CHAPTER 6

SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 SUMMARY AND CONCLUSIONS

Within the "Backfill and Plug Test Project" a material, which might be used as a sealing material in an engineered barrier for nuclear waste, was experimentally investigated. Thus, the objective of this thesis was to determine if this soil, obtained by mixing up two different soils, might be a good sealing material for the accessing galleries in a future barrier. There are three important requirements for such materials: *low hydraulic conductivity* and *diffusion*, *high enough swelling capacity* and *low cost*.

The mixture contains 30% of MX-80 sodium bentonite and 70% of crushed granite rock with a maximum grain size of 20 mm. This mixture was chosen after an initial experimental campaign performed by Clay Technology AB with different sodium bentonite contents (10, 20 and 30%). From the results of these tests, 30% of sodium bentonite was considered as a candidate for this purpose by assuring low permeability and required swelling capacity. Moreover, an important part of granite produced during the excavation of a future vault could be reused and recycled. Therefore, the three main requirements for this material can be fulfilled.

The study of this mixture (30/70 by weight) was focused on its hydraulic conductivity. As the compacted backfill can be in contact with saline environment, special attention was paid to the influence of salt water on backfill hydro-mechanical behaviour. Hydraulic conductivity can significantly change when pore fluid chemistry is altered in active soils. The bentonite content of this mixture is large enough if compared, for instance, with natural clayey soils mainly made up by kaolinites or illites. Therefore, backfill hydro-mechanical behaviour may be affected by changes in chemistry of pore fluid. It must be pointed out that studying and investigating the hydro-chemo-mechanical behaviour of this mixture is extremely complicated due to the big size of the granite particles and the high enough content of bentonite which makes very slow any hydraulic-diffusive test performed in such material.

Influence of pore fluid chemistry on hydro-mechanical behaviour was investigated by means of oedometer tests in Rowe cell, water uptake tests, compaction tests and determination of water potential in the soil structure (retention curve). Backfill hydraulic conductivity showed to be sensitive to changes in salinity of water used to saturate the specimens, however, backfill compressibility was not dependent on water salinity. Estimated backfill hydraulic conductivity from the oedometer tests showed variations larger than six times for specimens compacted at a dry specific weight of 16.7 kN/m^3 comparing the results of specimens saturated with distilled water and specimens saturated with salt water, and larger than one order of magnitude for specimens compacted at a dry specific weight of 13.7 kN/m^3. Backfill hydraulic conductivity ranged from $2\cdot10^{-12}$ m/s to $4.5\cdot10^{-12}$ m/s at a void ratio of 0.58 (dry specific weight of 16.7 kN/m^3) when specimens were saturated with distilled water. Backfill hydraulic conductivity ranged from $3\cdot10^{-11}$ m/s to $7\cdot10^{-11}$ m/s at the same void ratio when salinity of water used to saturate the specimens was 16 g/L.

Swelling pressure of the specimens compacted at the higher dry specific weight (16.6 kN/m^3) was not significantly sensitive to hydration with water containing salts in the investigated range of salt concentrations. However, those specimens compacted at a lower dry specific weight (13.7 kN/m^3) showed small swelling pressure (23 kPa) when hydrated with distilled water and no swelling pressure was measured in those specimens hydrated with water containing any salt concentration. Measured backfill swelling pressure at the largest dry specific weight was higher than 186 kPa for three different concentrations of salts in water used to saturate the samples. As backfill presented no swelling capacity at the lowest dry specific weight, it would be important to place bentonite blocks in those areas where compaction problems can appear in an accessing gallery (roof and ground). These bentonite blocks would assure the swelling capacity of the barrier.

If backfill is hydrated with salt water and compacted at simple energy, the maximum dry specific weight is higher than dry specific weight obtained when backfill is hydrated with distilled water. Water content at the maximum dry specific weight when backfill is permeated with salt water is smaller than water content obtained when backfill is hydrated with distilled water. However, at double energy, the chemical influence on compaction results is not very important. At this level of compaction, similar compaction curves were determined when backfill was hydrated with salt water or distilled water. Therefore, compaction response depended on chemical composition of pore water.

Backfill retention properties were studied by means of transistor psychrometer, filter paper technique and vapour transfer technique. The results showed the enormous difficulties to study the retention properties of this soil due to the big size of the granite particles. Measured total suction of backfill at 11% of water content (water content at which backfill was compacted in situ) is around 3 MPa. At this low range of total suction, osmotic suction plays an important role as a component of total suction in the project.

The osmotic component of total suction is usually neglected and assumed constant, which is not correct in wetting or drying paths in clayey soils. From vapour transfer tests in bentonite-sand mixtures (10, 30 and 70% of bentonite content) hydrated with distilled water and salt water (16 g/L) in drying conditions was clear that osmotic suction was not constant and the concept should be reviewed. Therefore, backfill osmotic suction was inferred from a mixture of a 30/70 bentonite-sand mixture. After the granite substitution by sand, osmotic suction was determined to be 1.7 MPa as a maximum value. The role of osmotic suction as a driving force in coupled flow transport is not clear yet and further experiments are necessary to clarify its importance within the framework of the project.

Some aqueous extracts and chemical analyses of water collected during the saturation phase of the oedometer specimens were carried out. From the chemical analyses it was concluded that there are three main reactions controlling the geochemical behaviour in the backfill: the ion exchange between sodium and calcium (because water injected in the backfill contained calcium chloride), gypsum dissolution and calcite dissolution. Therefore, it was confirmed that sodium bentonite is transforming into a calcium bentonite. The dissolution of gypsum and calcite and the ion exchange (among others) are responsible of the change of hydraulic behaviour of the clayey fraction of the mixture. Chloride ion transport showed to be nearly conservative as expected. No experimental study of backfill diffusion was carried out. However, it is important to study the diffusion of low permeability media, because diffusion can be the main mechanism of transporting solutes and radionuclides in low permeability media. The information available indicates that diffusion of Na^+ and Ca^{2+} in the backfill may be less than 10^{-9} m^2/s.

For these reasons, it is believed that this material is suitable to be used as sealing material in a future repository, however, further investigations, detailed in the next section, are still necessary to improve the current knowledge of the backfill behaviour.

A new minipiezometer, called dynamic pore pressure system (DPPS), was developed in order to perform pulse tests and constant head tests in compacted clayey soils. Thirteen DPPS were installed in section A4 at the ZEDEX gallery at the Äspö Hard Rock Laboratory. By performing such tests, backfill local hydraulic conductivity can be determined in situ. With this new mini-piezometer a map of local hydraulic conductivity and soil compressibility can be estimated. This information will be very important when analysing the global flow pulse tests to be performed throughout 2003 and 2004 in the ZEDEX gallery. In this thesis, development, calibration and mathematical interpretation of the results were carried out. That allowed the understanding of the pulse test and the development of the necessary tools to analyse them. The appropriate tools to carry out and analyse the pulse tests in situ were also developed.

Darcy's law was validated when constant head tests were performed at different hydraulic gradients (4 – 100) in the cylindrical cell designed to carry out the calibration of the mini-piezometer. The average backfill hydraulic conductivity was $6.5\cdot10^{-12}$ m/s when its dry specific weight was 15.9 kN/m^3 and the specimen had been saturated with distilled water. Estimated and calculated values of backfill permeability are considered small enough to guarantee the effectiveness of the barrier in reducing the flow of water, chemical species and radionuclides, even when salinity of water increases in the range investigated.

Pulse tests performed in laboratory provided with good results when hydraulic conductivity was estimated by means of finite element method. Four pulse tests were carried out in laboratory and the backfill hydraulic conductivity estimated from these tests was $8\cdot10^{-12}$ m/s at a dry specific weight of 15.9 kN/m^3. The estimated value is in agreement with hydraulic permeability estimated from the six constant head tests performed in the same specimen at different hydraulic gradients.

Influence of studying the pore water pressure dissipation by means of Biot's and Terzaghi's approach was investigated. From the calculations by using Biot's approach, it was clear that total mean stress changed when water was suddenly injected in the porous medium. Nonetheless, the calculated mean stress changes were not significant (8 kPa when water pressure increased up to 206 kPa). To overcome the variation of total stresses, it would be convenient to analyse the last part of a pulse test performed in situ in order to estimate the hydraulic conductivity and the soil compressibility (beyond t_{50}).

If the medium is big enough (at the field case if the minipiezometer is far away from the rock), Gibson's model can be easily used to estimate the hydraulic conductivity. Constant head tests can be performed in section A4 and analysed with the analytical solution provided by Gibson. If piezometers are close to the host rock (where boundary conditions can be more complicated) then, CODE_BRIGHT can be used to analyse the pulse tests performed in such piezometers. If accurate results estimating hydraulic conductivity and soil compressibility from slug or pulse tests are required, a simulation with a hydro-mechanical code via finite element method is, probably, the best option to minimise the errors introduced by the analytical or semi-analytical models available in the literature. In addition, the measurement of the necessary volume of water to increase the water pressure within the mini-piezometer is very important to correctly estimate the hydraulic conductivity.

Eighteen pulse tests were performed in different mini-piezometers placed at section A4 in the ZEDEX gallery. Some of them were analysed by using the finite element code and the Gibson's model. After the numerical analysis, a map of backfill local hydraulic conductivity and compressibility was established. Variations up to two orders of magnitude of hydraulic conductivity were estimated after those tests in situ. This large variation is mainly due to the variation of dry specific weight after the compaction of the backfill. It was confirmed that backfill compacted close to the walls, roof and ground of the gallery is more pervious than backfill compacted close to the centre of the section. The layout designed and built to carry out pulse tests in situ proved to be sturdy and reliable when performing those tests.

Finally, an analysis of flow of water and solutes in the ZEDEX gallery was performed by solving the hydro-chemical problem in a fully coupled way when intrinsic permeability was updated by changes in concentration of salts in backfill pore fluid. Moreover, the ion exchange reaction between sodium and calcium was considered. This geochemical model was very simple, and a more complicated backfill geochemical model was beyond the scope of this thesis. By doing so, the saturation process of the ZEDEX gallery was simulated and successfully reproduced by a THMC finite element code. Osmotic suction was computed by using the concentrations of ions in the pore fluid assuming the validity of Van't Hoff equation. Constant osmotic suction is not a valid hypothesis in this problem for different reasons, low range of total suction (below 3.5 MPa) or liquid mass transfer of salt water into the soil structure. Therefore, total suction was computed and compared with the measurements obtained by psychrometers placed at the ZEDEX gallery. Moreover, global flow tests, after the backfill saturation phase, were numerically simulated in order to check the influence of a non-homogeneous distribution of intrinsic permeability in the ZEDEX gallery. The influence of the non-homogeneous distribution of intrinsic permeability due to the injection of salt water on the saturation process and on global saturated flow tests was not very important in those computations performed.

Some effects can alter the evolution of the saturation process and global flow tests in the ZEDEX gallery. These factors are: 3D effects, backfill anysotropic behaviour, host rock should be studied as jointed medium, osmotic flow of water or variability of backfill dry specific weight after compaction. Some are more important than others, but all of them are difficult to study at this stage of the project and it would be really interesting to consider a plan to dismantle the field test in order to investigate the possible existence of these factors.

6.2 FUTURE RESEARCH WORK

After this thesis and the experimental work performed in this backfill some important uncertainties remain mainly related to pore fluid chemistry and their interaction with the macroscopic behaviour of active soils. Future work directly related to the Project it is also detailed.

Backfill hydraulic behaviour was always assumed isotropic. Backfill anisotropic hydraulic behaviour might introduce non-desirable preferential flow paths, decreasing the effectiveness of the barrier. Capacity of a compacted active soil to swell and to erase the previous orientation introduced by the compaction effort must be investigated in order to assure the low hydraulic conductivity and diffusivity of the backfill material. However, for backfill high dry specific weights (> 17 kN/m^3), swelling seems to erase the anisotropic effects induced by compaction.

Hydraulic fracture could occur if water pressure is suddenly increased in the backfill. There are not many works dealing with this subject in the literature. Because of its influence on assuring the stability of the barrier, it is important to study the maximum hydraulic gradient that does not produce cracking of backfill at different stress states.

Because of the requirements for a candidate material for sealing of a vault in a future repository for nuclear waste, more interest should be focused on diffusivity of ions and gas, and influence of water chemistry of the surrounding environment. Backfill hydraulic conductivity, as well as swelling pressure and compressibility, have been characterised taking into account the effect of salinity of incoming water from the surrounding environment. Backfill macroscopic behaviour (mainly hydraulic conductivity) is importantly affected by alterations of pore fluid chemistry. However, it is important to determine and establish a complete geochemical model able to account for the most important chemical reactions and the geochemical initial conditions since this knowledge is necessary if backfill long-term behaviour and stability is investigated. In this context, determination of diffusion of gas and ions is also important when solving the reactive transport problem. Owing to the low backfill hydraulic conductivity, the main mechanism of transport may be diffusion. Therefore, backfill non-advective flow of ions should be characterised.

Osmotic suction (or chemical potential) is usually disregarded or assumed constant. This is not correct as it was shown throughout this thesis. Role of osmotic suction as a driving force in moving water and ions (osmotic flow) or its mechanical influence on soil structure in wetting and drying cycles (suction as a valid stress state variable), has to be characterised. Further experimental characterisation of osmotic suction is necessary in soils where drying paths and hydration with mass liquid transfer containing chemical species occur. Moreover, influence of pore fluid chemistry on micro and macrostructure of active soils introduces a coupling between the pore fluid chemistry and matric suction because of the changes in soil structure.

Regarding to the Backfill and Plug Test Project, there are three remaining steps: pulse tests in situ and their analysis, saturated global flow tests and their interpretation and, finally, it would be very important a dismantling process of the Project. The study of the flow tests (local and global) will be the most important part of the Project. A complete map of local permeability will be obtained from the pulse tests carried out in section A4 and, therefore, indirect information of backfill compaction and its effectiveness as a barrier will be provided. Global backfill hydraulic conductivity will be estimated from the global flow tests (from mat to mat). Backfill interaction with host rock will be studied by means of these flow tests. Lastly, it is strongly recommended, depending on the resources available, to plan a careful dismantlement of the entire layout of the Project. Recalibration of still operating sensors, measurement of backfill water content, aqueous extracts and chemical analysis of backfill pore fluid can provide useful information in the characterisation of the backfill geochemical model and backfill undisturbed samples can be obtained and hydraulic conductivity and density may be eventually determined in laboratory.