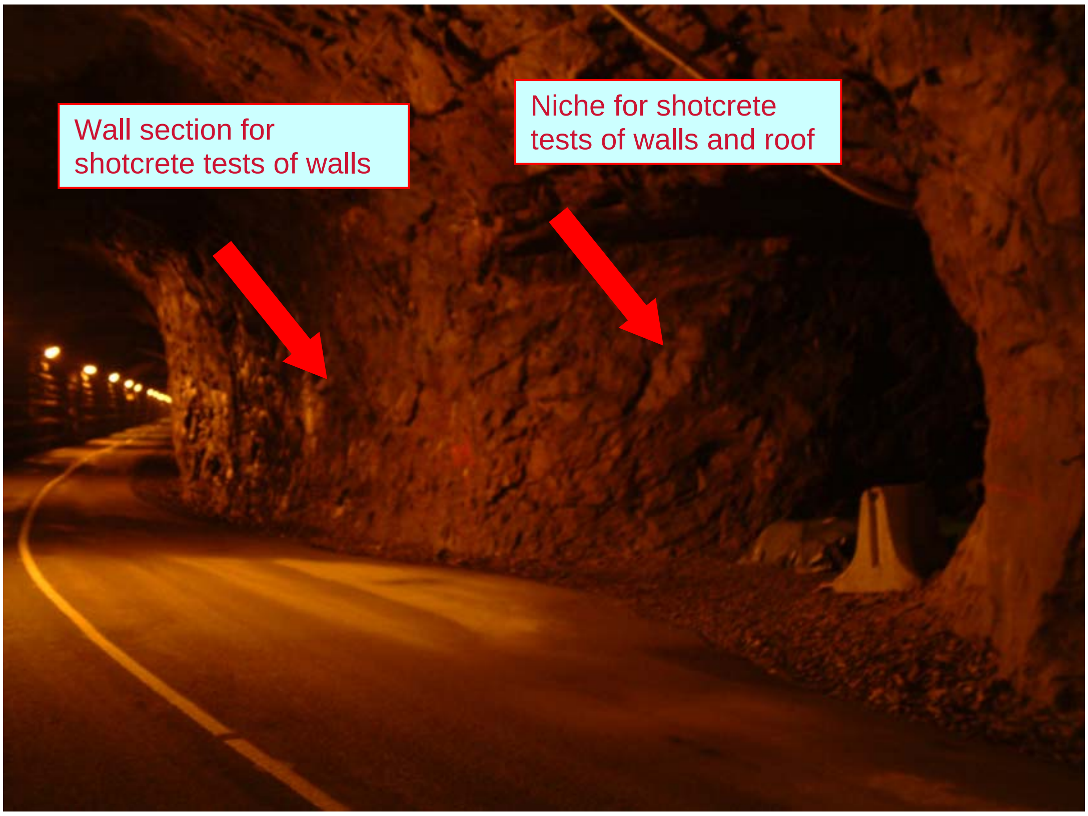


Figure 31: Photo from the ramp and the niche at Äspö HRL at level 200 selected for the rock wall shotcrete tests.

The compressive strength and Young’s modulus was sufficient although the water-binder-ratio had to be increased from 0.45 to 0.50. The beams did swell a little when placed in water. This indicates that the beams had lost some water before the drying started. If this is considered the drying shrinkage would be higher than for cast low-pH concrete as it was the case for the shotcrete from the Älvkarleby experiments.

Table 20: Compressive strength, Young’s modulus and density of samples from Äspö HRL.

	Recipe 10-2, quartz filler		
Age [days]	**$F_{ck,cube}$ [MPa]**	**Density [kg/m³]**	**E_0/E_c [GPa][5]**
7	19.7	2270	-
28	54.6	2240	28.0 / 37.0
91	64.7	2240	-

Figure 32 show the equipment used for the field test at Äspö HRL as well the test area after the testing.

Figure 32: Photo of the equipment for shotcreting at Äspö HRL at level 200 and a close photo of the surface.

A more detailed description of the work done after Step 1 including the pilot tests at Vattenfall´s Concrete Research Centre at Älvkarleby, Sweden, and the field tests at Äspö HRL in Sweden is given in Deliverable [D8.2].

|Meanwhile in Switzerland on the 11th of November 2006, a large-scale field test was carried out at the Hagerbach test gallery. Approximately 9 m^3 of low pH shotcrete mix 4 was sprayed onto approximately 20 m^2 of the sidewall and the crown of a drill and blast horseshoe tunnel. l. The rock consists of limestone. Whereas the sidewalls were unsupported, the crown was covered by a thin layer of former sprayed concrete.

The objective of this field test was to demonstrate the applicability of low pH shotcrete for underground excavation rock support. In particular it should be shown that spraying overhead with low pH shotcrete is feasible and that economically reasonable performance rates can be achieved that compare favourably with rates for common wet mix shotcrete work.

[5] E_0 and E_c are Young's modulus, measured in two different ways according to Swedish standard SS 13 72 32. E_0 corresponds to the CEB-FIP definition.

2.2.9 Summary and Analysis of main achievements

The work done is preliminary and further work will be needed before this low-pH shotcrete can be accepted for use in a future deep repository in Sweden, Finland and Switzerland.

- One area that requires further investigations is the selection of suitable superplasticizers and accelerators with regard to long term safety for the deep repository.

- The field tests were done without reinforcement of the shotcrete for rock support. In order to enhance applicability of low pH shotcrete for rock support, corrosion rate of wire mesh and steel fibre within low pH sprayed concrete structures in comparison with common shotcrete should be tested. The possibility to use other material for reinforcement should also be investigated.

- The low-pH concrete requires good mixing. Suitable mixers and equipment for pumping should be investigated and tested in underground conditions.
- Large scale tests under real conditions are also recommended in order to demonstrate its competitiveness to common shotcrete for repositories in hard rock in Sweden/Finland.

Based on the experiences made during the tests at Hagerbach in Switzerland it is also recommended that:

- The pH of hardened low pH shotcrete should be determined on cores taken from sprayed linings to ascertain the actual low pH. It needs to take into consideration that due to rebound, the proportion of the admixtures differs between sprayed shotcrete and the basic wet mix.

- Reliable data should be collected regarding durability of low pH shotcrete for instance by determining pore volumes, freezing tests and examining the micro structure of the concrete.

- Large scale tests under real construction work conditions (e.g. in Opalinus Clay at the rock laboratory at Mont Terri) in order to demonstrate its competitiveness to common shotcrete.

In general the tests have also indicated that the aggregate used must be reasonably controlled for gradation and roundness thus the mix will need modification based on aggregate source to ensure the shotcrete meets specifications.

Similarly, skilled personal will have to apply the shotcrete with an understanding that the mix should not be revised to improve application at the operational level, e.g. adding water to improve pumpability. Thus communication and quality control will be key issues to shotcrete placement.

2.2.10 Possible Improvements of the designs developed

Improve the mixing of the shotcrete and the control of the required amount of admixtures, for example superplastizicers and set accelerators, are areas for future improvements. Measuring the actual pH of hardened sprayed low-pH concrete “on the wall“ would also be of interest.

Research work concerning durability as well as long term behaviour of low-PH shotcrete reinforced with steel fibres and/or wire mesh is also recommended. It is known that low-pH concrete will have a higher shrinkage then normal concrete and it should be investigated if this would create a problem when using low-pH shotcrete.

3 Chapter 3: Summary and Conclusions

3.1 Construction of low pH concrete plugs using shotcrete techniques

As a main conclusion of the present project, it can be stated that concrete with a pH equal or below to 11, which is more compatible with engineered barriers such as bentonite than regular concrete, can be formulated and used as a shotcrete for the construction of plugs in underground galleries excavated in crystalline rock. Furthermore it is compatible with the use of standard wet-shotcrete equipment. The cement formulation selected for this purpose was 60% OPC and-40% SiF.

Several alternative formulations utilizing both OPC and CAC cements have been identified. It has been shown that a low-pH environment can be achieved in a shotcrete plug by adding significant amounts of mineral admixtures to prepare the binder. Obviously, the inclusion of high amounts of mineral admixtures in the cement formulation modifies most of the concrete "standard" properties as well as the microstructure of the obtained cement products. Thus when designing a concrete based on low-pH binders the modifications of the basic properties of the concrete must be taken into account, and it must be ensured that the functional requirements can be reached. Furthermore, due to the location and the long service life of these types of product, their durability properties must be also guaranteed.

The challenge of using low-pH concretes in shotcreting is particularly complex when taking into account that the chemical admixtures employed must also be compatible with the concrete mixture. Furthermore, their effectiveness must be assured without increasing the pH above the admissible levels. A new preliminary rapid method for assessing the pH of pore waters has been calibrated and is the subject of further work by several of the ESDRED partners (and others) but outside of ESDRED.

During the present project, functional requirements for gallery plugs were set up and the compliance with them was evaluated at a laboratory scale and a real scale, by making different trials with the shotcrete. Parameters such us the workability of the basic concrete, the quality of fresh and hardened basic concretes, the pumpability of the mix and the properties of the hardened shotcrete were tested.

From the results and interpretation of the short plug loading tests performed, as well as the construction and monitoring of the long plug test, the following main conclusions can be drawn:

1. Shotcrete with a pH equal or below to 11 can be successfully used for the construction of plugs in underground galleries with either small or large diameters and under restrictive working conditions.

2. The "failure" (sudden several millimetres movement of the plug behaving as a rigid body) of the short plug is governed by the confined rock-shotcrete interface mechanical characteristics. The loading test has made it possible to obtain a better estimation of these characteristics. The interlocking effect (represented in the calculation model by a dilation angle) plays a very important role in the shear strength of the confined interface. The obtained results of the loading test on the short plug were incompatible with a significant shrinkage of the shotcrete.

3. The feasibility of constructing shotcrete plugs measuring up to several metres in length in both small and large diameter galleries has been demonstrated, although some improvements could be introduced in the process to avoid or minimise the discontinuities between concrete layers and the potential heterogeneities in the bottom part of the plug caused by shotcrete rebound.
4. The plugs tested were not water tight. Whereas this is not necessarily a requirement for deep geological repositories the design and or construction techniques may be improved to secure water tightness if required.

3.2 Construction of low pH rock support using shotcrete techniques

The results from the work in Module 4 show that it is possible to design a concrete for low-pH shotcrete. In this project the rheological properties of conventional shotcrete were used as a starting reference and the composition of low-pH concrete was subsequently altered until it showed similar properties. This was done with the help of a concrete rheometer. The experiments showed that it is very important to have well graded sand with round particles to overcome the higher viscosity generated by the large amounts of silica fume in the low-pH concrete.

The final recipe selected includes natural sand and rounded natural quartz filler to be able to keep the amount of binder low. However, in the future quartz filler is likely to be replaced with limestone filler due the health risk imposed when using the fine quartz material under field conditions. Also this material does not need to be imported. Plastic viscosity and yield stress of the fresh concrete is lowered by using an air entraining agent to increase the air content in the fresh concrete. During shotcreting this entrained air is lost and therefore the concrete gives higher yield stresses on the rock wall. At the same time the hardened shotcrete develops good physical properties once the air is lost.

The mechanical properties of the hardened shotcrete meet the requirements. The compressive strength and Young's modulus obtained in laboratory tests are sufficient to allow some scatter in concrete properties which are to be expected under construction conditions.

The bonding to the rock at Äspö HRL was insufficient. Textural analyses showed that this was a result of inhomogeneities between layers of porous shotcrete. Closer analyses showed that the porous layers were a result of a too high set accelerator content, which in turn indicates poor mixing at the shotcrete nozzle. This was not found at the shotcrete experiment in Älvkarleby and is presumably mainly a technical problem due to the underpowered mixer available at Äspö HRL during the field tests.

Shotcrete with alkali free set accelerator shrinks more than normal concrete. Moreover, low-pH concrete shrinks more than normal concrete. Together they create a shrinkage problem. Furthermore, normal shotcrete sometimes contains steel fibers that will also change the properties of the shotcrete. Combinations of fibers may be used to create numerous small shrinkage cracks instead of some large cracks. This problem was not treated in Module 4 of ESDRED.

4 Chapter 4: List of references

[1] **PUSCH R., SVEMAR C.,** "Comparison of repository concepts & recommendations for design and construction of future safe repositories", (2004), CROP Project, Deliverable 6, Stockholm, Sweden.

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[5] **BARCENA I., FUENTES-CANTILLANA J.L., GARCIA-SIÑERIZ J.L.**, "Dismantling of the heater 1 at the FEBEX 'in-situ' test", (2003), ISSN 1134-380X, Madrid, Spain.

5 Annexes

1. List of people who participated in the Module
2. List of Module Deliverables complete with Dissemination level
3. List of ESDRED final reports
4. List of acronyms
5. Glossary

ANNEX 1: LIST OF PEOPLE WHO PARTICIPATED IN THE MODULE 4

Company	Name	First Name
AITEMIN	Fuentes-Cantillana I.	José Luis
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AITEMIN	Fernández G.	Pablo A.
AITEMIN	Llamas M.	Bernardo
AITEMIN	Gutierrez L.	Manuel
AITEMIN	Sanz M.	Francisco J.
AITEMIN	Llamas D.	Miguel
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CSIC-IETcc	García Calvo	José Luis
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CBI	Lagerblad	Björn
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ENRESA	Farias Seifert	Joaquín
ENRESA	Gago(Nota 2)	José Antonio
ENRESA	Huertas (Nota 3)	Fernando
ENRESA	Zuloaga (Nota 4)	Pablo
NAGRA	Fries	Thomas
NAGRA	Weber	Hanspeter
NAGRA	Schwyn	Bernhard
POSIVA	Äikäs	Timo
POSIVA	Salo	Jukka-Pekka
SKB	Pettersson	Stig
SKB	Karlzén	Rickard
VPC	Bodén	Anders

Nota 1: Module Leader from 1-1-2007 until 31-07-2008

Nota 2: Module Leader from 1-8-2008 until 15-09-2008

Nota 3: Module Leader from the beginning until 31-12-2006

Nota 4: Module Leader from 15-09-2008

ANNEX 2: LIST OF MODULE 4 DELIVERABLES

Reference	Title	Date	Dissemination Level
WP1: Input Data and Functional Requirements			
Mod4-WP1-D1	Input data and functional requirements	**08/11/2004**	**RE**
WP2: Design of low-pH cement			
Mod4-WP2-D2.1_WP3.1-D3.1	Design of low-pH concrete for the construction of shotcrete plugs [Combined Report including: • Mod4-WP2-D2.1 (Report on adequate formulations of low-pH cement (plug)) • Mod4-WP3.1-D3.1 (Interim report on selected solutions of low-pH cement shotcrete techniques (plug))]	**27/06/2006**	**CO**
Mod4-WP2-D2.2_WP3.1-D3.2_WP3.2-D4.2	Low-pH Shotcrete for Rock Support. Report on development of recipe including Test Plan for pilot and field testing. [Combined Report including: • Deliverable D2.2 (Module 4, WP2): Report on Adequate Formulations of Low pH Cement (Rock Support) • Deliverable D3.2 (Module 4, WP3.1): Interim Report on Selected Solutions of Low pH Shotcrete Techniques (Rock Support) • Deliverable D4.2 (Module 4, WP3.2): Test Plan for the Rock Support Demonstration)]	**15/03/2006**	**CO**
WP3: Full scale demonstration **WP3.1: Shotcreting technique development (formulation and testing)** **WP3.2: Plug and Rock support demonstration (full scale)**			
Mod4-WP3.2-D4.1	Low-pH short plug construction and testing. Test Plan	**20/07/2005**	**CO**
Mod4-WP3.2-D4.3	Test Plan for the full-scale demonstration of a Shotcrete plug	**27/04/2007**	**CO**
Mod4-WP3.2-D5	Plug constructed and instrumented (Nota1)	**07/02/2006**	**--**
Mod4-WP3.2-D6	Low-pH Shotcrete plug demonstration test monitoring data base	**19/07/2006**	**CO**
Mod4-WP3.2-D7	Concrete samples from the plug construction & dismantling phases	**19/07/2006**	**CO**
Mod4-WP3.2-D8.1 R1	Report on Short Plug Test Results	**29/05/2007**	**PU**
Mod4-WP3.2-D8.2	Low-pH Shotcrete for rock support. Report on full-scale demonstration	**18/06/2007**	**PU**
Mod4-WP3.2-D8.3	Report on the results of the long plug tests	**January 2009**	**PU**
WP4: Evaluation and final report			
Mod4-WP4-D9	Module 4 (Temporary Sealing Technology) Final Technical Report	**15/01/2009**	**PU**

Nota 1: This deliverable is a "Demonstrator" type which does not involve a report

Dissemination Level:
PU: Public
RE: Restricted
CO: Confidential

ANNEX 3: LIST OF ESDRED FINAL REPORTS

Reference	Title
Mod1-WP6-D6	Module 1 (Buffer Construction Technology) Final Technical Report
Mod2-WP7-D8	Module 2 (Waste Canister Transfer & Emplacement Technology) Final Technical Report
Mod3-WP5-D6	Module 3 (Heavy Load Emplacement Technology) Final Technical Report
Mod4-WP4-D9	Module 4 (Temporary Sealing Technology) Final Technical Report
Mod5-WP5-D11	Final Report on Communication Action Plan
Mod5-WP9-D12	Leaflet on Final ESDRED Results
Mod6-WP4-D6	Final ESDRED Project Report

ANNEX 4: LIST OF ACRONYMS

ABBREVIATION	MEANING
µSv	Micro-sievert
ALARA	As Low As Reasonably Achievable
BFS	Blast Furnace Slag
BH	Borehole
BN	Bentonite
CAC	Calcium Aluminates Cements
CBI	The Swedish Cement and Concrete Research Institute
BSK 3	German thin walled fuel rod canister (Brennstabkokille 3)
BWR	Boiling Water Reactor
C	Waste Canister Containing High Level Vitrified Waste
CA	Calcium Silicate Cement
CU	Spent Fuel Canister (ANDRA)
CU1	SF Waste Canister Containing 4 Spent Fuel Rods (ANDRA)
CU2	SF Waste Canister Containing 1 Spent Fuel Rod (ANDRA)
DADCS	Data Acquisition Display and Control system
Dn.n	Module 4 Deliverable n.n
EB	Engineered Barrier
EBS	Engineered Barrier System
EC	European Commission
EDZ	Excavation Disturbed Zone
EIA	Environmental Impact Assessment
ESDRED	Engineering Studies and Demonstrations of Repository Designs
FA	Fly Ash
GPa	Gigapascal
GNB	Gesellschaft für Nuklearbehälter mbH now part of GNS – Company for Nuclear Service Ltd.
HLW	High Level Waste
HRL	Hard Rock Laboratory
k	Hydraulic Conductivity, $m \cdot s^{-1}$
ICRP	International Commission of Radiation Protection
ID	Inside Diameter
ILW	Intermediate Level Waste (synonym for MLW)
IPC	Integrated Project Coordinator
KBS-3H	SKB/POSIVA Horizontal Disposal Concept (ESDRED Reference)
KTH	Royal Institute of Technology in Stockholm, Sweden
lp	Long plug
KBS-3V	SKB/POSIVA Vertical Disposal Concept (National Reference)
LILW	Low and Intermediate Level Waste
LL	Long Lived
LT	Long Term
LWR	German equivalent of PWR or Pressurized Water Reactor
MLW	Medium Level Waste
Mod4	Module 4
MPa	Megapascal
mSv	Milli-sievert

ABBREVIATION	MEANING
N/A	Not Applicable
NPP	Nuclear Power Plant
O/N	ONDRAF/NIRAS
OD	Outside Diameter
OPC	Ordinary Portland Cement
PU	Public (related to document dissemination level)
PA	Performance Assessment
pH	Unit of measure for acidity and alkalinity of a material
RH	Relative Humidity
Pkg	Package
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RB	Rock Bolt
Rc	Resistance to compression
RFP	Request for Proposal
SA	Set Accelerator
SCA	Sprayed Concrete Association
SiF	Silica Fume
SF	Spent Nuclear Fuel
SL	Short Lived
SP	Superplasticizer
Sv	Sievert
TBM	Tunnel Boring Machine
U/G	Underground
UCS	Unconfined Compressive Strength
URL	Underground Research Laboratory
VHLW	Vitrified High Level Waste
WP	Work Package
w/c	Water / cement ratio

ANNEX 5: COMMON GLOSSARY

WORD	Per IAEA	DEFINITION
ALARA	yes	An optimisation process for determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, “as low as reasonably achievable, economic and social factors being taken into account”.
Backfill	yes	The material used to refill excavated portions of a repository (drifts, disposal rooms or boreholes) during and after waste has been emplaced
Barrier	yes	A physical obstruction that prevents or delays the movement of radionuclides or other material between components of a system, for example a waste repository. In general a barrier can be an engineered barrier (see EBS below) or a natural or geological barrier.
Behind		away from the dead end of a disposal cell/drift
Bentonite	yes	A soft light coloured clay formed by chemical alteration of volcanic ash. It is composed essentially of montmorillonite and related minerals of the smectite group. Bentonite is used as backfill and buffer material in repositories.
Buffer	yes	Any substance placed around a waste package in a repository to serve as an additional barrier to: stabilize the surrounding environment; restrict the access of groundwater to the waste package; and reduce by sorption the rate of eventual radionuclide migration from the waste
Canister		See *waste container*
Cask	yes	A vessel for the transport and/or storage of spent fuel and other radioactive materials. The cask serves several functions. It provides chemical, mechanical, thermal and radiological protection, and dissipates decay heat during handling, transport and storage.
Clay		Within ESDRED this refers to indurated clay in the form of claystones and argillites. Clays differ greatly mineralogically and chemically but ordinarily their base is hydrous aluminium silicate. NB: “Swelling clays” refers to specific types of clays used in EBS (see “Bentonite”) and in seals.
Conditioning	yes	Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a waste form, enclosure of the waste in canisters, and, if necessary, providing an overpack.

WORD	Per IAEA	DEFINITION
Criticality	Per US Nuclear Regulatory Commission	A term used in reactor physics to describe the state when the number of neutrons released by fission is exactly balanced by the neutrons being absorbed (by the fuel and poisons) and escaping the reactor core. A reactor is said to be "critical" when it achieves a self-sustaining nuclear chain reaction, as when the reactor is operating. In waste disposal designs the objective is to keep any fissile material in a sub-critical state so that any heat generated is due to natural decay only.
Decline		An excavation, in rock, for providing access from surface to the underground. Also called a ramp or access ramp. Essentially an inclined tunnel.
Demonstrator		A custom designed prototype piece of equipment built to prove a design concept and to show that it works; hence used to demonstrate.
Disposal	yes	The emplacement of waste in an appropriate facility without the intention of retrieval i.e. permanently.
Disposal Cell		Typically a short tunnel/drift/borehole excavated in an underground repository for the purpose of disposing packages of radioactive waste.
Disposal Drift		Typically a long tunnel/drift excavated in an underground repository for the purpose of disposing packages of radioactive waste
Disposal Package		The final Waste Package which is placed into a repository without further conditioning i.e. the Super-Container, the Primary Package with Overpack or the Primary Package without Overpack.
Drift		A horizontal or nearly horizontal mined passageway
EBS	yes	Engineered barrier system; the designed or engineered components of a repository including waste packages and other engineered barriers. See also definition of barrier above.
EDZ		Excavation damage zone; used to describe the area surrounding a rock excavation which has been altered from its initial state usually by the formation of fractures or micro fissures.
ESDRED Concept		This is a variation of the reference National Concept which is used within the ESDRED Project. Example: Sweden's national concept is "Vertical" however SKB's concept within ESDRED is horizontal
Front, in front of		towards the dead end of a disposal cell/drift
Functional Req'mts		Within ESDRED, similar to flexible design criteria or flexible input data; generally refers to criteria or elements that are open to discussion and/or negotiation

WORD	Per IAEA	DEFINITION
Functional Requirements		Generally refers to expected functions and associated levels of performance that must be met by one or several design elements. Within ESDRED the term was used loosely to define design criteria that was somewhat flexible at the outset and needed to be fixed.
Gate		A type of radiation protection door installed on a cask as well as on the head of a disposal cell.
Hoist		A machine, driven by an electric motor, used to raise or lower a conveyance in a shaft.
HRL		Like a URL (see below) but located in hard crystalline rock.
Implementer		The private corporation or public body responsible for constructing and operating a repository.
Input Data (DBE preference)		Within ESDRED, similar to fixed design criteria; generally refers to criteria or elements that are unavoidable and not open to discussion and/or negotiation
Input Data		Within ESDRED the term was used loosely to define design criteria and other data which was well fixed from the beginning.
Long Term (DBE preference)		Generally intended to mean extending in time beyond the final closure of a repository
Long Term		Generally intended to mean extending in time beyond the final closure of a repository and covering the time period where safety needs to be demonstrated.
Matrix		A non-radioactive material used to immobilize waste. Examples of matrices are bitumen, cement, various polymers and glass
Matrix diffusion		Diffusion of solutes from a water-bearing fracture to pores and microfractures of the adjacent rock matrix and vice versa
Overpack	yes	A secondary (or additional) outer container for one or more waste packages, used for handling, transport, storage or disposal.
Plug		Sometimes used interchangeably with SEAL but not within ESDRED where it refers to a concrete mass that serves as a backstop or abutment to resist the pressures eventually exerted on a seal by the swelling buffers.
Primary Package (DBE preference)		A package of radioactive material as delivered by the producer; before conditioning, for disposal
Primary Package		A package of radioactive material as delivered by the producer to the repository; prior to further conditioning before disposal
Ramp		See decline.
Repository		A nuclear facility where waste is emplaced for disposal
Repository system		The combination of the repository and the host rock

WORD	Per IAEA	DEFINITION
Retrievability		The ability to remove radioactive waste from the underground location at which the waste has been previously emplaced for disposal.
Retrievability (NRG) (DBE preference)		The ability provided by the repository system, to retrieve waste packages for whatever reason retrieval might be wanted for.
Reversibility		Implies a step wise disposal process and in particular refers to the ability of a repository system, for whatever reason, to reverse the steps that have been executed so far in its development.
Safety Case	yes	An integrated collection of arguments and evidence to demonstrate the safety of a facility. This will normally also include a safety assessment.
Salt		One of the 3 main host rocks being considered world wide for the disposal of highly active waste materials. The rock form of common salt.
Seal	yes	Engineered barriers placed in passages within and leading to a repository to isolate the waste and to prevent seepage leakage of water into or radionuclide migration from the repository area. Sealing is performed as part of repository closure.
Shaft		A vertical access way, excavated in rock, used to connect the surface with one or more horizons underground. Typically outfitted with one or more hoist and one or more conveyances unless used exclusively for ventilation in which case it may be left bald.
Shielding	yes	A material interposed between a source of radiation and persons, or equipment or other objects, in order to absorb radiation and thereby reduce radiation exposure.
Shotcrete		Mortar or concrete pneumatically projected onto a surface at high velocity.
Spent Fuel	yes	Nuclear fuel removed from a reactor following irradiation, which is no longer usable in its present form because of depletion of fissile material & build up of poison or radiation damage.
Storage	yes	The holding of spent fuel of radioactive waste in a facility that provides for its containment, with the intention of retrieval. Storage is by definition an interim measure.
Super-Container		Generally seen as a disposal package that, unlike other disposal packages also incorporates bentonitic or cementatious buffer material.
Transmutation	yes	The conversion of one element into another. Transmutation is under study as a means of converting longer lived radionuclides into shorter lived or stable radionuclides.
Transuranic Waste		Alpha bearing waste that consists of material contaminated with elements that have atomic numbers greater than that of uranium (92), the heaviest natural element.

WORD	Per IAEA	DEFINITION
URL	yes	Underground Research Laboratory constructed for the purpose of conducting in situ testing. The objective is to conduct tests in a geological environment that is essentially equivalent to the environment of a potential repository.
Waste		Material in gaseous, liquid or solid form for which no further use is foreseen
Waste Container (DBE preference)	yes	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, the "canister" into which molten HLW glass would be poured.
Waste Container	yes	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, molten HLW glass would be poured into a specially designed container (canister) where it would cool and solidify. NOTE: One or more waste packages can be put inside an overpack to become a Disposal Package.
Waste form		Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid product) prior to packaging. The waste form is a component of the waste package
Waste Package	yes	The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and Liners), prepared in accordance with the requirements for handling, transport, storage and/or disposal.
Wireless Monitoring		System for monitoring phenomonology in front of a seal or plug without installing cables or wires through any of the barriers intended to isolate one or more disposal packages
Wireless Monitoring (DBE preference)		Monitoring in which the transmission of the signal does not rely on an electrical wire or optical fibre connection. For example this allows for monitoring the phenomenology in front of a seal or plug without installing cables or wires through any of the barriers intended to isolate one or more disposal packages.