

CHAPTER 1

INTRODUCTION

1.1 Background of the Research Project

Although coupled heat and moisture flows and their consequences on soil structure are involved in a variety of practical problems (high-voltage buried power cables, depth of frost penetration, extraction of energy from pressurised geothermal reservoirs, heating requirements for underground structures), thermal and hydraulic aspects are recently receiving more attention in the conceptual design of repositories for radioactive waste disposal in deep geological media. Unsaturated expansive clay either compacted *in situ* or as dense prefabricated material is often the material of choice for constructing barriers surrounding heat-emitting HLW (high level radioactive) waste canisters in repositories located in natural clays or rocks (marl and granite). Very active clays (bentonite) or compacted mixtures of less active clay powder and artificially aggregated clay pellets have been suggested as suitable natural or artificially prepared materials for these engineered barriers. Clays have been proposed due to the following favouring factors (Pusch, 1982; Chapman, 1985): very low hydraulic conductivity, a marked capacity to adsorb and retain radionuclides, a propensity for plastic deformation and an associated self-healing quality. Once installed in contact with the usually saturated host material, these initially unsaturated barriers experience a transient wetting phase governed by the rate of absorption of natural water with its own chemical characteristics and a transient temperature regime controlled by the decaying heat power input induced by the canister. This way, part of the barrier in contact with the hot canister will initially dry and shrink, whereas the outer boundary of the compacted barrier will hydrate and expand (or collapse). Stresses will be controlled by the relatively low initial stress state of the compacted buffer, the development of shrinkage, swelling and collapsible strains and the stiffness of the backfill and surrounding host material. In summary, barrier behaviour is highly complex involving a number of inter-related processes that take place during first heating and main hydration of the initially unsaturated clay barrier. This way, numerical analysis are being used and are receiving increasing attention to bridge the gap between theoretical and phenomenological understanding of the different processes and the evaluation of the performance of the barrier (Navarro, 1997; Alonso *et al.*, 1998a; Gens *et al.*, 1998; Thomas *et al.*, 1998). In addition, reliable experimental evidence, both at *in situ* conditions and at small scale, is needed to validate thermo-hydro-mechanical constitutive models, as well as to calibrate material parameters used in numerical analysis. In the *in situ* context, SCK-CEN (Belgian Nuclear Research Centre) performed a full scale hydration test of an engineered barrier made of artificially aggregated Boom clay in the underground laboratory of HADES (Mol, Belgium) excavated in the Boom clay formation at 220 m depth (Volckaert *et al.*, 1996b). French organisation ANDRA developed the CACTUS project (Trentesaux, 1997) in the same underground facility for the study of Boom clay massif in the near field of a heater.

There are a number of small scale laboratory results concerning thermal effects on saturated soils and recent works on this area are indicated in section 3.1.1. In contrast, experimental information concerning unsaturated soils is very limited: Saix (1991), Recordon (1993), Romero *et al.* (1998a), Romero *et al.* (1998c) and Wiebe *et al.* (1998). In addition, thermo-hydro-mechanical aspects such as wetting-drying paths at different temperatures and drained heating-cooling cycles and their consequences on volume change behaviour (shrinkage, swelling and collapse, thermal dilatation and contraction) and water content changes in unsaturated clays, both normally and overconsolidated, have not been systematically studied previously. In view of the increased use of clay in high-temperature environments and to enrich the existing body of knowledge in this area, a systematic small scale research programme involving suction and temperature controlled experiments has been designed and carried out to investigate volume change behaviour.

1.2 Scope and Objectives of the Research Programme

This thesis presents oedometer and isotropic test results of an extensive and well-controlled laboratory testing programme carried out on artificially prepared Boom clay powder obtained from HADES underground facility. The main aim of this study is to analyse the effects of temperature and hydration or drying stages on volume change behaviour, water permeability and water retention characteristics, under a variety of matric suction, net stress and temperature paths carried out on two unsaturated clay packings, which exhibit extremes of clay behaviour and cover a wide overconsolidation range from around 170 down to 1. The first packing is a high-porosity with meta-stable collapsible structure upon main wetting at a dry unit weight of 13.7 kN/m^3 , which also develops thermal contraction upon main drained heating. The second packing is a low-porosity fabric with swelling tendency upon main wetting and drained heating at a dry unit weight of 16.7 kN/m^3 . Some test results are presented for comparison on a third type of artificially prepared packing formed of 2-mm high-density pellets (dry density of around 2 Mg/m^3) compacted to an overall dry unit weight of 13.7 kN/m^3 . In this study, maximum temperature is limited to 80°C for no appreciable phase and chemical change to occur, which is somewhat lower than the value of 100°C prescribed for unsaturated backfill in many repositories reference designs.

Prior to this research there was some speculation of the volume change behaviour that would be expected on a heavily overconsolidated sample subjected to a drained heating path under controlled matric suction. To give the reader some insight of the problem, to the author's knowledge only the swell under load tests reported by Sherif *et al.* (1982) performed on saturated Wyoming montmorillonite at different temperatures showed the possibility of expecting a clear expansive behaviour, while other test results mainly related to slightly overconsolidated and normally consolidated states showed somewhat expansion (Baldi *et al.*, 1988; Towhata *et al.*, 1993) and a more consistent thermal contraction upon drained heating.

It is clear that temperature affects soil behaviour in different ways, inducing both microscopic and macroscopic effects, and that the relative influence varies with soil type and packing aggregation. For this reason, another objective of this research is focused on the characterisation of the clay powder and the artificially prepared structure being tested, both at microscopic and macroscopic levels. Chapter 2 is devoted to this aspect as further indicated in section 1.3. On the other hand, the success of this experimental investigation is associated with the use of suitable testing equipment, to the adoption of good instrumentation and calibration techniques to observe thermal aspects, which are usually smaller than stress and suction induced effects, and to the application of adequate stress paths. Therefore, another objective of this thesis is the development of special equipment, providing a reliable phenomenological description of the stress-strain behaviour of the soil. For this purpose, new oedometer and isotropic equipment were updated, designed, constructed and calibrated to perform stress, suction and temperature controlled tests, which formed a significant part of the research programme and are described in Chapters 3 and 4.

Soils present non-linear and irreversible stress-strain behaviour, which in addition of depending on temperature, suction and stress paths also depend on time and pore-fluid chemistry. Nevertheless, the scope of this thesis is limited to thermo-hydro-mechanical effects, where a constant testing period has been considered for the different stress, suction and temperature paths for minimising secondary effects (creep under constant load and stress relaxation in swelling pressure tests) that are of certain consideration at higher temperatures. In addition, effects associated with pore-fluid chemical changes are not considered, since a reference demineralised water reservoir has been used throughout the different tests. However, dissolution / precipitation phenomena and redistribution of soluble salts within the soil mass at higher temperatures may certainly have some influence on soil microstructural organisation and behaviour, as suggested by Cuevas *et al.* (1998).

At the beginning of the investigation the artificially prepared Boom clay, both in powder and pellet structures, was studied to be the potential backfill barrier, being used in the BACCHUS 2 project (Volckaert *et al.*, 1996b). However, its use as an engineered barrier has been limited due to its reduced swelling potential compared to other more active powders. Nevertheless, it is still the potential host formation in the Belgian outline for HLW disposal (RESEAL project, 1997). In the same way, the study of the characteristics and phenomena observed in Boom clay at lower suctions in wetting and drying processes is similar to the phenomena associated with more active clays at higher suctions, where the conventional air overpressure technique cannot be used and where the coupled measurements between the mechanical and hydraulic characteristics are more difficult to perform. This way, the research carried out on this clay with a smectite content of around 10% to 20% (dry mass basis) allows to know patterns of behaviour in a reasonable testing period that can be qualitatively extrapolated to more active clays with higher smectite content. In addition, Boom clay presents a mineralogy with similar percentages of other clayey minerals (20% -30% kaolinite, 20% -30% illite), being also representative of other less active clays.

1.3 Layout of the Thesis and Overview of the Experimental Programme

The thesis is divided in eight chapters, which are self-contained. In this regard, each chapter includes a state of the art review related to the main topics that are further presented. Chapter 2 describes the soil powder and the different artificially prepared packings used in the investigation. Chapter 3 presents the different testing equipment and in Chapter 4, testing techniques and sample preparation procedures are presented and discussed. In Chapters 5, 6 and 7 the main data of the testing programme is presented, where efforts are made to discuss the observed behaviour in the context of different constitutive relations. These chapters present oedometer and isotropic results and a phenomenological interpretation of temperature and suction effects on clay compressibility, reversible and irreversible features of volume and water content change behaviour under wetting-drying, heating-cooling and loading-unloading cycles. Finally, Chapter 8 contains the main conclusions of the work carried out, as well as future research proposals. An appendix containing low-vacuum ESEM photomicrographs and their processed images in a low-pressure wetting path complements the information of aggregate swelling at microscale.

The experimental programme comprises the following tests: general tests for powder and packing analysis; thermo-hydraulic tests presented in Chapter 5; and thermo-hydro-mechanical results presented in Chapter 6 (oedometer tests) and Chapter 7 (isotropic tests). Certainly, some tests do not fundamentally contribute to the development of the main objective of this thesis, nevertheless they complement the overall information of the tested material, which can be incorporated in future research works. Main wetting paths have been followed starting from a dry side compacted state with a continuous air phase, to study the effects that this aggregated structure induces on the subsequent behaviour. In addition, the departure from dry side allows to study a wide range of degree saturation changes, condition that is difficult to achieve when starting from a nearly saturated state, since its further de-saturation with air overpressure is evidently more difficult.

The general tests involved the following testing programme:

- Particle size analysis, X-ray diffraction, specific surface and consistency limits of clay powder;
- Osmotic suction of pore-water obtained by squeezing technique;
- High-vacuum SEM observations ($\times 5000$) of both packings dehydrated by freeze-drying;
- Low-vacuum ESEM observations ($\times 2500$) of aggregate swelling upon controlled wetting;
- Mercury intrusion porosimetry study of both dehydrated packings;
- Static compaction tests at different compaction energies and different temperatures (22°C and 80°C);
- Net vertical and horizontal stress evolution during one-dimensional compression tests at constant water content ($w = 15\%$) for both packings;
- Resonant column tests of both fabrics at constant water content ($w = 15\%$) and different confining pressures.

The thermo-hydraulic testing programme involved the following tests:

- Main wetting retention curves obtained from vapour equilibrium tests at different initial dry unit weights (14.4 kN/m^3 to 19.2 kN/m^3) and at different temperatures (22°C , 40°C , 60°C and 80°C);
- Main wetting, main drying and scanning wetting retention curves for both packings at different temperatures (22°C and 80°C) obtained from air overpressure technique (0.45 MPa to 0.01 MPa);
- Main wetting and main drying retention curves for both packings at different temperatures (22°C and 80°C) obtained from suction controlled swelling / shrinkage pressure tests in oedometer cells;
- Main drying retention curves obtained with transistor and thermocouple psychrometers;
- Saturated water permeability obtained from one-dimensional consolidation steps;
- Water permeability obtained from suction controlled oedometer cells at different temperatures (22°C and 80°C).

Thermo-mechanical testing programme involved the following tests in *conventional oedometer cells*:

- One-dimensional consolidation test of saturated high-density fabric;
- Soaking under constant vertical load tests of different fabrics compacted at hygroscopic humidity;

in *suction and temperature controlled oedometer cells*:

- Isothermal main wetting, main drying and scanning wetting paths under constant applied vertical loads and different temperatures (22°C and 80°C) for both packings and at different height to radius ratios;
- Isothermal loading and unloading paths under constant suction and at different temperatures (22°C and 80°C) for both packings;
- Isothermal suction controlled swelling / shrinkage pressure tests at different temperatures (22°C and 80°C) for both packings;
- Non-isothermal suction controlled tests with temperature cycles ($22^\circ\text{C} \rightarrow 80^\circ\text{C} \rightarrow 22^\circ\text{C} \rightarrow 80^\circ\text{C}$) at constant net vertical stress carried out on the high-density packing;

in *suction controlled lateral stress oedometer cell* at ambient temperature:

- Main wetting, main drying and scanning wetting paths under constant applied vertical loads for both packings;
- Loading and unloading paths under constant suction for both packings;
- Suction controlled swelling / shrinkage pressure tests for both packings;

in *suction controlled mini isotropic cell* at ambient temperature:

- Main wetting, main drying and scanning wetting paths under constant isotropic net mean stress for the high-density fabric;
- Loading and unloading paths under constant suction for the high-density packing;

in *suction and temperature controlled triaxial cell*:

- Main wetting, main drying and scanning wetting paths under constant isotropic net mean stress for both packings;
- Loading and unloading paths under constant suction for the low-density fabric;
- Non-isothermal suction controlled tests with temperature cycles ($22^\circ\text{C} \rightarrow 60^\circ\text{C} \rightarrow 22^\circ\text{C} \rightarrow 60^\circ\text{C} \rightarrow 22^\circ\text{C}$) at constant isotropic net mean stress carried out on the low-density packing (normally consolidated state);
- Non-isothermal suction controlled tests with temperature cycles ($22^\circ\text{C} \rightarrow 50^\circ\text{C} \rightarrow 22^\circ\text{C}$) at constant isotropic net mean stress carried out on the low-density packing (slightly overconsolidated state).