CHAPTER 8

SUMMARY, CONCLUSIONS AND FUTURE RESEARCH WORK

8.1 Summary and Conclusions

As a summary of the characterisation of the material, equipment used, tests performed and results obtained, the following conclusions may be drawn.

8.1.1 Characterisation of the material

Two artificially prepared packings of Boom clay powder with a dominant aggregated fabric, exhibiting extremes of unsaturated clay behaviour (collapsible/expansive upon main wetting and compressive/dilative upon main drained heating) and covering a wide overconsolidation range, have been used throughout the testing programme. Clay powder and artificially prepared packings have been extensively characterised, both at microstructural (X-ray diffraction, osmotic suction measurement, pore water extraction, specific surface, pore size distribution analysis) and macrostructural scale (static compaction tests at different temperatures, swell/collapse under load tests, conventional oedometer tests). Microstructural analysis were focused on MIP intrusion-extrusion results and complemented with SEM photomicrographs, where a pore size region of around 130 nm to 180 nm have been accepted for the limit value separating inter-aggregate (related to constricted porosity) and intra-aggregate (related to free porosity) zones (Fig. 2.21). Intra-aggregate porosity and its associated quasi-immobile water fraction (both diffuse-layer and strongly bonded water) can be indirectly estimated from this pore size region: around 54% of total porosity in the low-porosity fabric and around 28% in the case of the high-porosity packing (Fig. 2.22). Meta-stable phenomena such as collapsible strains upon main wetting and compressive strains upon first drained heating are mainly associated with inter-aggregate porosity reduction, while intra-aggregate porosity is not greatly affected. As confining stress is increased the amount of collapse and drained thermal compression increases up to a certain maximum, decreasing afterwards, due to the impossibility of further rearrangement as a consequence of inter-aggregate porosity reduction (maximum collapse/contraction zone in Fig. 6.40). In addition, factors influencing unsaturated hydraulic states with reference to water content retention curves (hysteresis and storage capacity in Fig. 5.7) and relative water permeability values as a function of degree of saturation (Fig. 5.39, Fig. 5.40 and Fig. 5.43) are mainly associated with this inter-aggregate porosity. This way, observations of the different structural levels and dominating fabrics detected by these experimental techniques allow gaining insight into the understanding of their interrelations from both hydraulic and mechanical viewpoints.

8.1.2 Experimental equipment, programme and procedures

A systematic research programme involving matric suction and temperature controlled experiments has been carried out to investigate the effects of temperature and hydration/drying paths on reversible and irreversible features of volume change behaviour (swelling, collapse and shrinkage, thermal dilatation and contraction), under oedometer and isotropic stress state conditions. Air overpressure technique maintaining a constant air pressure has been used, starting from continuous air phase conditions and conscious of certain limitation of this technique at high degrees of saturation. Maximum temperature has been limited to 80°C for no appreciable phase and chemical change to occur, as well as to limit spurious problems affecting axis translation technique. Two main test types were carried out with respect to thermal aspects: isothermal tests at two different temperatures and non-isothermal paths, where experiments are initially not true drained tests with restricted drainage due to soil permeability and ceramic disc impedance effects, followed by an equalisation phase at constant temperature (Fig. 6.27, Fig. 6.28 and Fig. 7.24). Isothermal paths were focused on wetting and drying cycles at constant net vertical or mean stress and loading-unloading cycles at constant suction.

The work has contributed to the development and design of experimental techniques and equipment that have not previously been carried out and used, and innovative results have been obtained. Mechanical and suction induced strains are usually much larger than thermal strains, and therefore special care has been taken in controlling ambient temperature, as well as adopting strict mechanical and thermal calibration procedures (section 3.2.4) and good pressure and temperature compensated instrumentation techniques (section 3.3.3 and section 3.3.4). In general, quite good repeatability and reproducibility are observed in oedometer tests in terms of volumetric strain and water content evolutions, when comparing different wetting paths carried out at the same temperature and with the same height to radius ratio (Fig. 4.13 to Fig. 4.18). Some scatter is only appreciable, mainly in the hotter specimen and in the first equalisation stage, because of some small variations in the initial conditions associated with the setting up phase. However, these deviations are progressively reduced in successive stages, when more homogeneous conditions have been established.

New oedometer cells were designed to perform stress, suction and temperature controlled paths (Fig. 3.1), and modifications were carried out for isochoric swelling pressure testing. These cells have been the most utilised equipment due to the following advantages: accurate direct volume change determinations and that testing paths follow a K_0 condition similar to the static compaction process. A lateral stress oedometer cell was updated, modified for suction control and adapted for isochoric swelling pressure tests (Fig. 3.6).

A new triaxial cell with a forced convection system has been developed for testing unsaturated soils under temperature- and suction-controlled paths in a wide range of stress conditions, though only isotropic stress states have been applied (Fig. 3.22). The simultaneous application of suction control to both ends of the sample ensures a significant shorter equalisation time. An extensive calibration, resolution and assessment of error study at different temperatures have been followed for the proposed electro-optical laser system for lateral local deformations, which has been adapted to travel the whole sample height. Isochrones of the progressive development of lateral profiles of the specimen have allowed to detect non-uniform features of sample deformation. Examples of local bulging at both ends in the high-density packing and collapsible behaviour affected by end restraint effects, as well as thermal contraction due to temperature increase in the high-porosity fabric, are presented (Fig. 7.12 and Fig. 7.23). Magnitudes of applied temperature corrections on zero and sensitivity shift are such that axial strains with internal LVDTs are determined with somewhat higher precision and lower bias than lateral strains.

The tests revealed important aspects concerning air overpressure technique applied to unsaturated states under a temperature field, mainly related to the maintenance of a relative humidity higher than 98% in the open air chamber at temperatures of 80°C in order to control evaporative fluxes that can have some influence on matric suction application (Fig. 4.44). A numerical simulation has been carried out based on measured properties of the high-porosity packing to analyse evaporative fluxes and suction application during main wetting at different temperatures. Measured evaporative fluxes (Fig. 4.34) are compared to model predictions prescribing a constant relative humidity at the upper soil surface and solving coupled heat and mass transfer equations for the soil profile. This way, it is possible to detect if matric suction equalisation throughout the sample height is achieved. In addition, higher air diffusion rates detected at elevated temperatures (Fig. 3.19) can affect water availability and induce shrinkage on the sample, which can be confused with the same volume change response associated with thermal contraction, due to bulk water evaporation and the loss of continuity with the measuring system. Therefore, it is extremely important to saturate ceramic discs with repeated pressurising processes and to periodically flush and control the accumulated diffused air volume.

Aspects related to experimental procedures of soil suction imposition under a temperature field have been extensively described and analysed, and expressions for vapour equilibrium control with unsaturated NaCl solutions at different temperatures have been proposed (Fig. 4.2).

Spurious effects due to ring friction aspects affecting the development of volumetric strains in both packings (Fig. 4.33), initial condition changes during specimen setting up phases (Fig. 4.23 and Fig. 4.27), periods of equalisation phases in loading-unloading paths (Fig. 4.28 to Fig. 4.32), as well as ageing effects on ceramic discs at high temperatures affecting water permeability and inducing consequences on impeded flow conditions (Fig. 3.15 and Fig. 3.16), have been extensively described and analysed.

8.1.3 Thermo-hydro-mechanical results

Temperature influences soil behaviour in different ways (both macroscopically and microscopically) and usually characterised by non-linear and irreversible effects. Firstly, it changes hydraulic properties of the soil (water permeability as well as water retention seem to be slightly affected), as well as the mechanical properties. For example, the preconsolidation stress, the air-entry value, the suction decrease yield locus, the compressibility coefficients and creep/expansion properties have been observed to depend on temperature. Secondly, it affects the mechanical response of the soil, causing expansion of water in clay pores, inducing expansion of clay particles and dilatancy due to water sorption, and activating rearrangements of clay particles and aggregates. The overall response of clay to these changes depends on the drainage conditions of the clay mass (drained or undrained heating paths), as well as on the stress state of the clay (normally or overconsolidated states). Finally, it alters soil microstructure (thermal breakdown of adsorbed water and thermal stability of minerals).

8.1.3.1 General aspects. Temperature effects on hydraulic properties

The water content associated with the pore size zone defined by mercury porosimetry results also appears as a delimiting point in the retention curve (Fig. 5.7), separating regions of 'intra-aggregate governing suction' (water content is not affected by mechanical effects) and 'inter-aggregate governing suction' (water content is sensitive to mechanical actions). In addition, a water content of around 13% is associated with a region that separates zones of greater water relative permeability in a generalised Darcian sense from others that present smaller values (threshold value $k_w / k_{ws} \leq 0.01$ delimiting mobile and quasi-immobile water in Fig. 5.39 and Fig. 5.40). Intra-aggregate quasi-immobile water estimated from relative permeability results represents 59% of the total volume of water in the low-porosity fabric and accounts for around 38% in the case of the high-porosity packing.

Moisture retention capacity of the clay is influenced by temperature, where for a given water content in the 'intra-aggregate governing suction' zone, the total suction tends to decrease with increasing temperatures (Fig. 5.16). However, temperature influence cannot be interpreted as representing only temperature dependence on contact angle or surface tension, where additional thermal disturbances induced on interlayer water lattice in relatively active clays and electrolytic soil water are expected. Temperature influence on water permeability is more relevant at low suctions corresponding to free water preponderance, whereas below a degree of saturation of 70% no clear effect is detected (Fig. 5.38). Experimental data show temperature dependence at constant void ratio and degree of saturation smaller than could be expected from the thermal change in water viscosity, indicating that thermo-chemical effects altering clay fabric and pore fluid chemistry could be of certain consideration. In addition to the important dependence of water permeability on degree of saturation and temperature, a high void ratio influence has also been observed (Fig. 5.36).

Specific aspects related to clay-water system, soil-water characteristic curves and water permeability evaluation under different temperatures have been extensively described and reviewed. Modified expressions for retention curves and water permeability functions at different temperatures based on a phenomenological experimental evidence, as well as values of the different parameters describing the different aspects (porosity, temperature and degree of saturation dependence), have been proposed and determined for both packings under a variety of conditions.

8.1.3.2 Thermo-hydro-mechanical aspects: oedometer tests

Hydro-mechanical experimental results have been represented in different stress state planes (suction : net stress and suction : intergranular stress in terms of the effective free water saturation) and work conjugate strain variables (volumetric strain and volumetric water content changes).

Suction controlled oedometer tests on heavily overconsolidated clays revealed irreversible expansion upon drained heating due to a rearrangement of the structure of clay skeleton, giving equivalent values in terms of volume and water content changes (thermal induced water sorption) compared to isothermal wetting paths at different temperatures (Fig. 6.29, Fig. 6.30 and Fig. 6.31). The existence of important plastic deformations associated with the first suction reduction is also a relevant feature of heavily overconsolidated clays, specially important at higher temperatures (Fig. 6.12). Non-isothermal data (main heating path in Fig. 6.29) have been presented that suggest some dependence of the suction decrease SD yield locus with temperature and inducing thermal hardening (upward movement in the suction : net stress plane). This way, drained heating at constant stress state generates a plastic volumetric swelling, with the thermal hardening induced by the increase in temperature being compensated for by the mechanical softening. In addition, this plastic swelling of the macrostructure is coupled to an inward movement of the LC yield curve (macrostructural strain softening) and to a downward movement of the suction increase SI yield locus inducing a lower air-entry value of the packing. In contrast, drained cooling at constant stress state is assumed to be an elastic process during which the yield surface moves downward, but further experimental evidence is needed. Reversible drained thermal expansion coefficients have shown to be dependent on stress level (Fig. 6.25) and on temperature (Fig. 7.41).

After main wetting, the drying-wetting path shows again a remarkable plastic shrinkage that also increases at higher temperatures (Fig. 6.12 and Fig. 6.37). Maximum shrinkage and water content changes appear when matric suction is increased over the air-entry value of the packing, which is associated with the suction increase SI yield locus as defined by Alonso *et al*. (1990). At this point, the degree of saturation decreases sharply due to the desaturation of the largest inter-aggregate pores, expelling water as air enters the soil and affecting the macroporosity of the packing, which can cause irreversible volume changes affecting in a poroplastic way soil behaviour. The simultaneous occurrence of plastic compressive strains and plastic volumetric water content changes associated with main drying paths are indicated in Fig. 5.32 and Fig. 6.66. The water content hysteresis in a further scanning wetting path arises therefore from plastic volumetric strains, which affect the topology and storage capacity of the macroporosity network. This way, as a preliminary choice for drying processes following a main inundation stage, it is adequate enough to admit a bounding surface that would be associated with the air-entry value of the packing (inter-aggregate voids with the widest entry routes) and not with the maximum suction ever experienced by the dry-side sample compaction process. It is expected that this maximum suction is not a permanent feature of the soil and is substantially influenced by the main inundation stage. In addition, SI yield locus is assumed to be sensitive to temperature, where a lower air-entry value under surface-tension reasoning is expected at higher temperatures (Fig. 6.17 and Fig. 6.44).

Isothermal loading at constant water content contained at intra-aggregate scale and main wetting results under normally consolidated conditions reflect temperature effects in the previous loading stage, which results in a rearrangement of soil structure to a more densely packed position mainly related to a decrease in the shearing strength of aggregate contacts. Maximum collapse zone is detected in the subsequent wetting stage, where at higher net vertical stresses the collapse is smaller due to the remarkable reduction of inter-aggregate spaces that the sample has experienced in the previous loading, heating and wetting stages (Fig. 6.40).

Isothermal loading-unloading results at constant suction systematically show somewhat higher values of the compressibility parameter in the post- and pre-yield ranges at higher temperatures (Fig. 6.57 and Fig. 6.67). Higher compressibility parameters in the pre- and post-yield ranges are obtained at lower suctions for both temperatures. Results also confirm that post-yield parameters increase with increasing void ratio. Yield points in relation to the loading-collapse LC yield locus of the original packings indicate a dominating strain softening induced on main wetting in the heavily overconsolidated packing (Fig. 6.58), whereas a dominating strain hardening induced on loading, main wetting and drying is detected in the high-porosity fabrics (Fig. 6.68). Constant suction paths at nearly saturated states tend to a unique relationship in virgin states (virgin compression lines in Fig. 6.55 and Fig. 6.65) in terms of specific volume and the equivalent effective stress. However, this unique relationship is transgressed by loading paths evolving under degree of saturation values corresponding to the preponderance of meniscus water (loading path at $s = 0.45$MPa in Fig. 6.65).

Different patterns of comportment are encountered during main suction reduction in the isochoric swelling pressure tests: a dominating swelling for the low-porosity packing, where a higher swelling pressure is detected, and a controlling macrostructural collapse compensated by the reversible expansion of the structure for the high-porosity fabric (Fig. 6.76). In this last case, swelling stress reaches a maximum controlled by the macrostructural loading-collapse LC yield surface and then decreases upon subsequent wetting following this yield locus at constant volume. A relevant feature of the data is the gradual softening of the sample upon wetting, reaching normally consolidated states on arriving to the maximum swelling pressure zone, as well as the progressive erasing of the fabrication anisotropy, reaching nearly isotropic stress state evolutions upon subsequent drying (Fig. 6.72 and Fig. 6.73). Temperature effects on the high-porosity packing are reflected in a somewhat lower value of swelling pressure under saturated conditions (Fig. 6.75) and consistent with thermal softening aspects indicated in section 7.2.3.

Specific features related to stress state variables and their associated work conjugate extensive variables, as well as to aspects related to clay volume changes and stability (stable and meta-stable packings) under stress, suction or temperature changes, have been described and reviewed. Suction and thermal induced changes were discussed within an elastoplastic point of view and parameters characterising their reversible and irreversible features (respect to suction decrease SD, suction increase SI and loading-collapse LC yield loci) were determined. Section 6.2.1.2 refers to suction and mechanical induced reversible features on volume change behaviour, while section 6.2.1.3 focuses on thermal induced reversible aspects.

8.1.3.3 Thermo-hydro-mechanical aspects: isotropic tests

Distortion features upon main wetting under constant net isotropic stress has been observed in both high-density and high-porosity fabrics, due to the anisotropic loading condition imposed to the specimen during static compaction. However, anisotropy decreases progressively upon suction induced plastic volumetric straining in the main wetting path due to the activation of the suction decrease SD or loading-collapse LC yield loci, displaying a constant shear strain evolution in the following drying-wetting cycles and indicating that initial anisotropy has been completely erased (Fig. 7.7 and Fig. 7.15). Expansion/collapsible transition zone detected by the local LVDTs in the first step of the main wetting path performed on the high-porosity packing (Fig. 7.15) is in agreement with loading-collapse LC yield locus of the original packing determined from static compaction and isochoric swelling pressure results under oedometer conditions (Fig. 7.22).

Isothermal loading-unloading paths at constant suction have indicated clear pre- and post-yield zones in terms of specific volume, state variable Gs.w and degree of saturation (Fig. 7.20). The evolution of the degree of saturation exhibits an increasing trend in the post-yield zone, while it is nearly constant in the pre-yield stages. This fact is associated with the higher efficiency of loading effects in deforming soil skeleton than expelling water, in opposite way to what happens during shrinkage, where it is more efficient to remove water by desaturating a pore than to deform soil skeleton (the degree of saturation diminishes, refer to Fig. 5.31). The limit between the pre and post-yield domains determined from incremental work input per unit volume associated with water content changes is in agreement with the equivalent one associated with volumetric strains (Fig. 7.20). The value of the parameter associated with water content changes in the post-yield zone is slightly lower than the post-yield compressibility, presenting the same value under pre-yield conditions (Fig. 7.20). In addition, the parameter associated with water content changes in the post-yield zone increases with increasing porosity (Fig. 6.50 and Fig. 6.59).

The testing program has provided first results of volume change behaviour of unsaturated clays, both in normally and lightly overconsolidated states, subjected to heating-cooling cycles under controlled matric suction and net mean stress (Fig. 7.41). The isotropic rise in axial and radial strains induced by main heating under quasi-undrained conditions mainly due to free water and entrapped air thermal expansion are clearly differentiated from the drained heating stage following thermal equilibrium (Fig. 7.24 to Fig. 7.27). The increase in pore water pressure in this quasi-undrained stage under nearly saturated conditions with no change in boundary confining stress and air pressure has been analysed assuming volumetric compatibility between soil matrix and its constituents and taking into account of both thermal expansion and compressibility coefficients, indicating that no water overpressure is generated. Testing results show that drained temperature increase on an open normally consolidated structure revealed irreversible isotropic contraction with some water outlet due to structure rearrangement of clay skeleton. Early undrained stages in a cooling step result in an isotropic compactive phenomenon, followed by some drained thermal expansion associated with water inlet that does not surpass the initial contraction (a dominating contraction upon drained cooling process as observed in Fig. 7.32 to Fig. 7.34). Similar trends of behaviour have been detected upon heating in the overconsolidated state with respect to the transition between the dilative quasi-undrained stage and the regulation phase, where some isotropic contraction associated with water outlet is detected (Fig. 7.36 and Fig. 7.37). However, lower dilative strains in the quasi-undrained stage are observed compared to those obtained in the main heating path followed on the normally consolidated sample, purportedly related to some porosity variation and entrapped air release by nucleation or coalescence of bubbles from soil water with increasing temperatures (Fig. 7.40). In addition, lower drained compression strains are observed in the regulation phase that do not compensate the initial dilative phenomenon, resulting in an overall expansion of soil skeleton, which is the major difference concerning normal and overconsolidated states (Fig. 7.41). Finally, thermal induced changes were discussed within an elastoplastic point of view and parameters characterising the thermal softening function and the reversible features, both under quasi-undrained and drained conditions, were determined (Fig. 7.40 and Fig. 7.41).

8.2 Future Research Work

The extensive experimental programme presented establishes a large set of paths for future work, in laboratory research, constitutive modelling and numerical simulations. As indicated in chapter 1, some tests presented in this thesis do not fundamentally contribute to the development of the main objective of this research, nevertheless they complement the overall information of the tested material, which can be incorporated in future research works related to unsaturated states, clay fabric characterisation, long-term compression and expansion phenomena, and osmotic suction aspects. In this regard, osmotic suction effects on mechanical soil behaviour are being currently analysed on the same high-porosity Boom clay packing and at the same initial water content, imbibing the inter-aggregate porosity with different solute concentrations of PEG-20000 or higher, and analysing transient and long-term effects. It is expected that intra-aggregate voids act as a restrictive semi-permeable membrane controlling solute and allowing pure water inlet/outlet to the intra-system. Clay fabric aspects related to heavily overconsolidated states could be further studied with environmental scanning microscopy under controlled wetting and drying paths and on different types of high-density aggregations. Aspects of time effects are also proposed for extending the rheologic soil volume change behaviour mainly related to control rate of strain tests at different temperatures and strain rates, control rate of loading tests at constant suction and control rate of suction tests at constant net stress and at different temperatures, as well as creep-type tests at different matric suctions and temperatures. In addition, aspects of static compaction procedures both under volumetric and stress criteria, as well as under oedometer and isotropic conditions, should be analysed in terms of sample homogeneity, specimen anisotropy and stress paths followed during fabrication.

With regard to the experimental techniques, air overpressure methodology should be evaluated with the purpose of improving its performance at high temperatures. These aspects should be focused on the use of nitrogen, as suggested in section 3.2.5.2, which presents a lower volumetric solubility in water at elevated temperatures, as well as in the implementation of an adequate control of relative humidity in the air chamber without transferring vapour to the soil (the water volume change must be solely determined by the flow of liquid water). In addition, alternative techniques to axis translation in low suction ranges should be analysed with the purpose of contrasting the results obtained in this investigation. Matric suction control by osmotic technique with PEG-20000 or higher, as well as direct determinations with Imperial College tensiometers (Ridley and Burland, 1993), are possible techniques and equipment that can be evaluated, but focusing on the analysis of temperature effects, membrane compressibility aspects and ageing effects (degradation of the membrane and activity of the solution as suggested by Dineen, 1997). Alternatives at high suction range and at different temperatures should also be considered, mainly focused on vapour equilibrium technique with unsaturated and saturated salt solutions. With respect to the experimental equipment, electro-optical laser systems should be evaluated and calibrated in terms of zero-shift consequences induced by increasing chamber pressures (loading paths) and mainly caused by the opening of cracks in the perspex wall that can affect optical properties of the confining wall. The incorporation of automatic systems to the triaxial and mini-isotropic cells to perform stress, suction and temperature controlled paths is also an important aspect that will require future attention. This system would allow contrasting results of volume change behaviour under an isotropic step loading approach, equivalent to those obtained in this research, with volume changes associated with a continuous loading system. Wetting/drying results in a matric suction step approach could also be compared with continuous results at specified suction rates. In addition, the triaxial cell will require a further modification for testing samples with a height to diameter ratio of 1:1, which would allow to perform wetting/drying paths and drained heating steps under isotropic stress states in lower elapsed times.

From a constitutive modelling and experimental point of view, an effort should be carried out to represent testing results in terms of alternative stress state variables and work conjugate strain variables. This aspect should be focused on the use of more than one stress state variable and in the possibility of incorporating the influence of hydraulic hysteresis via some dependence of degree of saturation or water content within at least one of the independent variables, or alternatively, in the use of the conventional net stress and suction stress variables and incorporating further refinements of hysteretic and coupled hydraulic features via work conjugate strain variables and elastoplastic concepts. However, the inclusion of these aspects should be carried out without losing the physical meaning of model parameters, which are also required to be measurable with relatively direct laboratory procedures. In addition, the qualitative framework described in this thesis and dealing with mechanical, suction and thermal aspects, is required to be formulated in mathematical terms, and further implemented in numerical codes after an adequate validation stage with experimental results.

Further research work is needed to include anisotropic phenomena induced by the fabrication history and their mechanisms of erasure upon plastic straining at isotropic stress states in an extension of the effects of the activation of the suction decrease SD yield locus, via some form of plastic behaviour inside the main yield surface or through a plastic anisotropy scaling function mainly dependent on plastic volumetric strains and the current stress point. In addition, attention is also required to assess the properties of anisotropic aspects related to the activation of the main q : p yield locus under unsaturated and thermal states. This aspect should be focused on equivalent volumetric and rotational hardening laws to those under saturated conditions dependent on plastic volumetric and shear strains, irrespective of their origin (mechanical loading, suction or temperature) as a first tentative or admitting certain weighting functions as more experimental evidence is available. Consequences on elastic moduli and thermal expansion coefficients dependent on the accumulated plastic pre-strain history should also be considered.

Further research work is also required to extend thermal softening aspects in normally consolidated and isotropic stress states under constant water content conditions covering the ‘intra’ and ‘inter-aggregate governing suction’ zones. In addition, the influence of the deviatoric stress on thermal softening has not been systematically studied to date, as most available data are obtained from isotropic tests. Therefore, more experimental research particularly regarding deviatoric behaviour is necessary for adapting the existing thermo-mechanical models.

The progressive implementation in numerical programs of the different proposed laws of retention curves and relative permeability functions, or other alternatives that present similar characteristics for describing the main phenomenological patterns observed in this research, is another task to be considered.