

Shrinkage behaviour of some plastic soils

by

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This Work is Dedicated to

My Father, My Mother, My Wife Norma and My Daughter Juliana

"There are three classes of intellect: one which comprehends itself; another that appreciates what others comprehend; and a third which neither comprehends by itself nor by the showing of others; the first is the most excellent, the second is good, the third is useless."

Machiavelli

"Men fear thought more than they fear anything else on earth - more than ruin, more even than death. Thought is subversive and revolutionary, destructive and terrible; thought is merciless to privilege, established institutions, and comfortable habits; thought is anarchic and lawless, indifferent to authority, careless of the well-tried wisdom of the ages".

Bertrand Russell

Abstract

This thesis presents a study of the shrinkage behaviour of plastic soils in which the main objective is to investigate the interrelationship between soil shrinkage and soil suction.

Experiments were conducted on different types of soil, with suction and volume change being measured using unconfined soil samples undergoing isotropic drying. A framework for the drying behaviour is described, and the concepts of Suction Capacity and General Air Entry point are presented, and their practical importance is highlighted.

The measurement of soil suction requires a knowledge of thermodynamic concepts which are explained briefly. Aspects of the influence of salts in the pore water of the soil, and in the suction measuring system, are also considered.

The filter paper technique for suction measurement is discussed, and results of experiments, designed to assess the filter paper method used for the measurement of both matrix and total suction, are described. A comprehensive review of the theory of the method is presented, and new recommendations are introduced concerning the use of the method for the measurement of total suction. It is concluded that the filter paper method is an efficient and practical tool for soil suction measurement.

A comprehensive study of static cavitation in water is presented which is a contribution to the development of suction measurement systems. Some results demonstrating the ability of the water to sustain high negative pressure are also presented.

The shrinkage phenomena of soils are also examined using the shear modulus obtained with the use of bender elements. This technique proves to be a useful tool for analysing the behaviour of soils during drying. The results obtained suggest that the effectiveness of the suction in controlling the shear modulus is much reduced at approximately the General Air Entry.

Recommendations are made for future work in the subject area.

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CHAPTER 1

Introduction

1.1. General Aspects

The mechanics of unsaturated soil is a multidisciplinary science involving soil science, physics, chemistry, geology, agronomy and geography, among others. This multidisciplinary nature of unsaturated soil behaviour puts the researcher in a very complex position, where the knowledge from many disciplines has to be assembled. This thesis aims to combine these data, gathered from other scientific areas, providing a more complete picture of unsaturated soil mechanics.

The main subject of this research is the shrinkage of clays. In reality this subject is closely linked to the environment, in particular climate, vegetation and balance flow of water or other liquids. The problems caused by shrinkage or swelling of soil are by no means new. As early as 1923, Haines drew attention to the engineering problems of shrinkage and swelling soils:

"... The phenomena of shrinking and swelling which take place in most soils as the water content decreases have attracted very general observation. Their effects may extend far beyond the range of purely agricultural interests, as for example, during the drought of 1921, when large numbers of houses suffered from shifting foundations, in consequence of the shrinkage of the subsoil which became dry to unusual depths".

Climate is a very important factor controlling the water movement in the soil. Soil can lose water either by evaporation from the ground surface or by evapotranspiration from vegetation. The reverse of the problem occurs by rainfall, leakage of water supply systems, irrigation, flood, etc. Figure 1.1 presents the possible negative pore-water profiles in the zone above the ground water table, called the vadose zone. This zone can be divided into two portions, one above the water table which is saturated ($S = 100\%$), overlain by an unsaturated layer ($S < 100\%$). The desaturation of the upper part of the vadose zone may be due to two phenomena: (i) the suction exceeding the air entry value of the intact soil, and (ii) the formation of fissures and cracks into which air penetrates.

If no evaporation or infiltration is allowed, the profile will come to equilibrium (curve 1 in figure 1.1). If water is extracted from the soil (e.g. by evaporation), the suction profile will move to the left (curve 2), increasing the suction in relation to the equilibrium profile (curve 1). On the other

hand, if infiltration occurs the suction profile will move to the right (curve 3), reducing the suction in relation to the equilibrium profile (Fredlund and Rahardjo, 1993b).

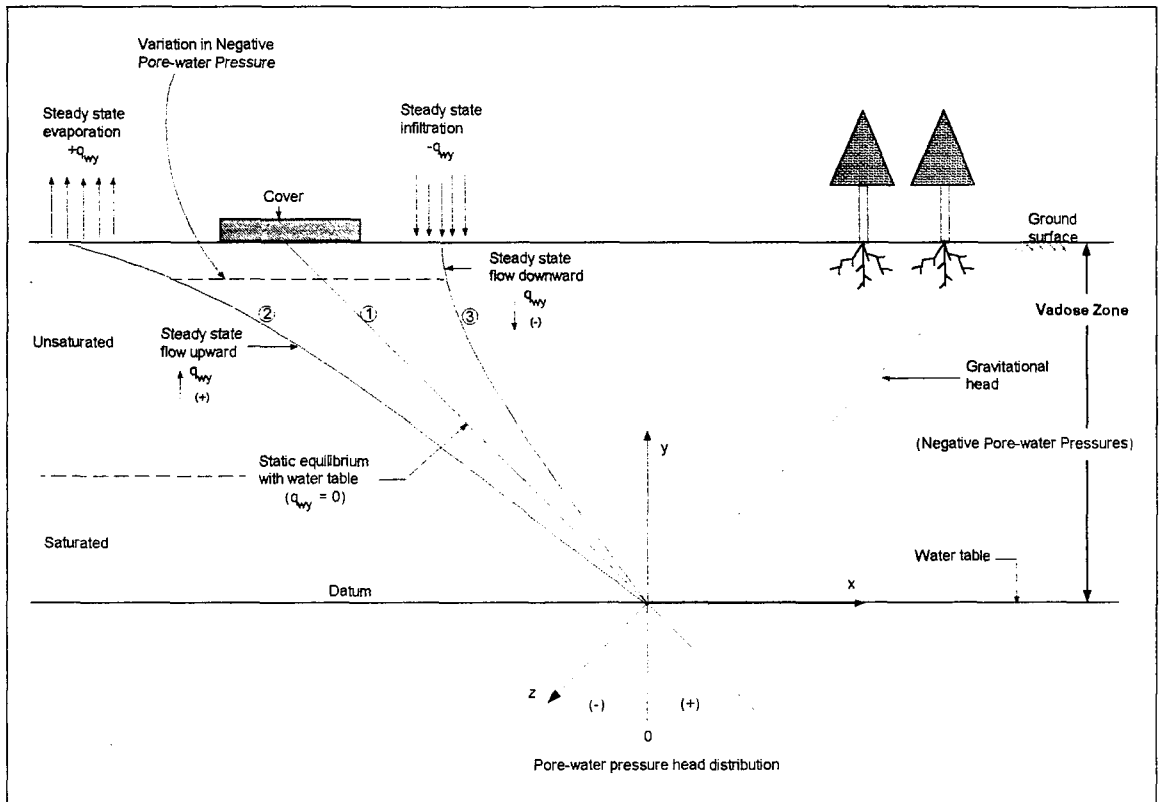


Figure 1.1 - Illustration of possible negative pore-water profiles in the vadose zone. (from Fredlund and Rahardjo, 1993b).

In most cases the consequences of swelling and shrinkage are undesirable (e.g. cracks or failure of buildings or earth structures). However, there are situations where the swelling and shrinkage are harnessed to produce a particular effect. For instance, the swelling characteristics of soils have been used in barriers for environmental protection. In particular, the use of bentonite or other clays for use in nuclear waste disposal has been extensively investigated (e.g. Dixon and Gray, 1985).

The importance of understanding the mechanical behaviour of unsaturated soil reflects its occurrence in a number of different engineering situations such as: lightly loaded buildings on expansive soils; slope stability (where residual soils or desiccated soils are involved); compacted materials (e.g. roads, dams); underground storage of nuclear waste; barriers for environmental protection, and many other engineering developments.

The recognition of the principles of unsaturated soil mechanics as opposed to soil physics, can be regarded as commencing at Imperial College (Bishop, 1959). Bishop presented what was probably the first step in unsaturated soil mechanics, defining the unsaturated state of the soil in terms of the degree of saturation. This he correlated with the χ parameter. Physical limitations in measuring suction was one of the reasons for using the degree of saturation.

The main variable affecting the behaviour of unsaturated soils is suction, and it is the main macroscopic soil property used in this work to analyse the shrinkage behaviour of soils. The complexities of the phenomena involved with unsaturated soils are widely recognised, in particular the relationship between suction and water content. Aitchison (1964) described precisely the difficulties involved:

"The subject of soil moisture does not lend itself to dogmatic statements supposedly representing incontrovertible facts. Uncertainties exist at all levels; in the understanding of the interaction between water and soil; in measurement techniques; in the definition of boundary conditions; and in the interpretation of experimental data obtained. In the face of such imperfections of knowledge the task of the applied scientist is that of making use of clear-cut principles where established, of empirical correlations where available and of rational direct experimentation and extrapolation where necessary."

Terzaghi (1925) recognized the importance of the negative water in soils in analysing the phenomena involved with the shrinkage process. Using indirect methods, Terzaghi observed that clays can sustain enormous suction (33MPa), at that time called capillary pressure. He wrote:

"... capillary pressure may be a force of enormous intensity Yet the very existence of this force has never been suspected up to this time".

Suction measurement in soils can be carried out using many different techniques. Indirect methods enable the measurement of suction at practically any level. However, direct suction measurement techniques are generally believed to be restricted to a range between 0 and 1atm. This limitation is due to cavitation of the water within the measurement system. The limiting negative pressure of 1atm for water has been generally accepted in soil mechanics and this has hindered the development of the soil mechanics of unsaturated soils, and in particular the measurement of suction. Sciences such as, physics, astronomy and medicine have done much work using the fact that water and other liquids can sustain very high negative pressure. A comprehensive literature review is presented in this thesis with experimental results that demonstrate that water can withstand a very high tensile stress, and cavitation in suction measurement systems only occurs due to the presence of micro air bubbles. With care, therefore, measurement of suction in excess of 100kPa may be made.

Recently Fredlund and Rahardjo (1993b) pointed out that *"there are still tremendous research needs and difficulties associated with problems involving unsaturated soils"*. They presented some of the key requirements as following:

- 1 - There is a need for investigation of direct and indirect methods of suction measurement.
- 2 - More complete information on the relationship between water content and suction is necessary. The test to obtain this relationship should become a standard test on unsaturated soils.
- 3 - Formulae for various problems involving unsaturated soils requires simplification.
- 4 - There is need for a complete database of case histories involving unsaturated soils.

This research focuses attention on points 1 and 2, and comprehensive information and data are provided that go a long way towards answering these two requirements.

1.2. Aims

The main objective of this thesis is to add to the sum of knowledge on the behaviour of clays on drying. It was soon recognized that in order to understand the phenomena involved with shrinkage it is necessary to build on a theoretical background, basically from thermodynamics. This knowledge is believed to be essential to the understanding of the suction in porous materials.

The detailed objectives of this research are listed below.

- 1 - To present a comprehensive literature review on the subjects required to understand better the phenomena involved with unsaturated soils.
- 2 - To investigate the role of suction on the behaviour of soil during drying.
- 3 - To characterize the influence of soil plasticity on the development of suction.
- 4 - To analyse the relationships between water content and suction, and extend the database for this correlation.
- 5 - To investigate the boundary between saturated and unsaturated soils on drying.
- 6 - To improve the use of the filter paper method of suction measurement, and in particular to establish the limitations of the use of filter paper for total and matrix suction measurements.
- 7 - To describe the phenomena of static cavitation in water and how it relates to suction measurements.

1.3. Organization of the thesis

The thesis presents a fundamental study of the behaviour of unconfined clays during drying. The investigation was performed with 23 soils, divided into two groups, naturally occurring soils and artificially mixed soils. The naturally occurring soils vary from non-plastic to highly plastic soils. The artificially mixed soils were used to cover a particular plasticity range, giving more control over variables such as type of mineral and pore sizes. The size of the particles and their distribution and arrangement affects water behaviour in the soil. The particles can be arranged having more or less space for water and air. The pore size distribution is important in characterizing the drying of soils. However, for the moment, it is not possible to obtain the pore size distribution for expansive (shrinkable) soils, unless the soil is completely dry.

Compacted, reconstituted, undisturbed and continuously disturbed sample were slowly dried and the volume change, water content and suctions were obtained. This thesis discusses the relationships existing between the phenomena involved in the shrinkage of soils and suction, giving a framework for the general behaviour of soils with increasing suction.

Most of the suction measurements were performed using the filter paper technique, and approximately 2,000 individual suction measurements were made, including both total and matrix suction measurements.

In Chapter 2 a comprehensive review of soil suction measurement is presented. The basic aspects of suction theory are given, together with a brief description of the available suction measurement methods. Description of the soil suction components (osmotic and matrix suction) are presented.

Chapter 3 contains a literature review of cavitation in liquids. The aim of this chapter is to present information about cavitation. This information is not available in the soil mechanics literature, and a proper understanding of the subject is believed to be vital for the development of suction measurement systems. The mechanism of cavitation is described and a technique to reduce the likelihood of cavitation is described based on information and experimental results from literature.

Chapter 4 presents a comprehensive literature review of the filter paper method, highlighting the thermodynamic mechanisms which take place during the test.

Chapter 5 presents a review of soil shrinkage, including the theoretical aspects of the phenomena involved. The behaviour of the soil in terms of volume change, water content and degree of saturation is described with respect to soil suction. The air phase in unsaturated soils and its importance in the shrinkage process is also considered.

Chapter 6 contains description of the soils, techniques and procedures used in this thesis.

The results from the tests performed are described in chapter 7. Section 7.1 presents results related to suction measurements. The precision of the filter paper method is considered, based on 1,500 individual matrix suction measurements. The results obtained using the filter paper method clarify aspects such as contact effects, non-contact calibration, and osmotic suction. The use of the filter paper method is carefully analysed illustrating its potential and limitations. Also presented are results from the tensiometer probe (described in Chapter 3). Attention is drawn to the importance of the interface (normally a porous stone) between the suction measuring device and the soil, in which osmotic effects were observed.

In sections 7.2 to 7.5 results of drying tests are presented and analysed. These sections are divided according to the type of sample tested. Section 7.2 presents the results obtained with compacted soils. Two compaction methods were used, *i.e.* dynamic and static. Section 7.3 presents the results of the reconstituted (slurried) samples. In section 7.4 the results of tests using undisturbed samples are presented, and section 7.5 contains the results from the continuously disturbed samples. Section 7.6 presents a global analysis of the results discussed in the previous sections, taking into account the differences in type of samples and soils.

Chapter 8 presents results of stiffness measurements made using bender elements in statically compacted London clay during drying. A brief literature review describes the use of bender elements, and the relationship between soil stiffness and soil suction. The conclusions take into account the observations made in chapter 7.

Chapter 9 presents the general conclusions from this thesis. In Chapter 10 recommendations for future research is given.

CHAPTER 2

Soil Suction

Effective stress in unsaturated soils is controlled, among others things, by the tensile stress in the pore water. This tensile stress is given by the difference between the atmospheric pressure (or air pressure) and water pressure, matrix suction. There are other components of soil suction apart from matrix suction and the aim of this chapter is present the basic definitions and concepts related to soil suction and the methods of measurement of soil suction.

In section 2.1 the definitions of the soil suction components are given and some aspects of suction theory are presented. The thermodynamics of soil suction are described (section 2.1.1) in order to form a background for description of the total suction given in section 2.1.2. In sections 2.1.3 and 2.1.4 some aspects of matrix and osmotic suction are considered.

In section 2.2 brief descriptions of the most commonly used techniques for suction measurement are given. The intention is to introduce the principles, advantages and limitations of each method. Understanding of the differences between methods allows a clear visualization of the differences between the components of soil suction.

2.1. Aspects of Suction Theory

Suction is the isotropic pressure that the pore water imposes to absorb more water. The suction of interest is the maximum pressure that a soil, in a given condition, can use to absorb water.

Soil suction is usually divided into two components, matrix (related to the soil matrix, *i.e.*, the combination of particle type and structural arrangement) and osmotic (due to the concentration of salts in the soil water). The total suction is the sum of the matrix and the osmotic suctions. The component of suction measured is directly linked to the technique used to measure it.

Aitchison (1964) suggested the following definitions for total, matrix and osmotic suction.

Matrix or capillary component of free energy

"In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapour in equilibrium with the soil water, relative to the partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water".

Osmotic (or solute) component of free energy

"In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapour in equilibrium with free pure water".

Total suction or free energy of the soil water

"In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapour in equilibrium with the soil water, relative to the partial pressure of water vapour in equilibrium with free pure water".

These definitions are generally accepted and depending on the technique that is used one can evaluate which component of suction has been measured.

There are many techniques for soil suction measurement. In table 2.1 the most commonly used techniques are given, together with range of measurement and some references (for more details see section 2.2).

Technique	matrix suction	osmotic suction	total suction	range (kPa)	references
Psychrometer		X	X	100- 8000	Spanner (1951) Dimos (1991)
Filter paper	X		X	0-29000	Chandler <i>et al.</i> (1991) and Chapter 4
Tensiometer	X		X	0-90 0->>1000	Stannard (1992) Ridley and Burland (1993) and Chapter 3
Axis translation	X			0-1500	Richards, L.A. (1941) Richards, B.G. (1980)
Thermal conductivity	X			0-400	Fredlund and Rahardjo (1993)
Electrical conductivity	X	X		entire range	Krahn and Fredlund (1972)

Table 2.1 - Techniques for soil suction measurement.

2.2.1. Thermodynamic concepts

Most of the definitions presented here are based on the comprehensive work of Edlefsen and Anderson (1943).

The thermodynamic term associated with soil suction is the free energy (f). It is defined as follows:

$$f = e + P_v - T_s = H - T_s$$

where: e is the internal energy (L^2/T^2)
 P is the pressure (M/LT^2)
 v is the specific volume (L^3/M)
 T is the temperature ($^{\circ}K$)
 s is the entropy (dimensionless)
 H is heat content (L^2/T^2)

The reference point for free energy of soil is pure water with a planar (flat) gas-water interface. This means that the free energy of the pore water (with or without salt, with meniscus or not) is measured relative to the free energy of pure water (with a flat gas-liquid interface). Hence, the absolute free energy of the water in an unsaturated soil is less than that of free (flat gas-water interface) pure water, and thus the absolute free energy of soil water in a dry soil is less than that absolute free energy of that in a wet soil. The free energy of the soil water of all unsaturated soils is negative. Only if the soil is saturated can its free energy be, at most, zero.

Soil water may exist in three phases: vapour, liquid and solid. If the three phases are in equilibrium it is possible to determine the free energy of the soil by obtaining the free energy of one of its phases. At equilibrium $\Delta f = 0$.

As will be seen in section 2.2.4 the presence of dissolved materials (*e.g.* salts) reduces the tendency of the solvent molecules (*e.g.* water molecules) to escape, and they hold part of those molecules that would normally escape (evaporate or condense). A quantitative measure of the escaping tendency of the solvent is the vapour pressure¹.

The free energy of the solvent of a solution (with respect to the pure solvent) is given by:

$$\Delta f = -v\Delta P_0$$

where: Δf is the change in free energy (relative to pure water).

v is the specific volume of the solvent (if the solvent is water $v = 0.001\text{m}^3/\text{kg}$)

ΔP_0 is the osmotic pressure of the solution.

The free energy of the soil water is, in general, determined by the amount of dissolved material, by the hydrostatic pressure in the soil water and by the adsorptive force field from the soil particles. It is normally impossible to calculate directly the contribution of each of these factors to the total free energy of the soil water. In order to determine the total free energy of the soil water at a specific water content, it is necessary to determine only the free energy of the vapour phase in equilibrium with the water within the soil. As will be seen later, the measurement of the relative humidity is necessary in order to determine the free energy of the vapour phase. The relative humidity can be measured using, for example a psychrometer.

¹ The vapour pressure is the equilibrium pressure, at a specific temperature, of the liquid's vapour which is in contact with an *existing* free surface (Knapp *et al.*, 1970). This concept is important in understanding the cavitation phenomena discussed in chapter 3.

Consider the system, shown in figure 2.1, in equilibrium at constant temperature. The vapour pressure (p_v) is different from the hydrostatic pressure (P_L) at a point A, except when $h=0$. The hydrostatic pressure of the liquid at A can be decreased (increase in suction) by increasing h . If the hydrostatic pressure is decreased the escaping tendency of the liquid decreases. In order to keep the equilibrium, the escaping tendency from the vapour phase has to be decreased by the same amount. A change in hydrostatic pressure is followed by a new equilibrium, where the vapour pressure will change and the free energies will adjust themselves so that

$$\Delta f_V = \Delta f_L$$

where:

Δf_V is the free energy change for the vapour and Δf_L is the free energy change for the liquid.

Since, $\Delta f_V = v_V \Delta p_V$ and $\Delta f_L = v_L \Delta P_L$

where v_V and v_L are the specific volumes of the vapour and liquid respectively.

It follows that

$$v_V dp_V = v_L dP_L.$$

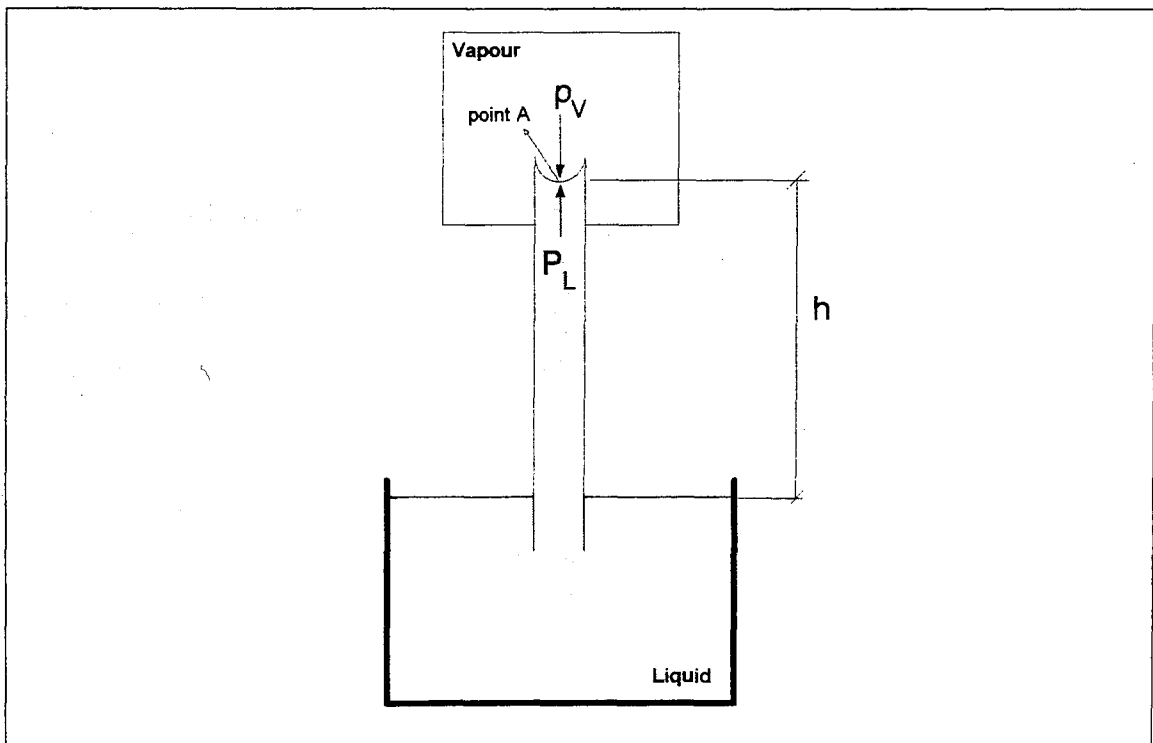


Figure 2.1 - Equilibrium of a vapour with the liquid through a curved vapour-liquid interface (Edlefsen and Anderson (1943)).

The specific volume of a liquid (v_L) is in general approximately constant with change of pressure, but the specific volume of a vapour (v_V) changes. Assuming that it obeys the ideal gas law, we have

$$p_V v_V = RT \Rightarrow v_V = \frac{RT}{p_V}.$$

where: R is the gas constant, which is different for different gases

T is the absolute temperature in °K ($T = 273.15 + t^{\circ}\text{C}$)

then we have,

$$v_L dP_L = RT \frac{dp_V}{P_V}.$$

Consider the change in going from one equilibrium state A to another equilibrium state B. Integrating the equation above between the limits of hydrostatic pressure P_A and P_B and the vapour pressure between the limits p_A and p_B , we have

$$v_L \Delta P = v_L (P_B - P_A) = \Delta f = RT \ln \frac{p_B}{p_A}$$

As the liquid and its vapour are assumed to be in equilibrium, their free energies must be the same. Thus the expression

$$\Delta f = RT \ln \frac{p_B}{p_A}$$

gives the free energy of both a liquid or a vapour in state B with respect to that in state A, expressed in terms of the vapour pressure.

The free energy can also be written as

$$\Delta f = \frac{\bar{R}T}{M} \ln \frac{p_B}{p_A}$$

where

M is the molecular mass of water vapour (18.011kg/mol) and $\bar{R}$ is the universal gas constant (8.31432 J/(mol K)).

In terms of suction the expression is

$$\text{suction} = \frac{\bar{R}T}{v_L M} \ln \left(\frac{p_B}{p_A} \right)$$

where

v_L is the specific volume of water (*i.e.* $\frac{1}{\rho_w}$) and ρ_w is the density of water (998kg/m³ at 20°C).

The equation above represents the total suction in terms of vapour pressure above a free surface (flat) of pure water (*i.e.* water with no salts or impurities). The relation $\frac{p_B}{p_A}$ is called relative humidity (RH). At 20°C this expression becomes

$$\text{suction} = 135055 \ln(\text{RH}) \quad (\text{in kPa}).$$

2.1.2. Total Suction

As presented in the section 2.1 the free energy of the soil water is the total suction. It can be determined by measuring the relative humidity in the surrounding of the soil mass or by using a semipermeable membrane.

The concept of total suction when a semipermeable membrane is shown in figure 2.2. Total suction is the pressure difference across a semipermeable membrane separating pure water from a soil that contains solution. Total suction is the sum of matrix and osmotic suction (see following sections).

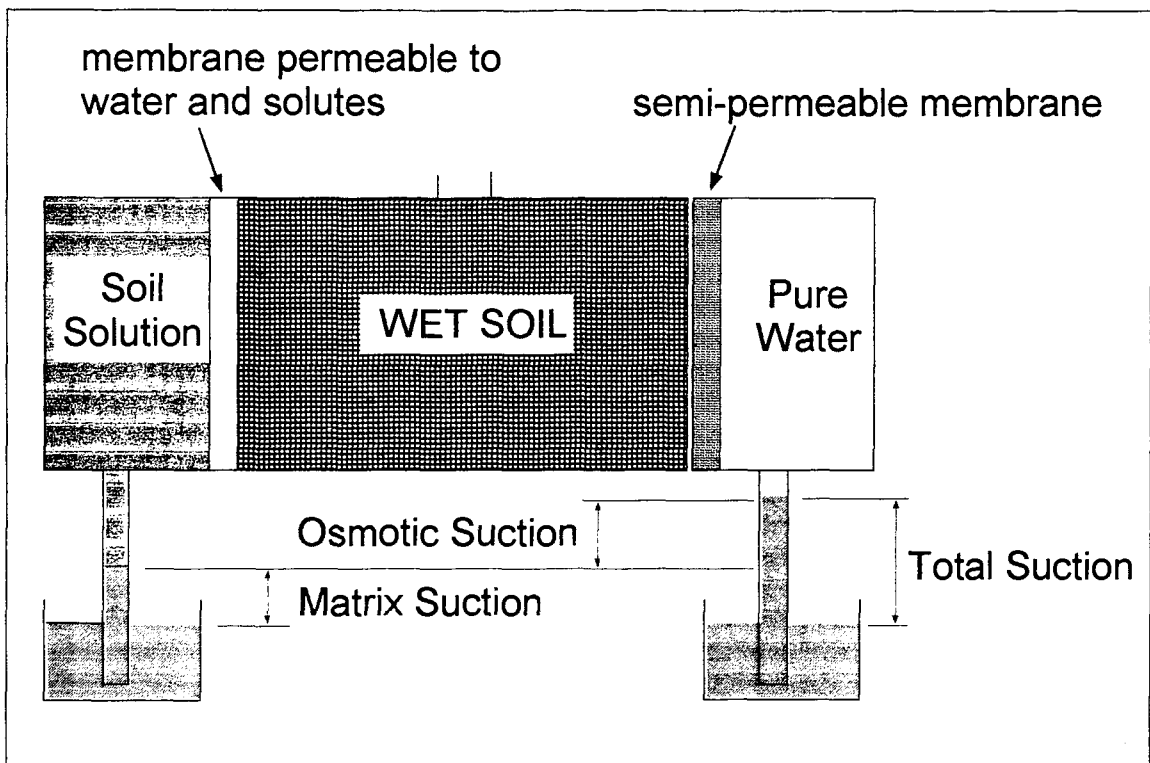


Figure 2.2. System showing the total and matrix suction concepts.

Since in most practical situations the osmotic suction is fairly constant, a change in total suction can, in some cases, be assumed to be equivalent to a change in matrix suction (Fredlund and Rahardjo, 1993).

2.1.3. Matrix Suction

Matrix suction is the negative water pressure developed in the soil water due to capillarity and adsorption forces. In figure 2.2 the concept of matrix suction is presented. Matrix suction is the pressure difference across a membrane separating soil solution *in situ* from the same solution in bulk, the membrane being permeable to solution but not to solid particles or air (Hillel, 1971).

The concept of capillarity helps to understand the influence of the soil matrix on suction. The understanding of how capillarity acts in a soil requires a knowledge of capillary rise.

Consider the capillary rise in a vertical capillary dipping into the free surface of water (figure 2.3a). In this case the meniscus is symmetrical with respect to the axis of the tube.

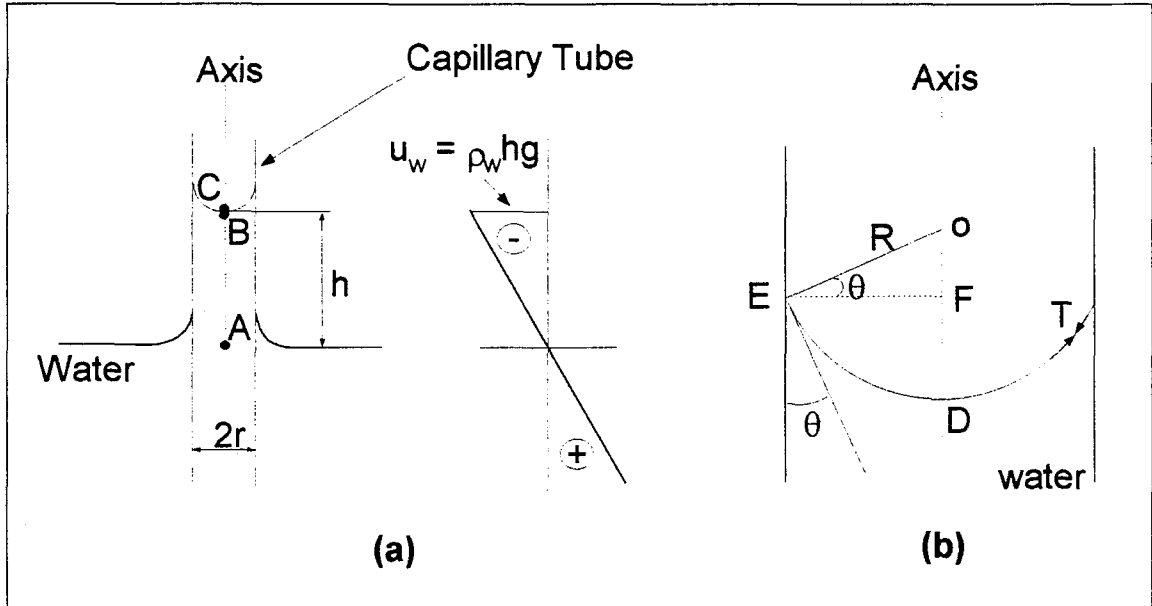


Figure 2.3 - (a) Capillary rise (b) The meniscus as a spherical cap.

The pressure P_c at C, just above the meniscus, is atmospheric. At B just below the meniscus the pressure is $2T/R$ less. Where,

R is the radius of curvature of the meniscus and

T is the surface tension of the water (73×10^{-6} kN/m at 21°C).

Thus,

$$P_c = P_B + \frac{2T}{R}.$$

At A, which is at the same horizontal level as the outer free surface of the water, the pressure P_A is also atmospheric and

$$P_A = P_B + \rho_w gh$$

Where, ρ_w is the density of the water.

The pressure at A is equal to the pressure at C. Then,

$$\begin{aligned} P_B + \rho_w gh &= P_B + \frac{2T}{R} \\ \text{or} \quad h &= \frac{2T}{\rho_w g R}. \end{aligned}$$

The radius of curvature of the meniscus (R) is not easily measured, and we must therefore make some assumption about the shape of the meniscus. Normally it is assumed to be spherical with an angle of contact θ (for details on the angle of contact see section 3.3).

If r is the radius of the capillary tube then (see figure 2.3b),

$$\begin{aligned} r &= EF = R \cos \theta \\ \text{and} \quad h &= \frac{2T}{\rho_w g r} \cos \theta \end{aligned}$$

If the liquid wets the tube then $\theta=0$, the spherical cap becomes a hemisphere and

$$h = \frac{2T}{\rho_w g r}$$

The air pressure at the surface of the meniscus is zero ($u_a=0$) and the water pressure is negative (*i.e.* $u_w = -\rho_w g h$). Matrix suction is given by the difference between the air pressure and the water pressure. Since $u_a=0$ the matrix suction is given by,

$$\text{matrix suction} = \frac{2T}{r}$$

Although the capillary model is useful in explaining how a negative water pressure can be maintained in capillaries, this model has severe limitations. It can only be used in inert soils and moreover the capillaries in the soil mass are very variable in size and shape which induce phenomena such as hysteresis. Using the capillary model it can be shown that nonuniform pore size distribution in a soil can result in hysteresis (Taylor, 1948; Hillel, 1971). The determination of the radius of the meniscus is not possible. For clays, others factors such as adsorptive forces, interfere with the matrix component of the suction.

2.1.4 Osmotic Suction

2.1.4.1. General Aspects

Capillary rise above the water table can act as an "ion pump" that feeds dissolved salts continuously to the top of the capillary fringe as water evaporates there. This results in a concentration of salts at the top of the capillary zone and the development of an osmotic gradient that attracts even more water to the top of the column (Gray, 1969). This phenomenon is due to osmosis.

The process of osmosis can be modelled by the system presented in figure 2.4. On the left side is a pure solvent, A, and on the right side a solution of solute, B, in the same solvent, A. The two liquids are separated by a membrane, M, which is permeable to A but impermeable to B. When such a system is set up, with the surfaces of the liquids on both sides at the same level, it is found that solvent A flows across the membrane from the left to the right side, *i.e.* from the pure solvent to the solution. This flow is called osmosis. A membrane, such as M, which is permeable only to the solvent, and not to the solute, is said to be semi-permeable.

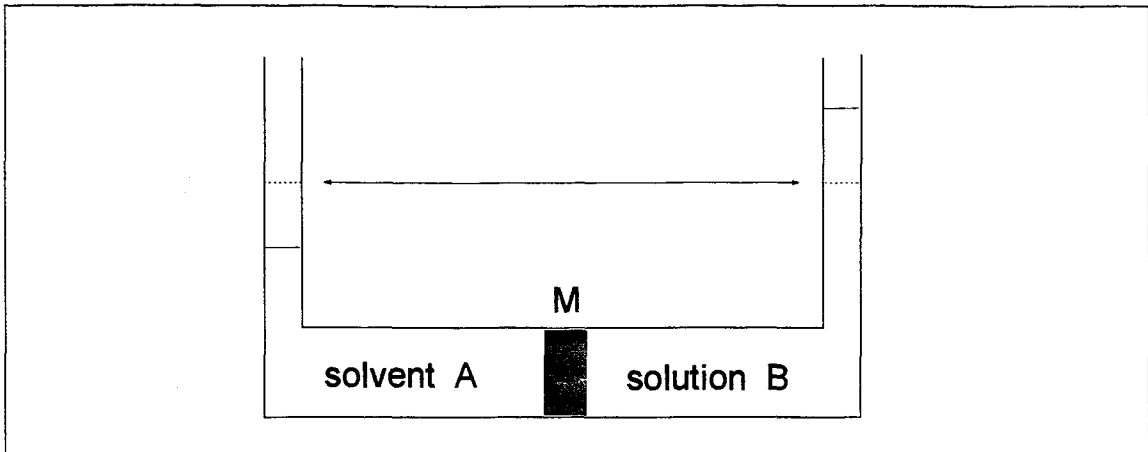


Figure 2.4 - Osmotic phenomena

The pressure difference required to produce zero flow of solvent is called the osmotic pressure of the solution B. Osmotic pressure and osmotic suction are numerically the same but have opposite sign.

The International Society of Soil Science gives the following definition of osmotic suction (from Aitchison 1964).

"The negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable membrane with a pool containing a solution identical in composition with the soil water."

It is very important to note that the above definition is dependent on the properties of the membrane.

Atchhison (1964) suggested a definition based on the technique used to measure osmotic suction (i.e. psychrometer), which is as follows:

"Osmotic suction is the equivalent suction derived from the measurement of the partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapour in equilibrium with free pure water."

The osmotic pressure is a relative concept expressing the decrease of the potential energy of water in solution relative to that of pure water. An increase in the osmotic pressure of a solution is usually accompanied by a decrease in the vapour pressure, a rise of the boiling point and a depression of the freezing point.

A more general definition is as follows: *"The osmotic pressure of a solution is that pressure which must be applied to the solution to make the chemical potential of the solvent in the solution equal to that of the pure solvent at the same temperature"* (Thain, 1967).

The osmotic pressure itself is not responsible for liquid flow unless a membrane or a diffusion barrier is present which transmits water more readily than salts (Hillel, 1971).

So, two factors are necessary for osmotic flow:

1. a semi-permeable membrane or diffusion barrier,
2. pure water or solutions with different concentrations.

If a saline solution is brought into contact with pure water, through a diffusion barrier, the volume of water will, in the first instance, increase on the side of the solution and decrease on the solvent side (figure 2.4). If the diffusion barrier is an impermeable membrane to a specific salt, the difference in volume will remain. However, if the diffusion barrier acts only as a less permeable medium to salt, after some time the level and salt concentration on both sides will be identical.

2.1.4.2. Solute Concentration and Relative Humidity

The proportionality between salt and pure water is called molarity of the solution (a solution with a molarity of one comprises the molecular weight of the salt, in grams, diluted in one litre of pure water). Changing the solute concentration represents a change in osmotic pressure.

There is a direct relationship between solute concentration and relative humidity. Robinson (1945) performed some experiments in which the relationship between NaCl molarity and relative humidity at 25°C were obtained. This relationship is shown in figure 2.5.

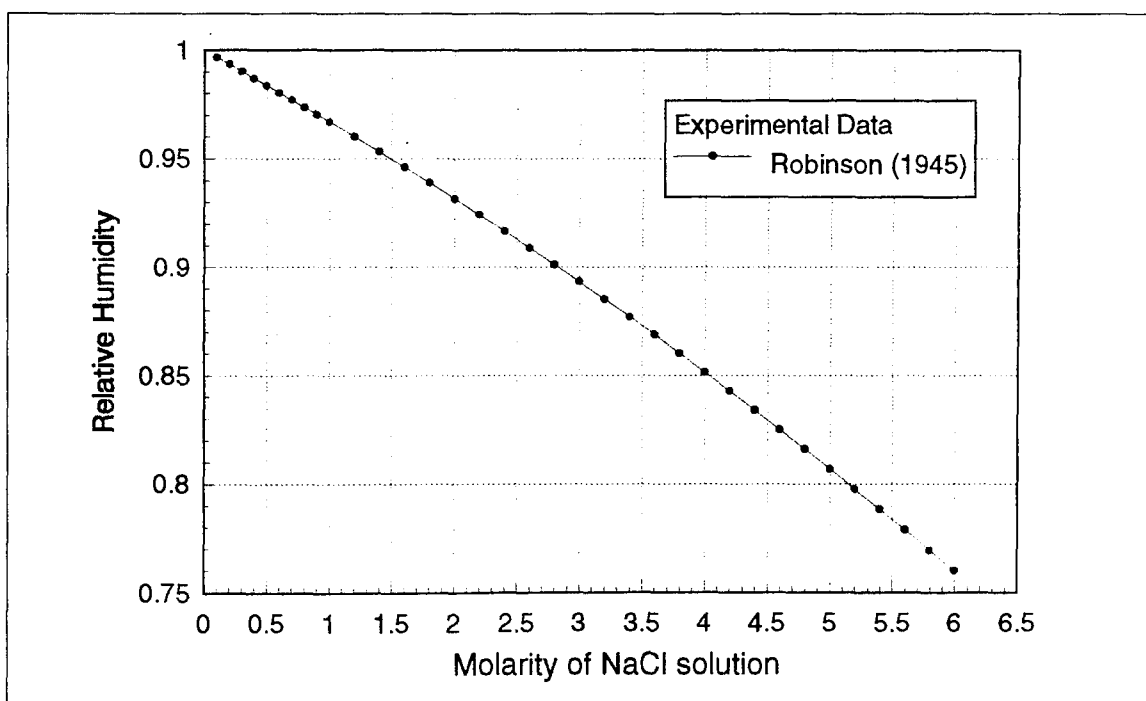


Figure 2.5 - Relationship between relative humidity and NaCl molarity.

Using this relationship it is possible to determine the equivalent suction generated when a soil is in equilibrium with a solution of NaCl. The equation below represents the thermodynamic relationship between soil suction and relative humidity, as given previously in section 2.1.1.

$$\text{suction} = 135055 \ln(RH) \text{ (in kPa)}$$

Figure 2.6 shows the relationship given by the equation above. The equation below can be used for estimating suction for a given molarity (m) of NaCl between 0 and 1.

$$\text{Suction} = 4598.95 * m^{1.00122}$$

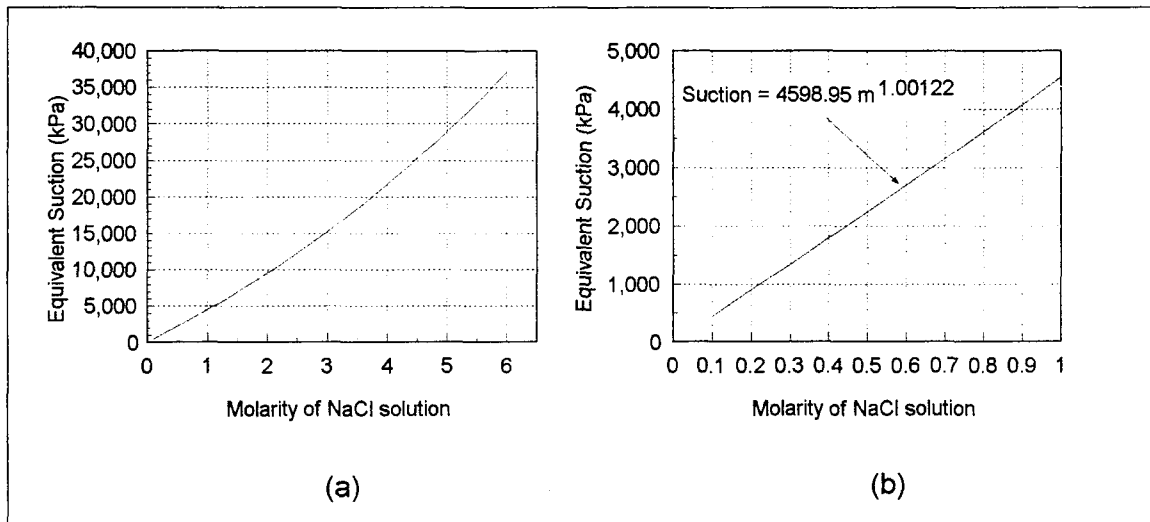


Figure 2.6 - Relationship between suction and NaCl molarity.

2.1.4.3. Osmotic Suction in Soils

Osmotic phenomena can occur in saturated and in unsaturated soils. It is well known that by changing the concentration and/or type of salts in the soil water, a change in soil behaviour occurs (*e.g.* Bolt, 1956; Sirapullaiah and Sridharan, 1987; Thomas and Lentz, 1990). The changes in soil salt concentration act as a modifying agent, altering the characteristics of the soil.

As described in section 2.1.1, salt concentration alters the vapour pressure of the water. The change in vapour pressure is reflected in the escape tendency of the water molecules. The higher the concentration of salt, the more difficult it is for the water molecule to escape (evaporate).

Figure 2.7 represents a clay-soil system in which two different concepts of osmotic suction are shown. In figure 2.7a it is assumed that the salt solution extracted from the soil (or added to the soil) will be identical in composition to that which is present in the soil system. This definition is

an abstraction. Osmotic suction defined in this way does not act in the soil system, unless free water is put in contact with the soil water.

Within the soil, the semi-permeable membrane does not exist and free water will seldom be pure. However, the diffuse double layer could play a role in the distribution of salts between the free water and the water in the double layer². Although a definition involving the double layer and the free water is a simplification of the phenomenon, it may be more realistic. Figure 2.7b represents the balance that may exist between free water and absorbed water. Until an equilibrium is reached an exchange of volume can occur between the free water and the water in the double layer. This is caused by osmotic forces. As will be seen none of the existing methods for measuring osmotic suction is able to measure the osmotic suction acting between the free water and the absorbed water.

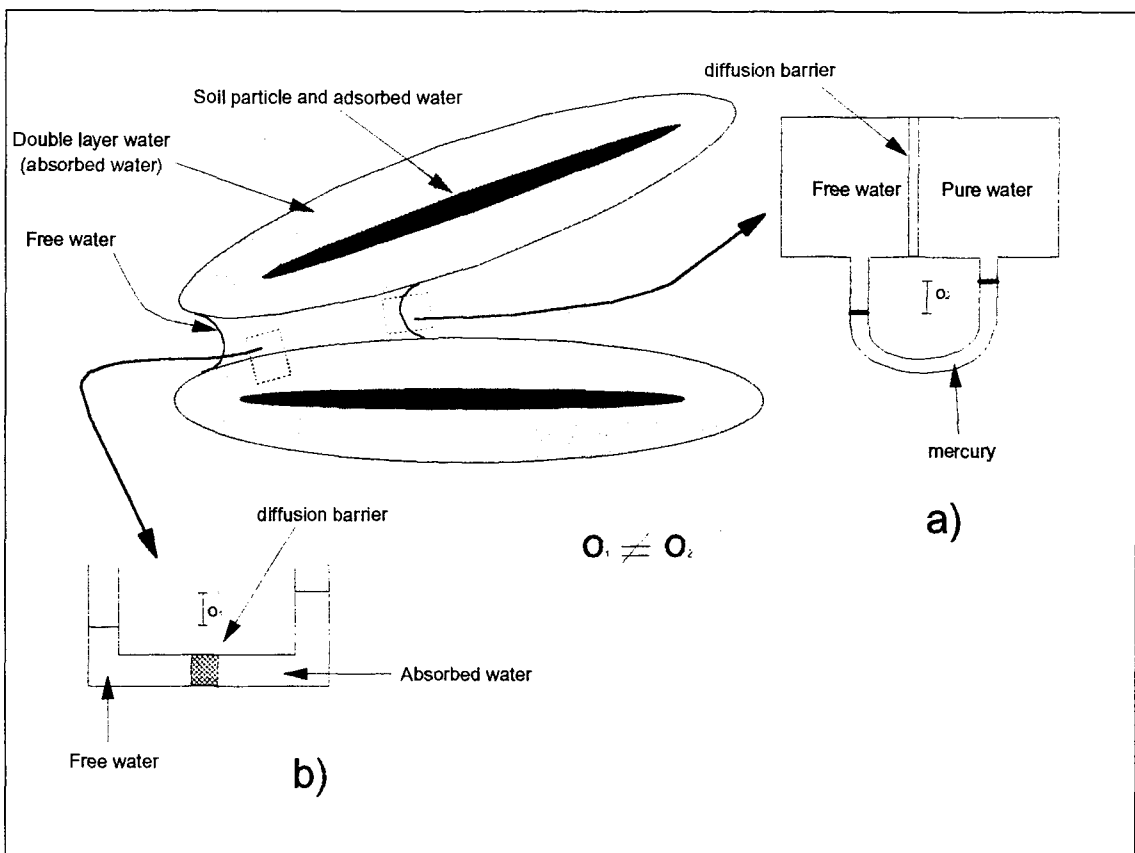


Figure 2.7 - Osmotic suction in the soil system.

No osmotic force will act if the salt content in the free water and in the absorbed water are the same. However, if the diffuse double layer acts as a semi-permeable membrane, there will be an osmotic pressure in the system after some volume change. The system described is a microsystem.

² It is important to note that there are two phenomena involving osmotic pressure in soils, one being the flow of water and the other is osmotic consolidation (see for example Barbon and Fredlund, 1989).

The more probable situation is that osmosis occurs in the macro system. Contaminant in a form of a liquid placed in contact with a soil may create a flow due osmosis. The presence of vegetation may induce osmotic flow and eventually consolidation, the osmotic suction being controlled by the difference in concentration between the plant and the soil water. Usually solute levels in the cell sap are greater than in the soil solution and aid the inward flow of water. If the solute concentration in the soil water exceeds that within the cell sap, the flow may be reduced (Bache and MacAskill, 1984). However in this case the suction generated in the soil is matrix suction.

2.1.4.4. Using Osmosis to Control Matrix Suction

Matrix suction can be controlled by osmosis. A semi-permeable membrane is used to separate the soil sample and a specific solution used to generate the osmosis. The solution normally used is polyethylene glycol (PEG). The PEG has large molecules which cannot pass through the membrane. By varying the concentration, matrix suctions of up to 2MPa can be generated. This technique was initially developed by biologists (Lagerwerff et al., 1961) and has been used for geotechnical purposes. Kassiff and Ben Shalom (1971) and Delage et al. (1992) developed an osmotic suction controlled consolidometer. Triaxial cells were also developed (e.g. Kormonik et al., 1980 and Delage et al., 1987). The osmotic technique has the advantage of applying a matrix suction in the soil water without using the axis translation technique (described in 2.2.5). It is more realistic in dealing with soils with high degree of saturation, where some air may be occluded. However, the solution of PEG is calibrated against pure water and if the soil pore fluid has some salt, the suction generated will not be known, but must, clearly, be less than the value obtained from the calibration. In addition the dilution of the solution has to be controlled, since water tends to dilute the solution used to generate the suction.

2.1.4.5 Quantification of Osmotic Suction

Defining what aspect of osmotic suction should be measured is probably the most difficult aspect of osmotic suction quantification.

The generation of osmotic suction can be dependent on the environment and type of engineering problem (e.g. contaminated lands, reservoirs, foundations, etc.). As described previously, osmotic suction is a relative concept and depends on the difference between solute and solvent.

In normal usage, suction in a soil is divided into two components, matrix and osmotic suction, the sum of them being the total suction. The matrix suction is the suction due to capillary effects

in the soil mass. The osmotic part of the soil suction can be defined and determined in different ways.

Richards (1980) pointed out the confusion and difficulties in using soil suction in practice, mainly in expansive clays. The confusion predominantly conjoins the osmotic component and how to measure it.

Electrical conductivity is one of the methods that can be used for measuring osmotic suction. The electrical conductivity of the solution can be used to infer the total concentration of dissolved salts which, in turn, can be related to the osmotic suction of the solution.

There are two ways to obtain the pore fluid for electrical conductivity measurements. One is by squeezing the soil water using a high pressure. The other method is by adding water to the soil until it becomes a slurry and then draining off the pore fluid; this method is called *saturation extract technique*. The first method is only possible when the soil has a high water content. The second one gives lower results since it dilutes the pore fluid by adding water and extrapolation to the correct moisture content is not very accurate. Krahn and Fredlund (1972) measured osmotic suction using electrical conductivity measurements on samples of pore fluid obtained by the squeezing technique; their results are shown in figures 2.8a and 2.8b. The tests were performed on Regina clay and glacial till. The sum of osmotic and matrix suction obtained (squeezing technique and pressure plate, respectively), agrees with the total suction measurement (obtained using a psychrometer). In Krahn and Fredlund's (1972) results the total and matrix suction curves are almost parallel (*i.e.* the osmotic suction is constant over the range of moisture content tested). Richards (1980) did not obtain good agreement between total suction and the sum of matrix plus osmotic suctions in his results. When a soil is drying an increase in salt concentration is expected and hence the osmotic suction should increase rather than stay constant.

The psychrometer can also be used to infer the osmotic suction of solutions, using pore water obtained by one of the two techniques described above.

2.1.4.6. Osmotic Efficiency of Porous Materials

Even though osmotic suction has very little importance in most engineering problems (*e.g.* Fredlund and Rahardjo, 1993) it has a very important role in suction measurement, since osmosis can influence the values of suction measured, making the interpretation of results very difficult.

The question to be asked is: do we need to measure osmotic suction?

If the salt content in a soil changes, there will be a change in the overall volume and shear strength of the soil; this is a consequence of the change in the physical properties of the soil. Fredlund and Rahardjo (1993) pointed out that "most engineering problems involving unsaturated soils are commonly the result of environmental changes". Some examples of soil environmental changes are:

- 1 water content changes below houses, which can reduce or increase the matrix suction;
- 2 slope instability due rainfall that reduces the matrix suction; and
- 3 excavations in clays generating matrix suction.

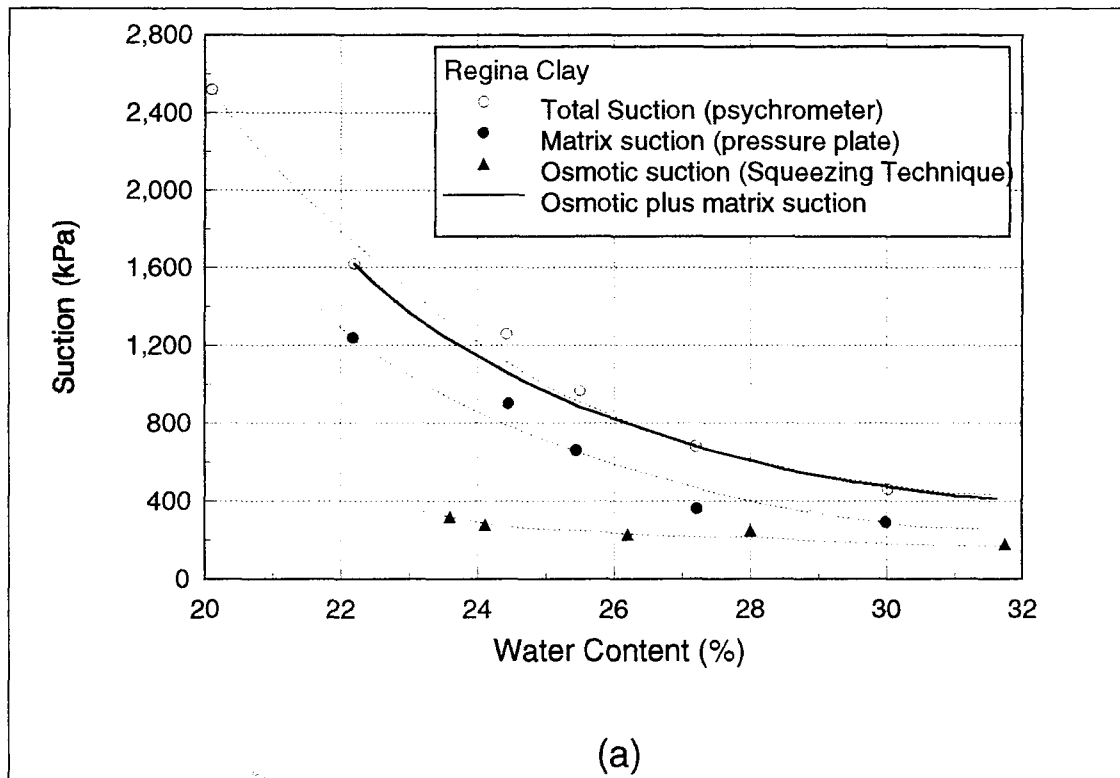


Figure 2.8a - Suction measurement in Regina clay (modified from Krahn and Fredlund, 1972).

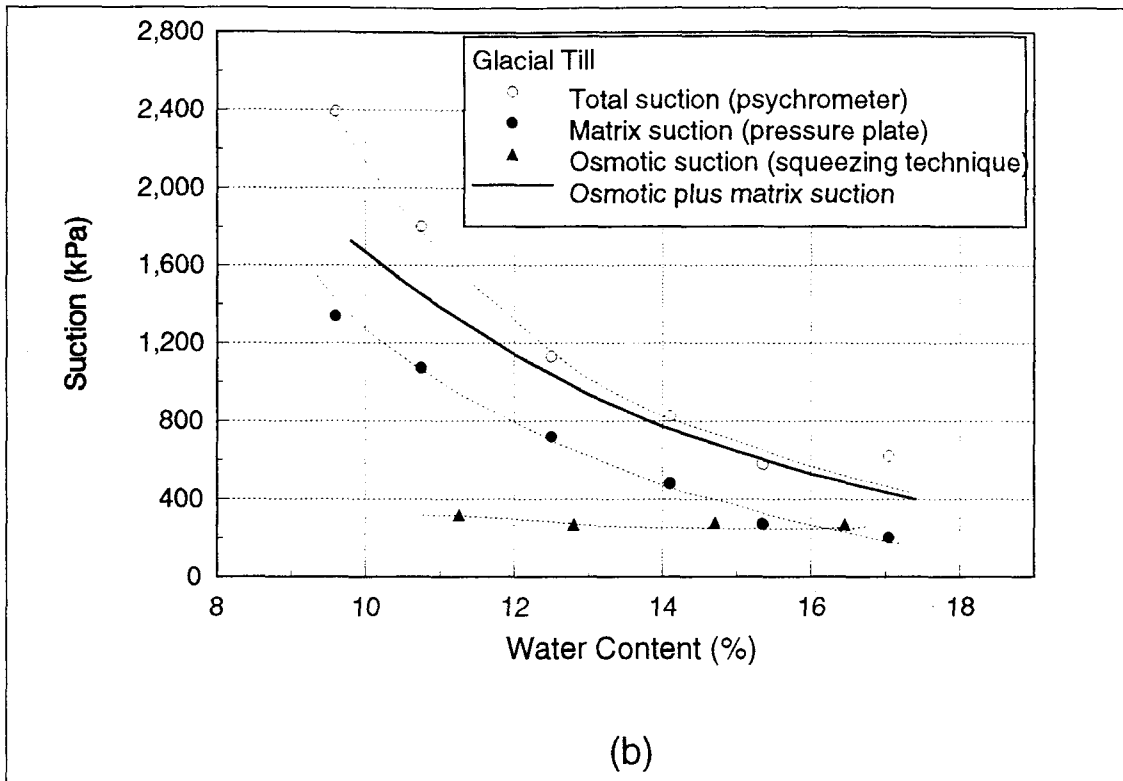


Figure 2.8b - Suction measurement in Glacial till (modified from Krahn and Fredlund, 1972).

Osmotic suction changes are generally less significant than matrix suction changes in these cases. However, changes in osmotic suction can be significant in the following situations.

- 1 Soil contamination. osmotic suction may be generated due to differences in the pore fluid concentrations.
- 2 Soil testing technique. osmotic suction can be generated depending on the test performed (e.g. every time a diffusion barrier is present.). Normally samples are put in contact with a fluid which differs from the pore fluid through a porous material that has some osmotic efficiency³. Osmotic suctions generated in this way are usually temporary, since the porous material is not a semi-permeable membrane.

Edlefsen and Anderson (1943) made the following observation in relation to in situ suction measurement: "Some times a porous bulb connected to a manometer is immersed in a moist soil where capillary potential (matrix suction) is to be measured. The tension recorded by the manometer is then taken as the capillary potential of the soil moisture, which always contains varying amounts of dissolved material. The concentration of solutes inside the bulb at the time of measurement is less than the concentration of the soil solution. One wonders whether the tension usually recorded is not, therefore, a combination of the true capillary potential plus the osmotic potential, rather than just the capillary potential alone". It can be concluded that osmotic aspects are of great importance on suction measurement. Mitchell (1960), Aitchison and Richards (1965) and Schreiner and Gourley (1993) also observed that there is an initial osmotic effect in the pressure plate apparatus due to the high air- entry value of the porous stone used.

³ Osmotic efficiency is a measurement of the effectiveness in causing hydraulic flow under osmotic pressure gradient and also the ability of the material to act as a semi-permeable membrane in preventing the passage of ions, while allowing the passage of water (Mitchell (1991)).

Pore water pressure (negative or positive) are normally measured through a porous material which provides the interaction between the soil and the measurement system. Thus, when dealing with soils with high concentration of salts it is important to know the osmotic efficiency of the porous material.

Figure 2.9 shows a system where matrix and osmotic suction are acting between two soil particles. A device to measure suction directly is placed in contact with the free water. In a case like this where the only requirement in order to measure total suction (matrix plus osmotic) is that the device has to be fitted with a diffusion barrier as a porous material. If the filter paper technique is used, the diffusion barrier is the air space that must exist between the paper and the soil. Air is the most efficient semi-permeable membrane that exists.

Mitchell *et al* (1973) developed a theory which describes chemico-osmotic flow and consolidation processes. They also showed that osmosis is significant only for fine grained and active clays (*e.g.* expansive soils). They suggested that the water flow in the early stages of consolidation is controlled by total suction gradients and only at a later stage, when the salts are redistributed, does matrix suction control consolidation.

Performing a very simple test, Mitchell *et al* (1973) were able to show the osmotic effect in soils very clearly. A thin sample of soil was immersed in a tri-ethylene glycol solution and weighed at various time intervals. The difference between the weight, at any time, of identical samples immersed in water and in solution is a measure of the chemico-osmotic effect and is termed the chemico-osmotic weight difference. Figure 2.10 shows the results obtained, the initial weight loss being due to osmosis and the subsequent swelling (water absorption) due to equalisation of the salt concentration in both soil and water. Point A indicates the maximum chemico-osmotic weight loss. The weight loss is greater for plastic soils.

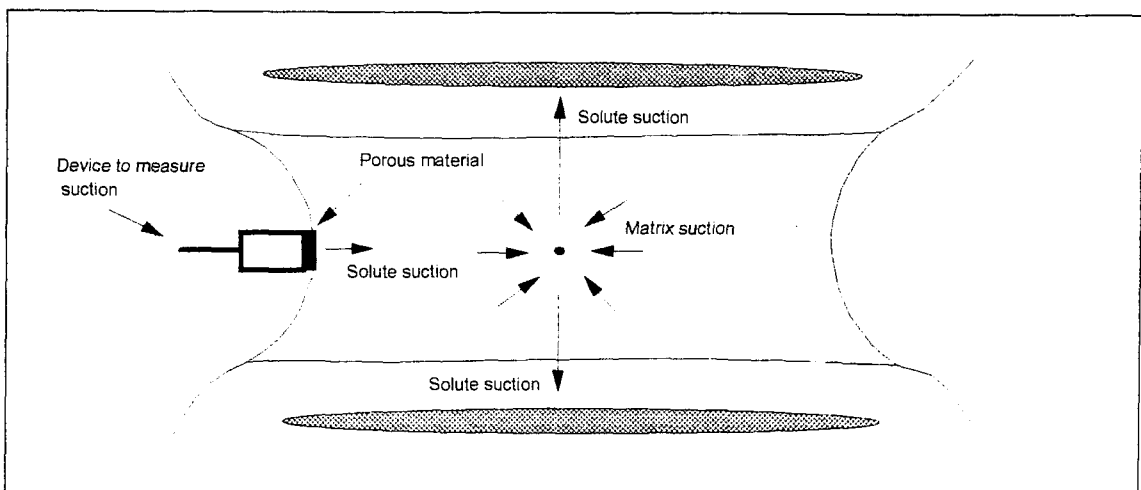


Figure 2.9 - Suction measurement and the forces involved.

Another very simple experiment can be performed using beans. When immersed in a salt solution, beans lose water and contract. However, after some time the volume is recovered due to diffusion of the salt into the beans.

Ridley (1993) suggested the term *differential suction* as a substitute for osmotic suction. However, the difference between total suction and matrix suction is clearly due to chemical-osmosis, and thus the term osmotic suction or solute suction would seem to be applicable.

The definition of osmotic suction should be one that does not change with the way the suction is measured. When measuring total suction, matrix and osmotic suction are included in the measurement. However, the sum of matrix and osmotic suction (independently measured) does not necessarily represent the total suction. Thus, the two terms of the soil suction (matrix and osmotic suction) are additive depending on the technique used to measure the suction. Total suction includes capillary, adsorption and osmotic effects (defined in any way).

Osmosis is a factor which must be considered when measuring suction, and the understanding of osmotic phenomena is essential in the interpretation of suction measurements.

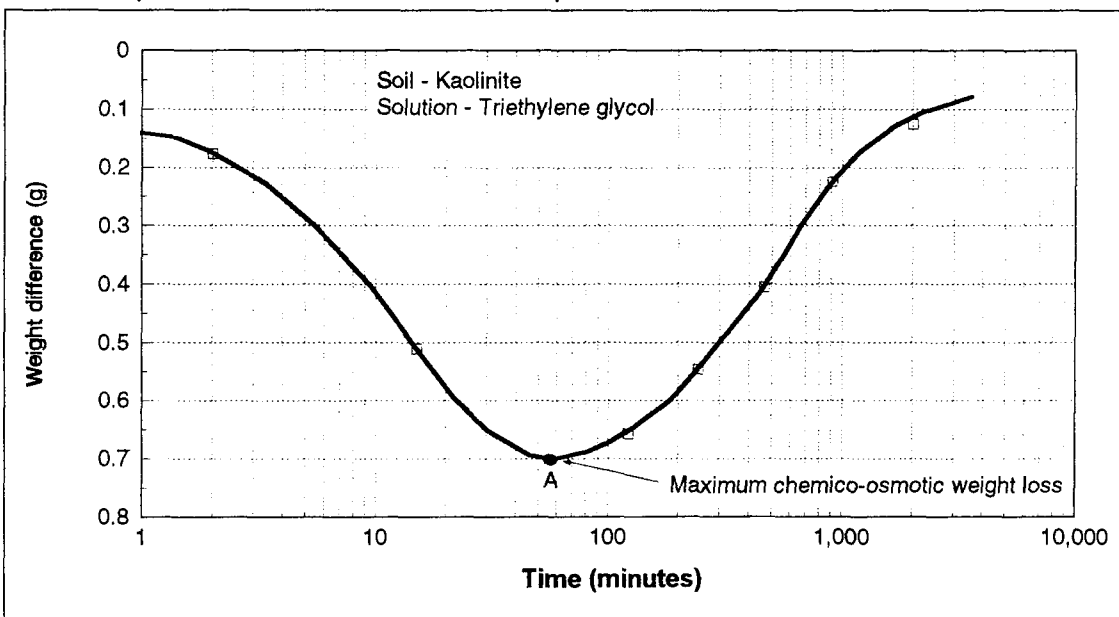


Figure 2.10 - Weight loss due to chemico-osmotic consolidation (modified from Mitchel et al., 1973).

2.2. Soil Suction Measurement Methods

At the beginning of the century Livingston (1906), used a chemically prepared semi-permeable membrane and sugar solution to obtain the soil suction in the desert. The initial interest in measuring soil suction was related to the growth of plants. It was in the field of soil science that most of the concepts and techniques for suction measurement were developed.

The following sections describe the most important techniques of suction measurement. The techniques described are: psychrometer, filter paper, tensiometer, thermal conductivity sensors, axis translation and electrical conductivity.

2.2.1. Psychrometer

Principle: The psychrometer measures the relative humidity of the air phase of the soil water or of the air phase of any solution. It works by measuring the temperature difference between a nonevaporating surface (*i.e.* a dry bulb) and an evaporating surface (*i.e.* a wet bulb). The difference in temperature between these surfaces is related to the relative humidity.

Advantages: It can measure total or osmotic suction, depending on whether the psychrometer is exposed to the soil or only to the soil pore water.

Disadvantages: It is very sensitive to temperature changes. This sensitivity is higher in the high relative humidity range (*i.e.* low suction).

It requires a long time for the soil and air phases to reach the equilibrium. This time depends on the suction level and protective cover. It is expensive.

Bibliography: Dimos, 1991; Fredlund and Rahardjo, 1993a.

2.2.2. Filter Paper

Principle: The filter paper technique uses the absorption capacity of the paper to exchange moisture with the soil. The filter paper will reach an equilibrium (*i.e.* no flow of water or vapour) with a particular soil suction. The moisture flow can occur by capillary flow or vapour flow between the soil and the filter paper. Usually the flow is from the soil to the paper, since the latter normally has a very high absorption capacity. More details will be given in chapter 4.

Advantages: Can be used for measuring total, matrix or osmotic suction (see chapter 4 for details).

It is inexpensive. Can be used in the field or in the laboratory.

Disadvantages: Requires extreme care in carrying out the test. A minimum of seven days is necessary for the filter paper reach equilibrium. For total suction measurement the equilibrium time depends on the level of suction. If small samples are used the water exchange increases the suction in the soil.

Bibliography: Chandler and Gutierrez (1986); McKeen (1985); ASTM - D5298-92.

2.2.3. Tensiometer

Principle: The tensiometer is a means of transmitting the negative pore water pressure to a measurement system. Tensiometers generally comprise a porous cup, water and a pressure measurement system. The measurement system can be a manometer or an electrical or mechanical pressure transducer. The water inside the system has the same negative pressure as the pore water in the soil. The water exchange is from the system to the soil.

Advantages: Normally requires a very short period of time to reach the equilibrium. The interpretation of the data is simpler than in other methods. It can be used in the field and in the laboratory. It can be incorporated in most soil testing equipment (*i.e.* triaxial cell, oedometers, etc.)

Disadvantages: Usually the system cavitates at about -1 atm of pressure (see chapter 3). Depending on the porous material used and the soil tested, osmosis can occur (see section 2.1.4).

Bibliography: Watson, 1967; Stannard, 1992.

2.2.4. Thermal conductivity sensors

Principle: The method uses the thermal conductivity properties of an absorbent material (*i.e.* ceramic), which is placed in contact with the soil for equilibrium to be reached. The thermal conductivity of a porous material increases with its degree of saturation. The calibration is obtained by measuring the thermal conductivity of the material under known matrix suctions.

Advantages: It can be used in the field.

Disadvantages: The method may be influenced by temperature. There is a difference in the suction measured depending on whether the ceramic is placed dry or wet. The measurements suffer from hysteretic effects.

Bibliography: Fredlund (1992); Fredlund *et al.* (1994).

2.2.5. Axis translation

Principle: Negative pore water pressure in soils is given by the difference between the air pressure around of the soil and the water pressure within the soil. At atmospheric pressure the water pressure within the measurement system cannot go too much into tension, since cavitation usually occurs. By increasing the air pressure, the origin of reference (*i.e.* atmospheric pressure) is translated so that the water within the system is usually kept

in the positive range or with a small tension. A high air entry value porous stone has to be used in order to prevent the air from entering the water pressure measurement system. Once the porous stone is saturated it does not allow the air to pass through, only the water can flow.

Advantages: Suction can be measured or controlled. The method can be incorporated into many types of soil testing equipment in the laboratory (*i.e.* triaxial, oedometer, shear box, etc.)

Disadvantages: The technique may overestimate suctions in soils with degree of saturation greater than approximately 80% or soils with occluded air. Air can diffuse through porous stone, resulting in underestimates of the suction. Osmotic effects can occur depending on the porous stone and soil type (see section 2.1.4).

Bibliography: Bocking and Fredlund, 1980; Fredlund and Rahardjo, 1993a.

2.2.6. Electrical conductivity

Principle: This method uses the electrical conductivity of the salt solutions to infer the soil suction. The calibration is obtained using solution with known osmotic suctions. This method can be employed for measuring osmotic or matrix suction. When measuring matrix suction the electrical conductivity is measured in a porous material which is in equilibrium with the soil water. For osmotic suction measurement, the soil water is extracted from the soil by one of the techniques described in section 2.1.4.5 (*i.e.* squeeze technique or saturation extract technique).

Advantages: It can give a value of osmotic suction of the pore fluid or any other solution.

Disadvantages: Because the electrical conductivity is affected by the salt concentration, measurement of matrix suction can be overestimated. It is not clear whether the extraction technique is adequate for obtaining the pore fluid to measure the osmotic suction.

Bibliography: Krahn and Fredlund, 1972; Richards, 1974; Fredlund and Rahardjo, 1993a.

CHAPTER 3

Cavitation and suction measurement.

3.1. Introduction

Many papers about the direct measurement of suction mention the impossibility of measuring pressure below -1atm (e.g. Bishop and Blight, 1963; Bocking and Fredlund, 1980; Edil *et al.*, 1981; Delage and Suraj de Silva, 1992; Fredlund and Rahardjo, 1993). The water is always considered to be responsible for this failure, since cavitation is observed in the system. This supposition is incorrect, since it is not generally appreciated that water, or liquids in general can, under appropriate conditions, sustain high tensions.

The ability of liquids to withstand tension has been proved by direct measurement of the tension (e.g. Meyer, 1911; Chapman *et al.*, 1975). However, the theoretical value for the tensile strength of water is very high when compared with the values observed experimentally. Harvey *et al.* (1944) developed a theory in which they shown that cavitation occurs only when persistent air or gas nuclei are present. In other words, cavitation will not occurs if the system is completely free of any kind of nuclei.

When a bubble (or cavity) is present in a liquid there are two ways for it to grow, *i.e.* slowly or abruptly. Slow growth can result from the diffusion of dissolved gas into the existing cavity; abrupt expansion of the gas may be due to temperature rise or pressure reduction. When the cavity growth is abrupt it is called boiling if due to temperature rise, and cavitation if caused by pressure reduction (Knapp *et al.*, 1970).

In experiments which have been conducted to measure the tensile strength of water (or any liquid), the water (or liquid) has normally been inside the measurement system. However, for soil mechanics applications, the water whose tension is to be measured is inside the pores of the soil. This situation requires the use of an interface between the measurement system and the soil water; normally, the interface used is a porous stone. Such a stone is used to facilitate both positive and negative water pressure measurements.

Tensiometers have been used in both the field and the laboratory for direct suction measurements (e.g. Stannard, 1992). Standard tensiometers are generally unable to measure water tensions greater than approximately 1atm and, therefore, their use in high plasticity soils is limited to the saturated range, since the soil remains saturated to very high values of suction (typically around 1MPa). However, a tensiometer probe capable of measuring suction up to

1.8MPa has recently been developed (Ridley and Burland, 1993 and Ridley, 1993). The development was based on the observation that a small pressure transducer probe used for positive pressure measurement inside triaxial cells (Hight, 1982), was able to register values of suction up to 500kPa when a soil sample was unloaded under undrained conditions (Standing, 1994). Further work on that observation showed that small pressure transducers with a very small gap between the porous stone and the diaphragm can measure negative pore water pressure when previously submitted to high positive pressure (Ridley, 1993). It was believed that the small volume or small gap behind the porous stone was the key factor in avoiding cavitation (Ridley and Burland, 1993; Ridley, 1993).

The technique of using a "small" volume of water reduces the probability of cavitation, since the number of potential nuclei is also "small". This technique has been used with success in experiments to determine the tensile strength of water (*e.g.* Apfel, 1970; Henderson and Speedy, 1980; Angel, 1980; Ohde *et al.*, 1992)

As will be shown the use of a "large" volume of water inside the measurement system, requires considerable care in preparing the water and the container (*e.g.* the transducer). Using small volumes, it is easier to generate tensile stress in water. In the literature most of the work was done using Berthelot tubes to generate the tensile stress. (*e.g.* Chapman *et al.*, 1975; Richards and Trevena, 1976; Jones *et al.*, 1981). Most of these used a "large" volume of water.

The onset of cavitation has handicapped direct suction measurement attempts for many years. A better understanding of the phenomena involved with cavitation may allow further development on the subject.

Because cavitation is a instantaneous phenomenon, its study is a very complex matter. Although the high speed at which it occurs complicates the investigation of cavitation as a phenomenon, it can be of advantage during suction measurement. The rapid drop in measured suction when cavitation takes place is obviously unrelated to suction change. This helps in the interpretation of tensiometer data. This chapter presents a review of the literature on how and why cavitation occurs inside suction measurement systems and goes on to make recommendations for techniques to reduce the probability of cavitation.

3.2. Physics of water under tension

The assumption that measurement of suction greater than approximately 1atm, using tensiometers, is impossible, has been based on the "theoretical" explanation that a liquid cannot sustain a tension greater than its vapour pressure. However, the stress required to induce a rupture in a liquid is given by its tensile strength and not by its vapour pressure (*e.g.*

Knapp et al., 1970). Theoretical values for the tensile strength of water are of the order of thousands of atmospheres (*e.g.* Fisher, 1948; Plesset, 1969).

Measurement of matrix soil suction, using a tensiometer, requires that the water inside the measuring system is at the same value of tensile stress as the soil pore water, and this may induce cavitation inside the system. In soil suction measurement, cavitation is the result of pressure reduction and has the effect that, after cavitation has occurred, the pressure measured by the system will be approximately equal to the pressure of the gas. This is probably why the belief that it is impossible to measure suctions greater than 1atm has developed.

The conditions under which a liquid with a flat liquid-gas interface (free water¹) will vapourise are given by the vapour pressure-temperature curve for that particular liquid. However, if the liquid-gas interface is not flat, as in the case of a vapour cavity in a liquid (bubbles), it is possible to reach a state normally associated with the vapour phase without the vapour phase developing (Apfel, 1970).

A phase diagram for a simple substance, as shown in figure 3.1, indicates the regions where under a given pressure and temperature combination the substance is solid, liquid or vapour. The substance at point A would be a vapour. However, under certain circumstances it is possible, starting from A₁, to reduce the pressure and reach A, at a pressure lower than the vapour pressure and for the substance to remain liquid. In the same way it is possible to go from A₂ to A remaining a liquid. When the phase boundary is crossed without the substance changing phase, the phase boundary is said to be transgressed. If transgression has occurred, the system is said to be in a metastable state (Apfel, 1970). Water under tension is in a metastable condition and this metastability can be destroyed if nucleation occurs. Nucleation is the formation of vapour cavities within the liquid itself or at their boundaries (Trevena, 1987).

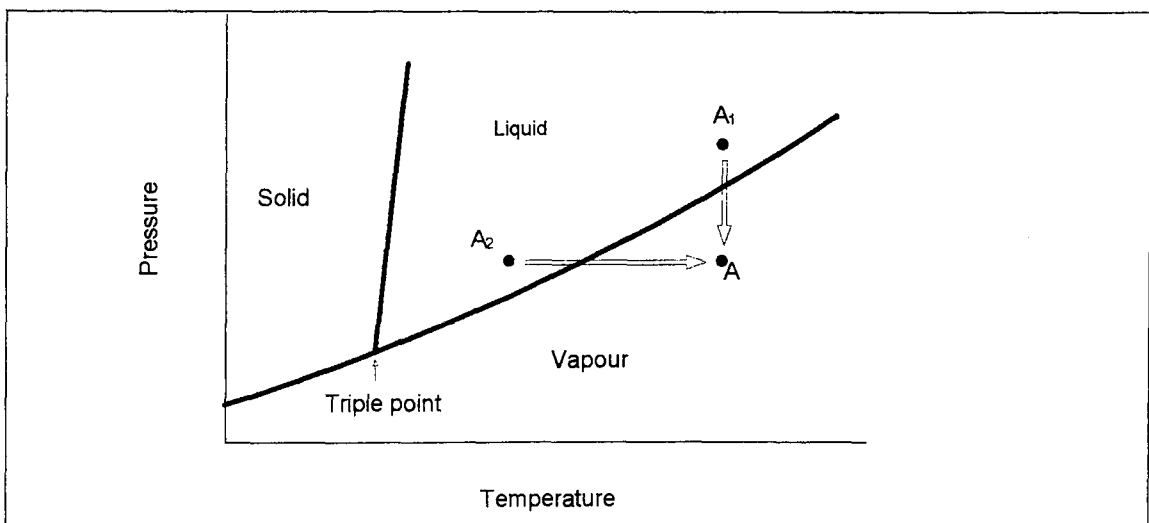


Figure 3.1 - Phase diagram for a simple substance.

¹ Free water here has not the same meaning of the water outside particles double layer.

Cavitation in a metastable liquid can result from two types of nucleation: nucleation in pure liquid, and nucleation caused by impurities in the liquid. Impurities can be other pure substances, solid impurities or even radiation acting on the liquid. Nucleation within a pure liquid is called "homogeneous" nucleation and nucleation due to impurities is called "heterogeneous" nucleation. Heterogeneous nucleation is more common and it is responsible for most cavitation occurring in suction measurement systems.

Inconsistencies between the theoretical values of the tensile strength of water and the values measured in experiments lead to the development of the crevice model (Harvey *et al.*, 1944). This theory states that cavitation will occur at the wall of the containers (loss of adhesion) and not in the body of the liquid (loss of cohesion).

A bubble with 0.1mm radius will rise at about 1.5m/s, and will dissolve in about a minute in air-saturated water² (Epstein and Plesset, 1950). If cavitation originates from a macroscopic bubble of air this bubble has to be "stabilized". Stabilization prevents the bubble disappearing either by rising to the surface or by dissolving as result of surface tension. Gas or vapour bubbles can only be stabilized in a liquid under very special conditions. The stabilized bubble is called a cavitation nucleus.

There are four theories which try to explain the presence of cavitation nuclei in a system that contains water.

1. There may be solid particles in the water with gas trapped in crevices in these particles (Apfel, 1970; Crum, 1979).
2. Gas can be trapped in tiny crevices in the walls of the liquid's container (Harvey *et al.*, 1944; Winterton, 1977; Overton and Trevena, 1980).
3. Air bubbles may be stabilized by a ionic skin that exists between the gas and the liquid (Akulichev, 1966).
4. Bubbles can be covered by surface-active substances and thus stabilized against dissolution (Sirotyuk, 1970; Yount, 1979). The nuclei in this case are considered to be small enough to remain in suspension.

The existence of several minute spherical gas bubbles stabilized against gaseous diffusion by a skin of organic impurity was suggested (Fox and Herzfeld, 1954). However, Herzfeld (1957) abandoned this model, following results obtained by Strasberg (1959).

Ohde *et al.* (1989) presented a theory (gas-supply assumption) in which crevices are supplied with gas from sources in the solid surface of the container. They suggested that the material used for the container should be degassed.

3.3. Surface Phenomena

When a drop of water is put on a solid surface an angle is formed between the solid surface and the liquid. Figure 3.2 shows a liquid gas interface in contact with a solid surface. The angle is a measure of wetting. If $\Theta = 0^\circ$ the surface is said to be hydrophilic with perfect wetting. If $\Theta > 0^\circ$ the surface is hydrophobic and imperfect wetting occurs. The wetting angle (Θ) varies depending whether the liquid is advancing or receding (figure 3.3); this is very important when saturating the suction measurement system. Measurements of the wetting angle indicate that no liquids wet any solid perfectly and that all liquids wet all solids to some extent (e.g. Adam, 1941; Bikerman, 1958). An interesting observation is that liquids for which the wetting angle is less than 90° (e.g. water) will climb up a capillary tube immersed in it, whereas mercury, which has $\Theta > 90^\circ$, will go down the tube.

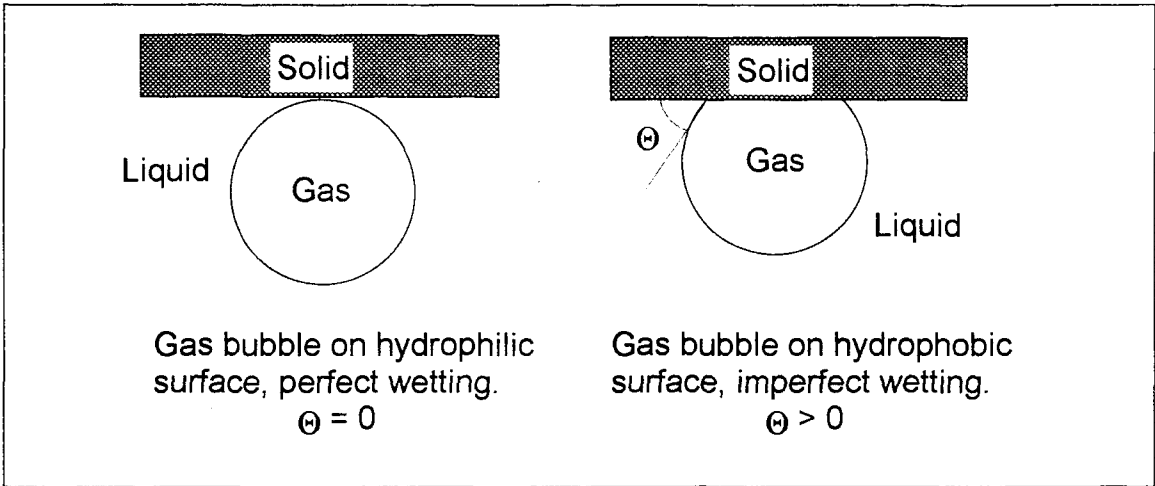


Figure 3.2 - Liquid-Gas interface showing the wetting angle.

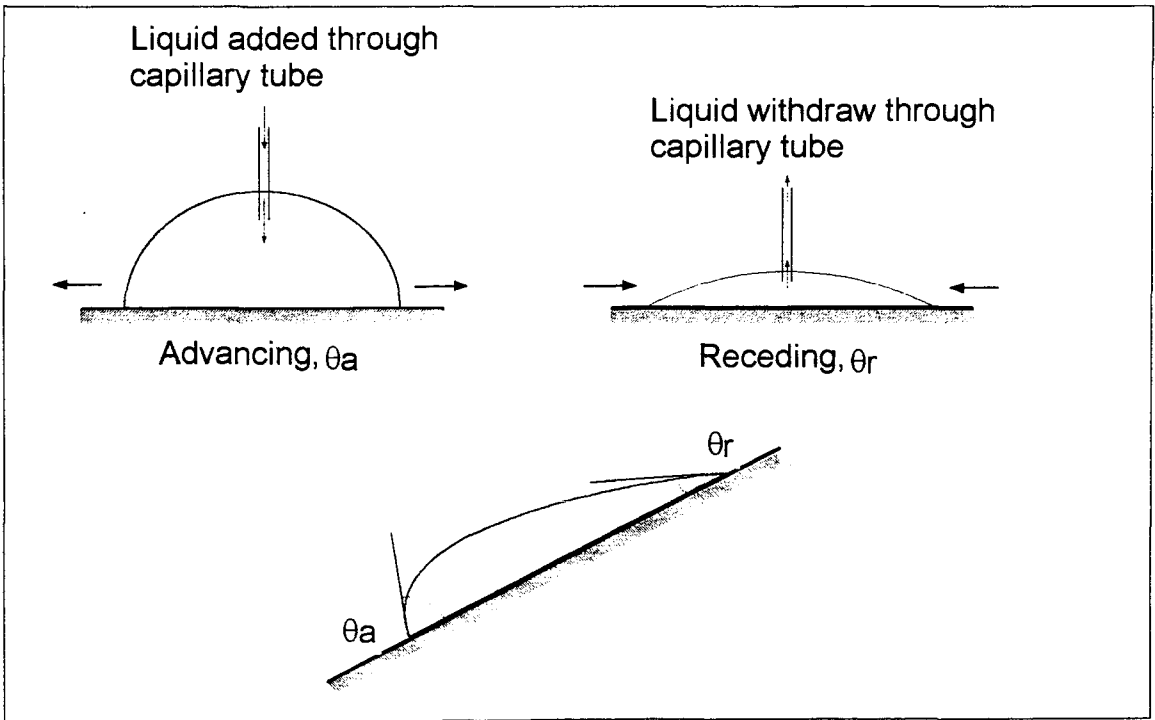


Figure 3.3 - Advancing and receding angles (modified from Bose, 1993).

The most widely accepted model for nuclei stabilization is the crevice model. Harvey *et al.* (1944) proposed that undissolved gas nuclei could exist as submacroscopic bubbles in hydrophobic cracks and interstices in the container's walls. The surface tension under such conditions acts to decrease rather than increase the gas pressure, and the gas is not forced to dissolve. Figure 3.4 shows cavitation resulting from a gas nuclei in a crevice in a solid surface.

Harvey *et al.* (1944) observed that stabilized nuclei could be forced to dissolve if high pressure is applied. The high pressure reduces the bubble size and increases its solubility. It can be shown (*e.g.* Knapp *et al.*, 1970) that if the crevice has an acute angle, with zero radius of curvature, an infinite pressure is required in order to dissolve the bubble. In this case the stabilization would be permanent and it would be impossible to avoid cavitation when tension is applied. However, if the crevice is rounded a finite pressure is required to dissolve the bubble.

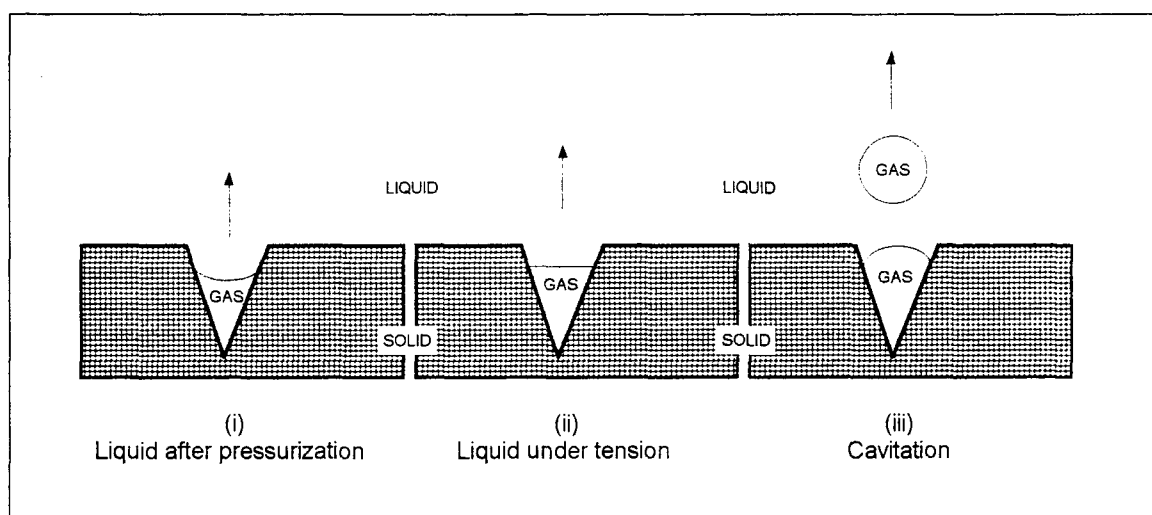


Figure 3.4 - Bubble formation from a stabilized cavitation nuclei.

Dissolved gas seems to have a very small influence on reducing the tensile strength of water (*e.g.* Kuper and Trevena, 1952; Knapp *et al.*, 1970; Lauterborn, 1970). However, dissolved gas can diffuse to existing nuclei. Cavitation can also occur in the liquid itself (not at the boundary). However, this process involves considerable energy concentration at a point in the liquid (*e.g.* from ultrasonic radiation), and this will not normally occur in pore water pressure measurement.

3.4. Generation of tensile stress in water

Tensile stress in a liquid can be applied statically or dynamically. Our main interest is statically generated tension.

The necessity for studying the behaviour of liquid under tension resulted in the development of some techniques for the generation of tension in liquids. The most commonly used technique for the generation of tension in liquids is the Berthelot Tube (Berthelot, 1850). Other controlled

techniques to generate tension include: metal bellows (Vincent, 1941); centrifuge (Reynolds, 1878; Briggs, 1950); Acoustic radiation (Ellis, 1955).

The Berthelot tube is a glass or steel tube which contains the liquid to be tested. The tube is sealed leaving a small air bubble inside. By gently warming the sealed tube the water expands increasing the pressure and forcing the air bubble to dissolve. At that stage the water fills the tube completely. By cooling the tube slowly, the water adheres to the walls of the tube, and a negative pressure is generated. When rupture occurs (*i.e.* cavitation) an audible click is heard and a bubble appears in the tube. The tensile strength is calculated by assuming that the volume modulus of the expanding liquid is the same as measured under compression and by assuming that it is possible to seal the container and maintain zero pressure. More recently the sealing pressure has been measured directly (*i.e.* without assumptions) showing that it is not zero. The apparently high tensile strength values obtained for water by early researchers is due to the incorrect assumption of zero pressure at the instant of filling.

The first direct measurement of tensile stress generated using the Berthelot tube was made by Meyer (1911). He used the interesting apparatus shown in figure 3.5. It represents a Berthelot tube, with a mirror fixed to a capillary helix at one end of the tube. It was filled with water, calibrated in the positive range and extrapolated to the negative range. Measurements were made with the aid of a beam of light focussed on the mirror. Evans (1979) and Henderson and Speedy (1980) used similar techniques to generate and measure tensile stress in water.

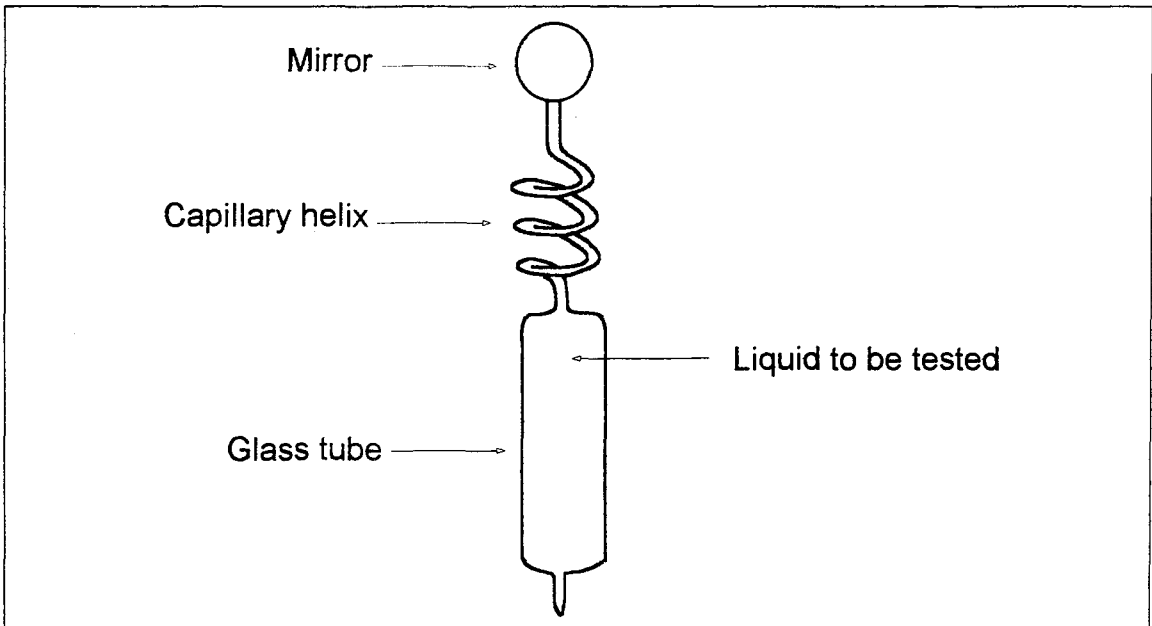


Figure 3.5 - Meyer's apparatus for generation and direct measurement of the tensile strength of water.

The use of Electric transducers was introduced by Chapman *et al.* (1975). They measured tension using a strain-gauged pressure transducer connected to one end of the Berthelot tube. The transducer was calibrated in the positive range and extrapolated to the negative range.

Table 1 presents results of direct measurement of tensile stress in water obtained using the Berthelot tube. The values of maximum tensile strength found are extremely variable.

Berthelot Tube Type	Tensile Strength (MPa)	Reference
Glass	-3.4	Meyer (1911)
	-16	Henderson and Speedy (1980)
Steel	-1.3	Rees and Trevena (1966,1967)
	-1.2	Chapman et al. (1975)
	-3	Richards and Trevena (1976)
	-4.6	Jones et al. (1981)
	-17	Ohde et al. (1991)

Table 1 - Maximum tensile strength in water obtained using the Berthelot technique of tension generation.

The variability of the tensile strength of water observed in table 1 is a reflection of the complexity of the problem. The tensile strength that is measured is probably due to the force of adhesion between the liquid and the surface of the container. This adhesion depends on the cleaning procedures and on the degassing of the system. These two factors are dependent on the material used as container. It has also been suggested that ionization and cosmic rays can act as sources of nuclei (*e.g.* Trevena, 1987).

It is important to notice that the value presented in table 1 are maximum negative pressure obtained. A different value is obtained at each attempt, showing how random is the phenomena.

3.5. Avoiding cavitation

Undissolved gas is the basic source of reduction in the tensile strength of water from its theoretical values to the much lower values measured.

A soil suction measurement system is formed by a container (normally a transducer), porous stone and water which will be under tension. If cavitation is to be avoided, undissolved air cannot be present. It is very difficult to fill the system without entrapping air in microscopic

crevices on the wall of the container. To reduce the likelihood of trapping permanent undissolved air in the system, the following recommendations should be considered:

1. The use of de-aired water is important to avoid air saturation (boiling the water is a good technique).
2. The water and all surfaces within the measurement system must be extremely pure and clean (*e.g.* Henderson and Speedy, 1980).
3. The surfaces in contact with the water system must be as smooth as possible to avoid or reduce the number and size of crevices. The smaller the surface area the easier it is to avoid cavitation.
4. The system should be evacuated by vacuum application in order to remove the maximum amount of air entrapped into the crevices, though it is unlikely that all the air will disappear (*e.g.* Jones *et al.*, 1981).
5. The system should be cycled from positive to zero (or negative) pressure. It may help in dissolving persistent bubbles (*e.g.* Chapman *et al.*, 1975; Richards and Trevena, 1976).
6. Pre-pressurization of the system to high pressure is required in order to dissolve all the free air (*e.g.* Harvey *et al.*, 1944).

It is important to point out that cavitation can be delayed if the nuclei are stabilized against tension. The procedures above probably only stabilize the nuclei. In the case of soil suction measurement the stabilization of the nuclei should allow the measurement of a certain level of suction, before cavitation occurs. Cavitation will not occur if no cavitation nuclei are present.

3.6. The use of an ordinary pressure transducer for suction measurement

In order to better understand the phenomena involved, an attempt was made to use a ordinary pressure transducer.

A porous stone (15 bars air-entry value ceramic) was incorporated on to a Keller transducer (PR-27-100, 0-100 bars) using a special cap as shown in figure 3.6. The transducer was calibrated in the positive range and this calibration was extrapolated to the negative range. This can be strongly criticized, since there is no evidence to prove that the transducer should behave in the same way when under tension. The only confirmation of the calibration is when the system cavitate, at this moment the pressure drops quickly to near -100kPa and then goes slowly to zero. The calibration obtained for the transducer is presented in figure 3.7 (The transducer was energized using 5V)

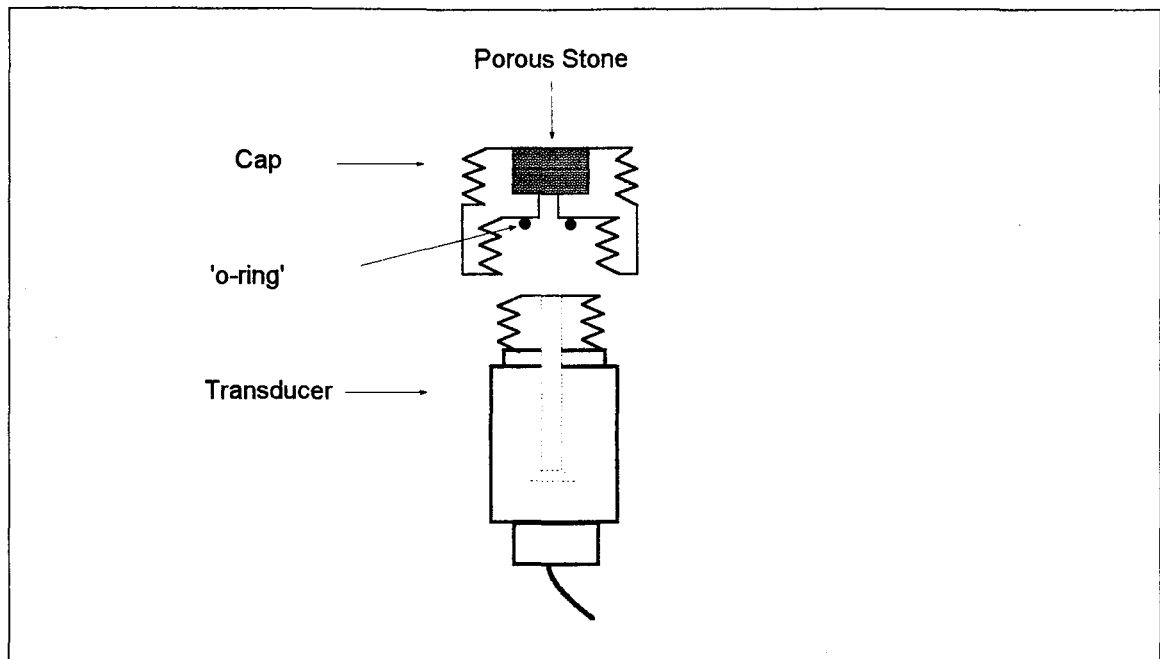


Figure 3.6 - Pressure transducer with the porous stone.

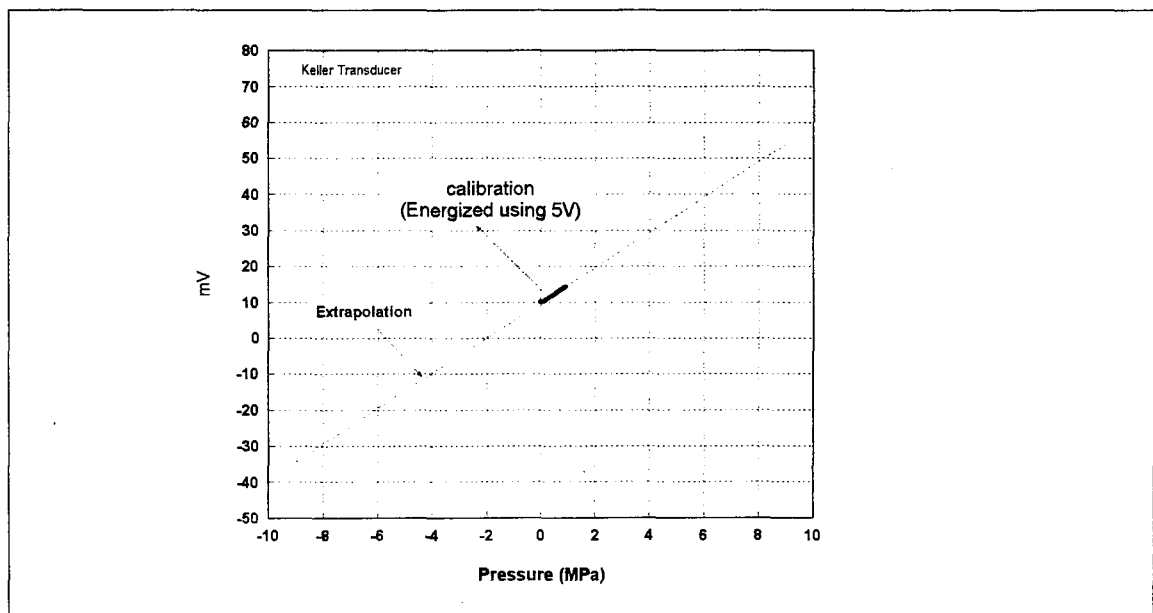


Figure 3.7 - Calibration of the transducer in the positive range.

The transducer was filled with water (purified by electro-osmosis and de-ionized) and a vacuum was applied to the system for few minutes. The cap containing the porous stone was left under vacuum with the same purified water for 48 hours and the cap was placed under silicon oil, allowing a space for the water go down. Because the oil and the water can not mix and they have different densities, the water will be removed from the stone and replaced by oil. After this process the oil was replaced by water using the same process. It is believed that this procedure may have induced a better wetting of the stone. After that, the cap was fitted to the transducer under water to avoid air entrapment. After fitting, a vacuum was applied for a few minutes. The system was then pressurized for 4 hours under a pressure of approximately 8MPa. After pressurization the porous stone was allowed to dry, thus generating suction. Figure 3.8 shows

the increase of the suction when the porous stone was allowed to dry continuously. In approximately 5 minutes, suction up to 1.6MPa was generated and registered. The response time is function of the compressibility of the system, but in this case also depends on the porous stone. When cavitation occurred the pressure increased instantaneously to approximately -1atm. The point at which cavitation occurs is easily identified, since the pressure drops immediately to a value near -1atm and then slowly go to zero.

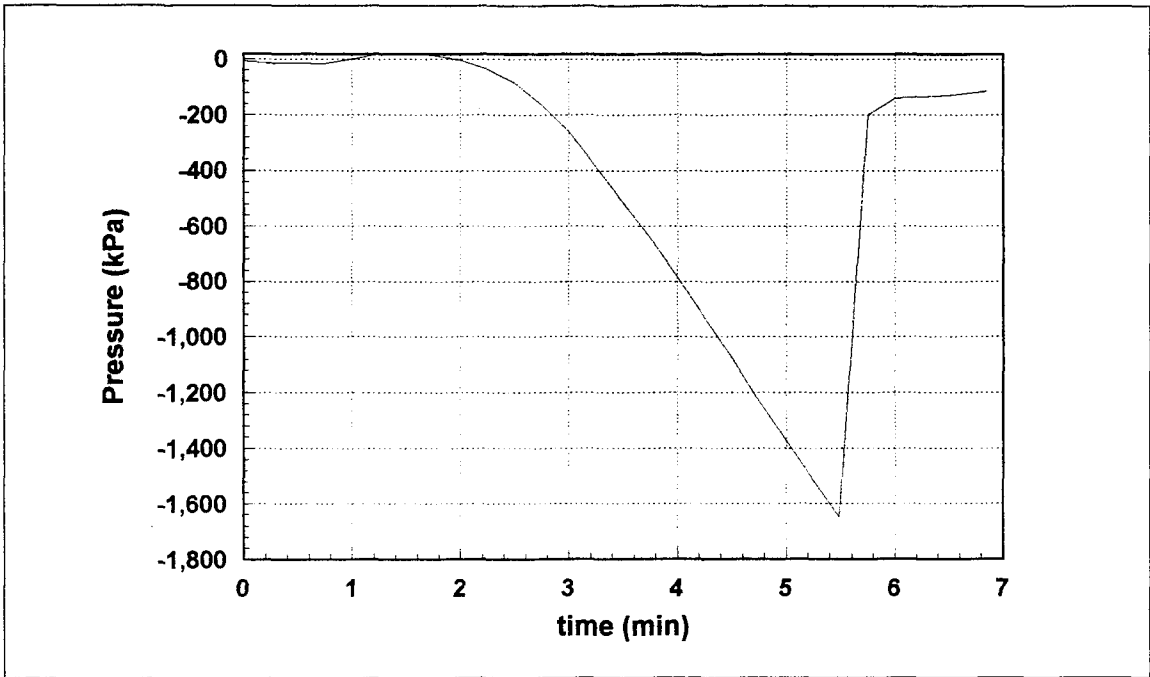


Figure 3.8 - Suction development and cavitation.

Figure 3.9 shows a test where a soil sample at a very low water content was placed in contact with the porous stone. Prior to placing the sample the system had been pressurized for 24 hours at 8MPa. A suction of approximately 3.3MPa was measured before cavitation occurred.

Figure 3.10 shows the results obtained in a test where the porous stone was allowed to dry to some value of suction before bringing the pressure back to zero by placing a drop of water on the porous stone. As before, the system had been pressurized at 8MPa for 24 hours before starting the test. The drying/wetting procedure was repeated five times. It is clear that the pressure returns to zero only if no cavitation occurs. On the fifth occasion, the drop of water was wiped off before the pressure reached zero. Three cycles were obtained in this way. The stone was then covered and the pressure was constant for about 8 minutes at -1.5MPa. The porous stone was allowed to dry again, until -1.8MPa and another drop of water was placed on it. By drying one more time the pressure went down to -2MPa and held for 1 minute. The stone was uncovered and the pressure went to -3.7MPa. A drop of water increased the pressure, and before it reached zero, a reduction in pressure was again generated. This time the pressure reached -2.3MPa and then cavitation occurred in the system. This test showed that the transducer can respond very well to changes in pressures in the negative range.

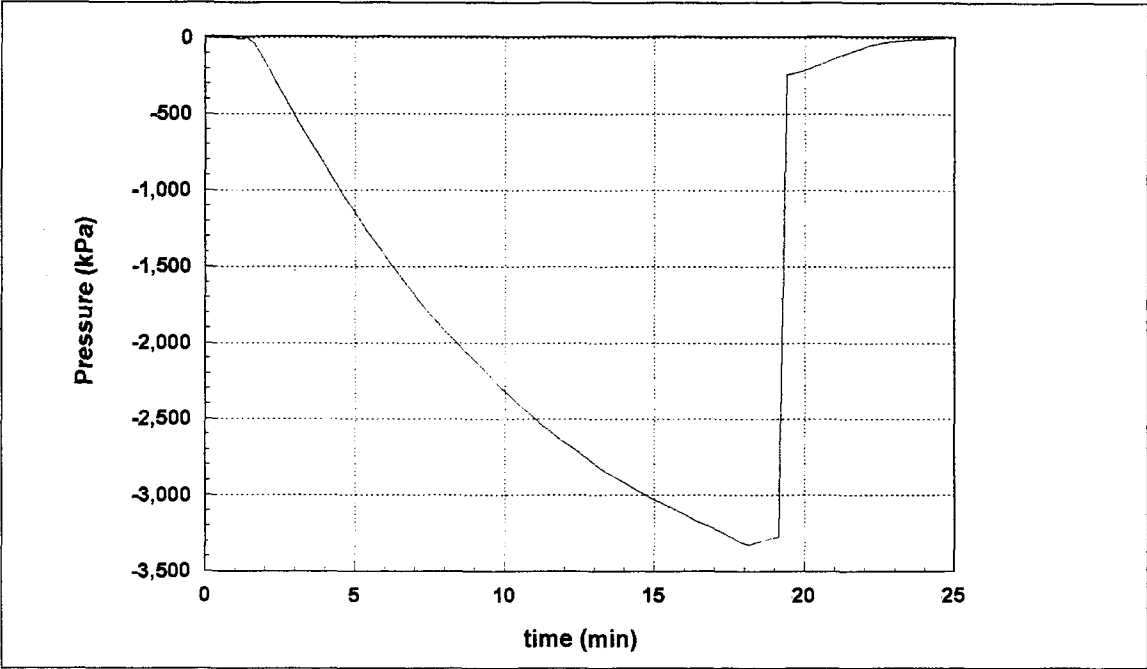


Figure 3.9 - Suction development and cavitation.

Following the recommendations given, it is possible to reduce the probability of cavitation in suction measurement systems without using a small volume of water inside the measurement system . However, there is little information on the time that a system with a large volume of water inside a transducer (as used) can sustain a high suction.

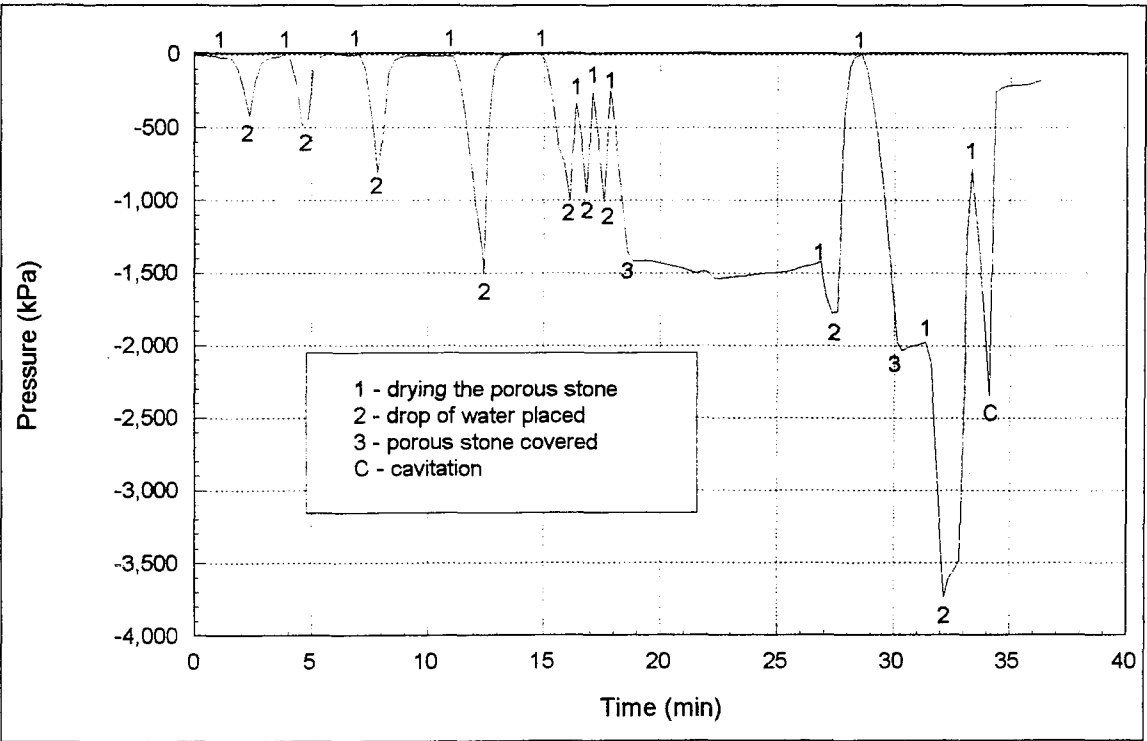


Figure 3.10 - Suction development and cavitation.

3.7. Conclusions

Suction measurement is a multidisciplinary subject. The lack of integration among the sciences involved has delayed the development of direct suction measurement in soils. Although the process of cavitation is not very well understood, it is possible to use the ability of water to sustain tension and in this way measure suction directly.

The use of a small volume of water in the suction measurement system is the easiest way to avoid cavitation. However, the minimum volume possible is limited by the displacement of the diaphragm of the transducer.

Cavitation will not occur if the system is free of cavitation nuclei.

One point that should be taken into account in future research is internal flow inside the measurement system. The pressure gradient generated when measuring suction is very high. It is due to the difference in pressure between the soil and the measurement system. The porous stone has an important role in this flow. When the porous stone is left drying the gradient generated is small and the flow is probably non turbulent.

The characteristics of the interface used between the soil and the measurement system has to be investigated, and aspects such as the air entry value of porous materials has to be better understood for a situation that differ from the one observed on the pressure plate.

Another important factor to be investigated is the interaction between the measurement system and the soil. Water pressure measurement in soils requires an interface. The porous material isolates the measurement system from the soil sample. Care must be taken to avoid osmotic effects between the system and the soil through the porous stone, which can have some osmotic efficiency (see section 7.1.2).

The calibration of the system has to be improved. A transducer that allows pressure to be applied from both sides is probably the best way to get accurate calibrations.

The final remark has to be one given by Dr. Yount in 1988, who said that the subject of bubble formation is associated with "*amusement, beauty, mystery and surprise*" and continues saying "*... In spite of the great effort and great progress that has been made in recent years, these basic elements have not changed. There are still mysteries to be solved, and no doubt there are still many surprises just over horizon. Above all, there is beauty and delight awaiting those who venture forth.*"

CHAPTER 4

Filter Paper Method of Suction Measurement

4.1. Historic

Shull (1916) was probably the first to use the absorption phenomenon as a tool to measure suction. Based on the discovery of semi-permeable membrane coats on seeds by Brown (1907) and Schröder (1911), Shull used a specially selected seed as an absorbent material. His intention was to measure "... the force with which particles of soils of varying fineness retain moisture at different degrees of dryness". Shull (1916) pointed out that the semi-permeable characteristic of the seed is not important. This aspect was used during the calibration of the seeds. For seeds with a semi-permeable membrane the calibration is performed by osmotic means and for seeds without the semi-permeable membrane the vapour pressure method is used.

The calibration of the seeds consists essentially of measuring the equilibrium water content of the air-dry seeds over different concentrations of sulphuric acid. Shull emphasised that the space of air left in the system to be brought into equilibrium with the solution vapour pressure is very small, and it seems that the whole system of liquid, air and seed came to an equilibrium in the time of the experiment (15 days), except possibly in the case of pure water. During the suction measurement, after the seeds and the soil had reached an equilibrium, the seeds were weighed and the water content determined. By using a calibration curve, which related the water content of the seeds to the vapour pressure, it was possible to obtain the suction of the soil at a particular condition. The main source of error was concluded to be evaporation during the handling of the seeds after the equilibrium.

Using the absorption concept, Hansen (1926) made use of filter papers to obtain the soil suction. Filter papers saturated with sugar solution of previously determined vapour pressure were put in a closed environment with the soil sample, but without contact with it. After an equilibrium time the filter paper is weighed and depending on whether the paper loses or gains weight, the suction is higher or lower than the corresponding vapour pressure of the sugar solution used. The method does not take into account the capillary effect in the filter paper and assumes that the corresponding suction is given only by the vapour pressure of the solution, measured with a flat air-solution interface.

Probably the first to use a filter paper as an absorbent material, without any solution previously absorbed in it, was Gardner (1937). The method adopted by Gardner was essentially the same

as that used by Shull (1916). The use of filter paper as an absorbent material gave more reliability to the measurement, since the industrial process involved in the production of the paper ensures that the absorption characteristics of the filter paper are essentially the same, and are independent of the box or batches used (*e.g.* Fawcett and Collis-George, 1967).

4.2. The Filter Paper Method

4.2.1. Principle

When a wet soil is placed in contact with a porous material with the power to absorb water, the water will pass from the soil to the porous material until an equilibrium is reached. The operation of the filter paper method is based on this principle. If a suction versus water content relationship is determined for the porous material, the soil suction can be obtained by referring to the calibration curve. The equilibrium state gives the same suction in both materials (soil and porous material) but different water contents. The equilibrium time is very important in obtaining a correct measurement.

Normally an 'ash-free quantitative filter paper', type II, such as Whatman N° 42, or Schleicher & Schuell N° 589 white ribbon is used. The filter paper should be used directly from the box (*i.e.* in an air-dry state) (*e.g.* Fawcett and Collis-George, 1967; McQueen and Miller, 1968; Chandler and Gutierrez, 1986; Greacen et al, 1987). The ASTM standard for the filter paper method (D5298-92) suggests that the filter paper should be dried in the oven for at least 16 hours before use. This procedure may affect the absorption characteristics of the paper.

4.2.2. Calibration

4.2.2.1. Equipment necessary

The materials necessary to calibrate and use filter paper as a suction measurement sensor are as follows.

- 1 - An analytical balance accurate to at least 0.0005g.
- 2 - Small lightweight weighing containers (*e.g.* flat plastic bags with a seal or another container that can easily be sealed).
- 3 - Tweezers and scissors.
- 4 - Oven (105°C).
- 5 - Filter paper (*e.g.* Whatman N° 42, Schleicher and Schuell n° 589 white ribbon). A calibration curve is required for each type of filter paper used.
- 6 - In some cases, to inhibit biological decomposition a treatment is required (using 0.005% HgCl_2 or similar). Hamblin (1981) and Chandler and Gutierrez (1986) observed that the lack of treatment does not alter the results. The decomposition depends on the type of

soil and equilibrium time. Equilibrium times greater than 30 days, in non organic soil, can induce bacterial attack.

4.2.2.2. Procedures

The filter paper used in this work was the Whatman N° 42 brand. The filter paper to be used is air-dry and is taken directly from the box (the relative humidity in the laboratory is approximately 60%). As the initial water content of the Whatman N° 42 is approximately 6%, this allows suction measurement from zero to approximately 29MPa. This is the maximum soil suction with which the filter paper can absorb water. The filter paper can be used in an initially wet state, though a specific calibration is required for this procedure (e.g. Gardner, 1937).

Several methods may be used to generate the suction for calibration purposes. The main techniques and their usual range of suction are presented in table 4.1.

Technique	Range used for filter paper calibration	Comments
Suction Plate	0 - ≈ 1 atm	Direct suction generation
Field Samples	0 - ≈ 2MPa	Uses the ability of plastic soils to sustain the equivalent mean effective stress when unloaded under undrained conditions. The matrix suction is assumed to be numerically equal to the mean effective stress of the sample in the ground.
Oedometer Samples	0.1MPa - ≈ 2MPa	Assumes truly one-dimensional and undrained unloading. The consolidation stress applied should be numerically equal to the matrix suction in the unloaded sample.
Pressure Plate	0 - 1.5MPa	Uses the axis translation technique (see section 2.2.5).
Desiccator	≈ 0.5MPa - 30MPa	A salt solution, with a known vapour pressure, is used. The filter paper is placed in a closed environment with the solution. The transference of water is by vapour. The equilibrium is reached when the affinity for water of the salt solution used and the filter paper are equalized

Table 4.1 - Techniques used for the calibration of filter papers.

From the methods presented in table 4.1 the only one in which the water is transferred to the filter paper by vapour is the desiccator. The main consequence of that is related to the equilibrium time (see section 4.3.3.2 and 7.1.1).

The calibration procedure consists of allowing the filter paper to reach equilibrium with a known suction. After the equilibrium time is reached the filter paper is weighed and oven dried. The water content is then obtained and related with the suction generated. Several measurements are necessary to cover the necessary range of suction. The choice of the method for generating the suction depends on the level of suction required.

One of the most important aspects for obtaining a good suction measurement is to ensure that the filter paper, after equilibration, is removed from the closed environment without losing too

much moisture. Gutierrez (1985) and Duran (1986) showed that when the filter paper is removed from the equilibration environment, it loses water at a rate of approximately 1.5% per minute. This was for the case of a filter paper drying from a water content of 34.5%. When removing the filter paper from the oven it absorbs moisture from the air. The absorption rate, in the short term, may be similar to the drying rate depending on the laboratory environment. The evaporation may be influenced by the initial water content. For low suction measurements the drying effect is greater. Schreiner (1988) suggested the use of flat plastic bags to weight the filter paper after removing it from the soil environment, and also when weighing the paper from the oven.

4.2.2.3 - Existing Calibrations

Most of the calibrations curves for filter paper consist of two parts that are clearly identified on the calibration curve. At high suctions, the moisture is retained as a film adsorbed to the fibre surfaces of the filter paper, while in the low range moisture is absorbed by capillary or surface tension forces between fibres (ASTM- D5298-92).

Gardner (1937) presented a calibration curve for Schleicher & Schuell N° 589 white ribbon filter paper (figure 4.1). The calibration represents an average of drying and wetting papers on the higher range of suction ($>1\text{MPa}$) and only drying papers on the lower range of suction. Gardner pointed out that at low suctions the calibration curve overestimates the suction, since only drying papers were used. The filter papers were washed in 0.2% of HgCl_2 and dried before use. This procedure was adopted with the aim of avoiding biological decomposition.

Fawcett and Collis-George (1967) presented results of a calibration for Whatman N° 42 filter paper. They also treated the paper with HgCl_2 solution to stop fungal and bacterial growth. The filter papers were calibrated from air-dry condition and hence, used the wetting path. Figure 4.2 presents the calibration points obtained by Fawcett and Collis-George (1967). It can be seen that the relationship is non-linear and that a bi-linear relationship can be adopted. Filter papers from different batches were analysed and a reasonable consistency in the results was observed. They pointed out that the hysteresis envelop is different depending whether the filter paper is absorbing or losing water.

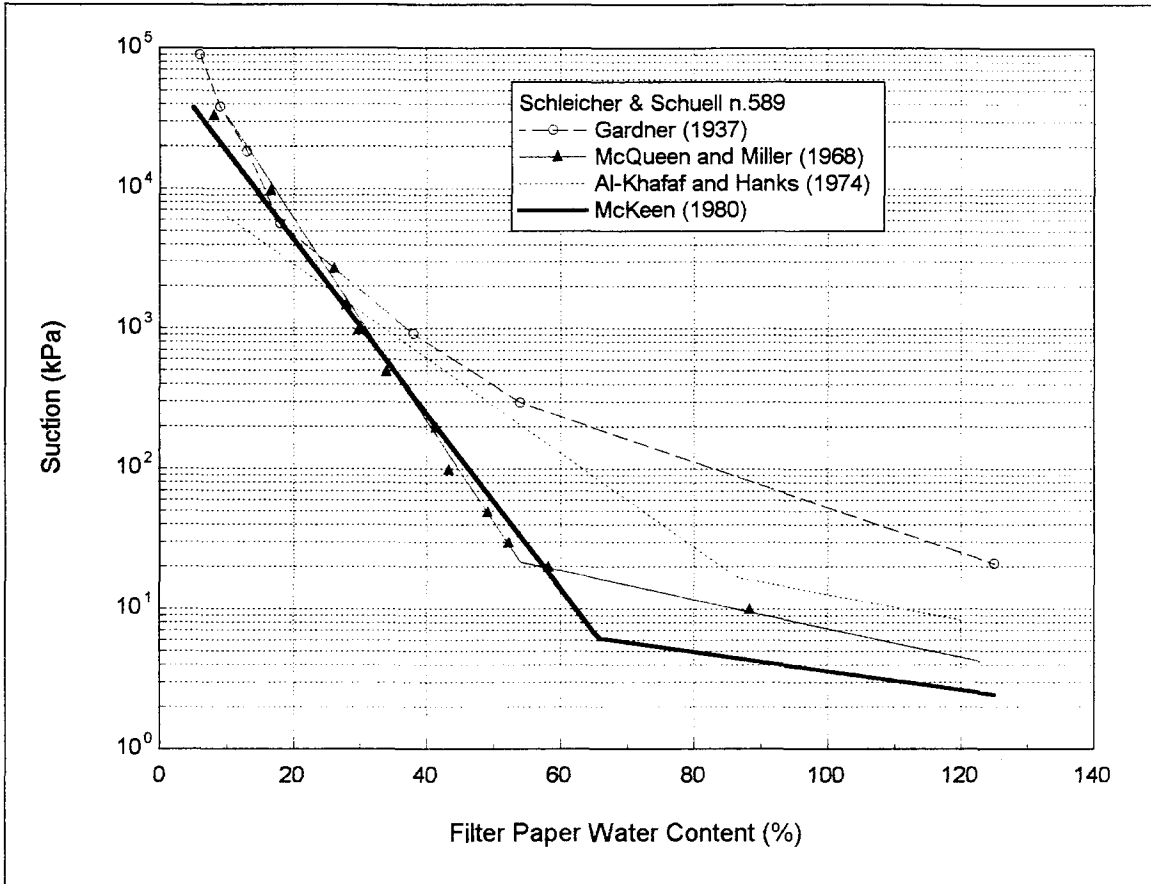


Figure 4.1 - Calibration Curves for Schleicher & Schuell N° 589 Filter Paper.

McQueen and Miller (1968) calibrated the Schleicher & Schuell N° 589 white ribbon filter paper, the same as used by Gardner (1937). The filter papers were treated against biological decomposition and allowed to air-dry before use. McQueen and Miller (1968) used samples obtained in the field, with suction estimated according to its height above the water table. In using this technique, the fact that the filter paper will absorb water and hence, increase the suction in the soil has to be considered. The volume of the sample has to be such that this effect is minimised. The pressure membrane, pressure plate and desiccator were also used as calibration methods. When compared with Gardner (1937), the calibration curve obtained by McQueen and Miller (1968) (see figure 4.1) showed a great difference in the lower suction range.

Al-Khafaf and Hanks (1974) also used the Schleicher and Schuell N° 589 filter paper and obtained the calibration curve presented in figure 4.1. The method used by them involved a soil sample which was equilibrated with the filter paper. It seems that the equilibrium time was 2 days. The suction of the soil sample was measured using a psychrometer, induced with a pressure plate or determined from a known height above the water table. They presented results classified according to the type of contact the filter paper has with the soil (e.g. "good contact", "uncertain contact" and non contact). The calibration curve presented in figure 4.1 refers to the data from the filter paper in "good contact". In this case ("good contact") it seems that the use of the psychrometer for low suction measurement can overestimate the suction,

since it will be measuring total suction, while the filter paper is absorbing water by capillary flow and hence measuring matrix suction (see section 4.2.3.1).

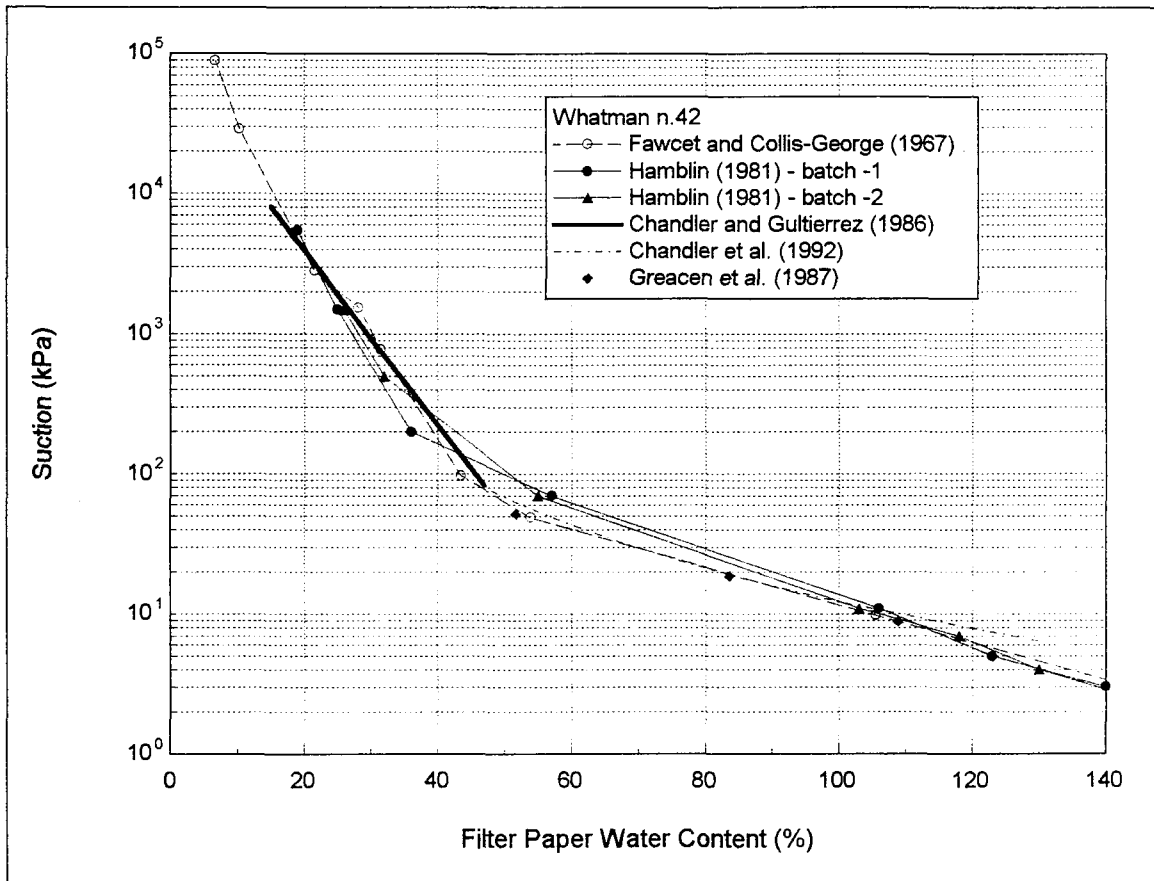


Figure 4.2 - Calibration Curves for Whatman N° 42 Filter Paper.

McKeen (1980) presented another calibration curve for the Schleicher and Schuell N° 589 filter paper which is shown in figure 4.1. The calibration curves obtained by McQueen and Miller (1968) and McKeen (1980) are similar while the one obtained by Gardner (1937) and Al-Khafaf and Hanks (1974) seems to overestimate the values of suction.

Hamblin (1981) performed calibrations on two batches of Whatman N° 42 filter paper. One of the batches was treated against biological decomposition and the other batch, obtained two years later was untreated. The results showed that for the period of time used for equilibrium (maximum 36 hours) it was not necessary to treat the filter paper. As can be seen in figure 4.2, the results obtained by Hamblin (1981) were in good agreement with the calibration performed by Fawcett and Collis-George (1967).

Chandler and Gutierrez (1986) presented a calibration curve for Whatman N° 42 filter paper which includes their own results and also those from Fawcett and Collis-George (1967) and Hamblin (1981). The technique used for generating their data was to consolidate soil samples in the oedometer to a known effective stress and to unload them under undrained conditions. The matrix suction generated was assumed to be equal to the mean effective stress. The range of

suction generated with this method was from approximately 6 kPa up to 2000 kPa. However, for the purpose of determining the calibration curve, only values above 80kPa were considered. At that time they concluded that their results showed a considerable variability below 80kPa and the method used was unreliable at these lower stresses. Figure 4.3 presents the results obtained and the calibration curve adopted. Later, a calibration curve for suctions below 80kPa was presented by Chandler *et al.* (1992) and the regression determined is shown in figure 4.2. This calibration was obtained using pressure plate, triaxial samples, oedometer samples and in the limit by submerging the filter paper into distilled water. The calibration also includes points obtained by Fawcett and Collis-George (1967) and Hamblin (1981). In figure 4.3 it can be observed that the data from Gutierrez (1985), for suctions below 80kPa, is located well below the calibration curve obtained by Chandler *et al.* (1992). The regressions obtained are expressed by the following equations.

$$\text{For filter paper water content (W)} \leq 47\% \quad \text{Suction (kPa)} = 10^{(4.84 - 0.0622W)} \quad \{4.1\}$$

$$\text{For filter paper water content} > 47\% \quad \text{Suction (kPa)} = 10^{(6.05 - 2.48 \log W)} \quad \{4.2\}$$

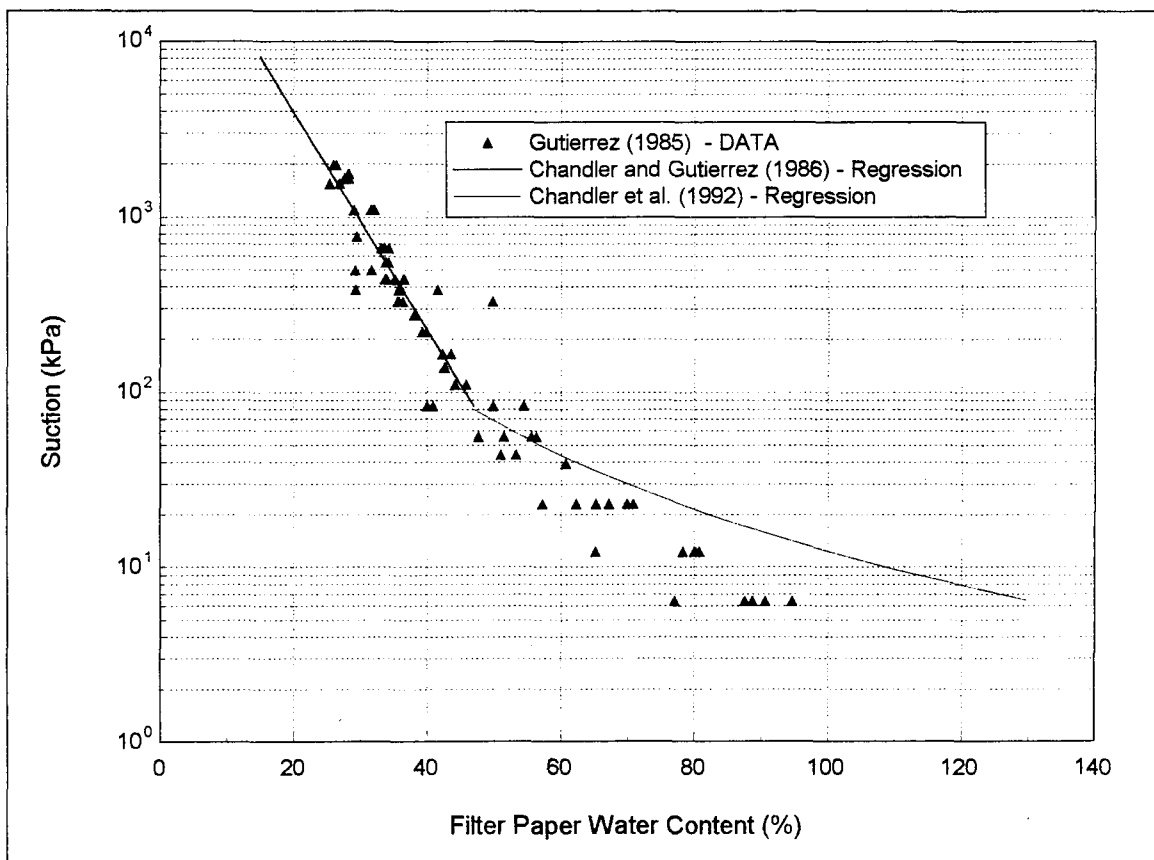


Figure 4.3 - Calibration curve obtained Chandler and Gutierrez (1986) and Chandler *et al.* (1992) together with Gutierrez data for the low range of suction.

Greacen *et al.* (1987) obtained three more points for the calibration of Whatman N° 42 filter paper (see figure 4.2) which agree very well with previous data, and in particular with Chandler *et al.* (1992).

When a specific type of filter paper (Whatman N° 42, Schleicher and Schuell N° 589, Whatman N° 1, *etc.*) is calibrated it is assumed that all papers with the same specification will behave in a similar way. The industrial processing of the absorbent material used has to be such that its ability to absorb water does not change with batches. This aspect has been investigated by Fawcett and Collis-George (1967) and in some extent by Hamblin (1981). Their work showed that filter papers from different batches can be considered to have the same characteristics for suction measurement. Sibley *et al.* (1990) performed a statistical analysis, on a series of results in order to investigate the characteristics of Whatman N°42 filter paper between boxes. The tests were performed with boxes of filter paper from the same batches. No significant differences were detected on filter papers from the different boxes.

El-Ehwany and Houston (1990) presented a calibration curve for the Whatman N° 1 filter paper (this is a *qualitative* filter paper with an ash content of 0.06%). They questioned whether the previous calibrations were valid for total suction measurement and so performed a calibration using salt solutions and pure water; the water transfer occurring only by vapour. The relationship between relative humidity and filter paper water content was observed to be linear in the range tested. However, the suction showed an strong sensitivity to changes in filter paper water content for water contents higher than approximately 21%. Figure 4.4 presents the data obtained by El-Ehwany and Houston and the calibration curve adopted by them; the equilibrium time used was seven days.

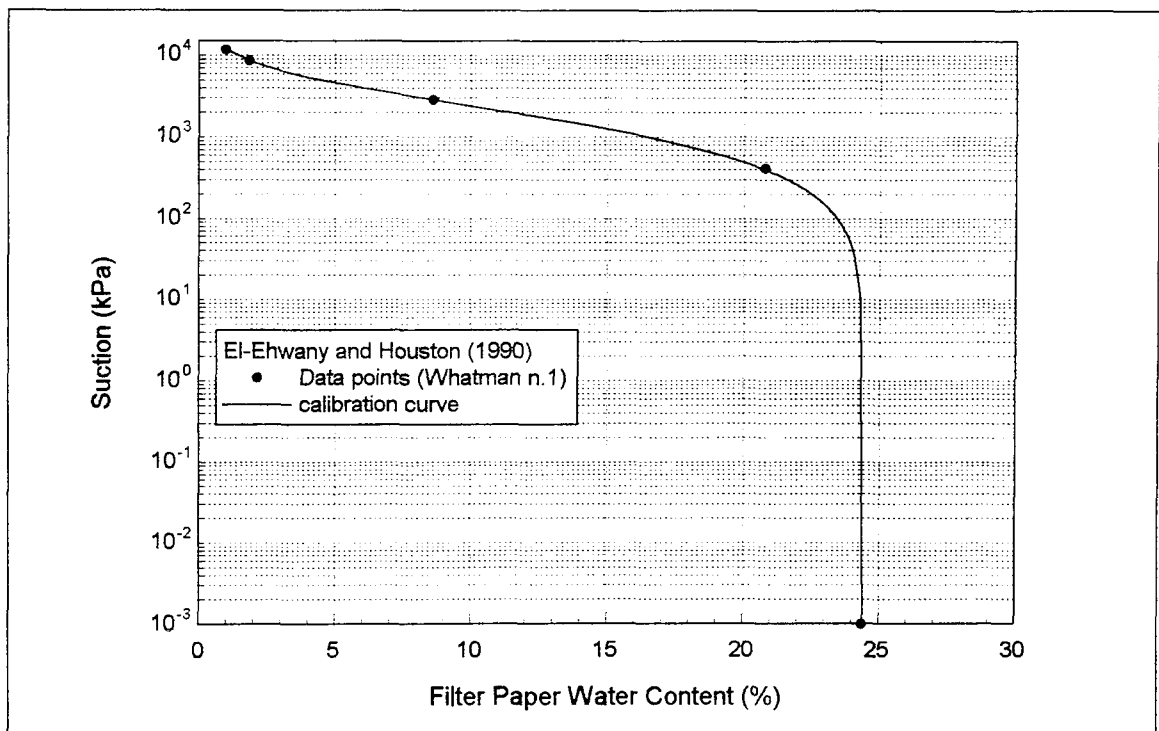


Figure 4.4 - Calibration Curve for Whatman N° 1 Filter Paper Using non-contact technique for the whole range of suction.

Sibley and Williams (1990) performed calibrations on five different absorptive materials for suction measurement (Whatman N° 42, unwashed dialysis tubing, washed dialysis tubing,

millipore MF 0.025µm and millipore MF 0.05µm). According to their sensitivity the materials were classified as shown in table 4.2. Based on their results Sibley and Williams (1990) suggested that among the materials tested the Whatman N°42 has good absorptive characteristics over the entire range tested (0 to 195MPa).

Material	Range of higher sensitivity
Whatman N° 42	0 to 30 MPa
Unwashed dialysis tubing	10MPa to 100MPa
Washed dialysis tubing	1000kPa to 10MPa
Millipore MF 0.025µm	30kPa to 300kPa
Millipore MF 0.05µm	30kPa to 1000kPa

Table 4.2 - Absorbent material classification according to sensitivity (Sibley and Williams , 1990).

Miller and Nelson (1992) presented a calibration curve for another type of filter paper, Thomas Scientific N° 4705-F10 (Thomas quantitative grade papers, pore size equal to 3µm and ash content = 0.01%). In the calibration of this filter paper only salt solutions were used (KCl). The filter paper was allowed to equilibrate with the salt solution in a constant temperature chamber for 7 days (Miller, 1994). The data and the calibration curve adopted by Miller and Nelson (1992) are presented in figure 4.5, together with the calibration obtained by Chandler and Gutierrez (1986), for reference.

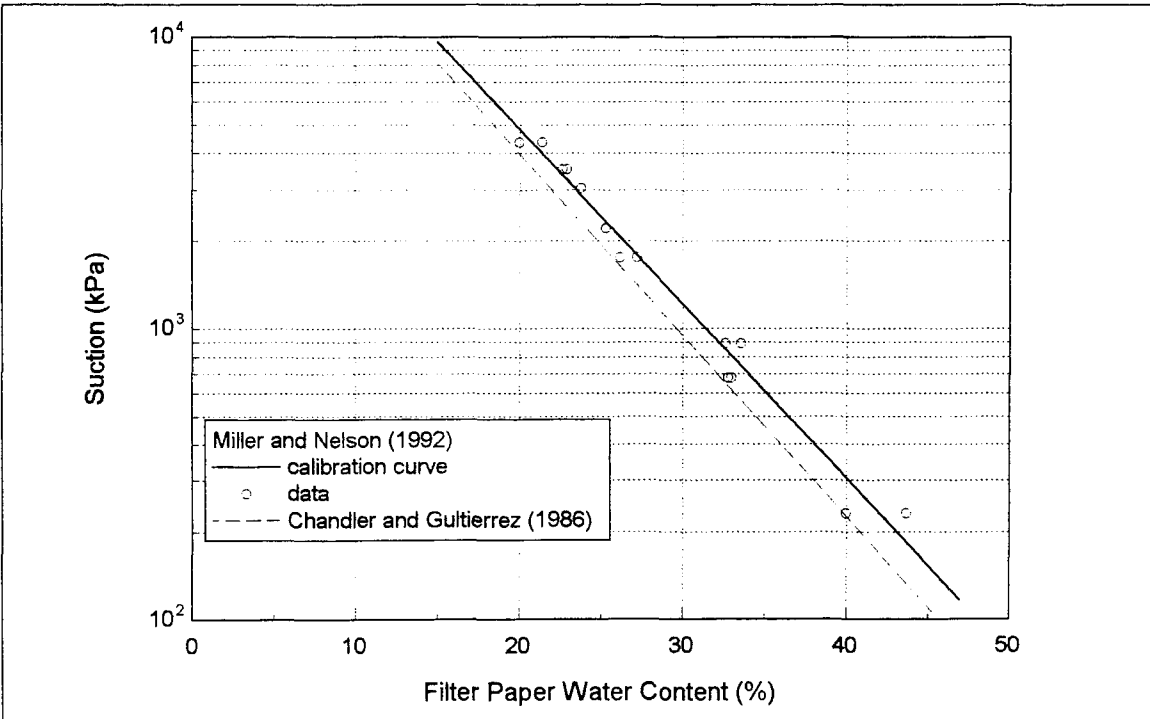


Figure 4.5 - Calibration data and adopted regression for Thomas Scientific N° 4705-F10 filter paper.

In all calibrations it is necessary to know the value of the action that has been applied, and in filter paper calibrations it is fundamental to know the actual suction generated in order to correlate it with the filter paper water content. Duran (1987) investigating the effect of not having good contact between filter paper and London clay samples, presented some results in which the samples were consolidated in the oedometer and unloaded under undrained conditions. A filter paper was then placed, without contact with the soil, to absorb water by vapour transfer, hence measuring total suction. Knowing the mean effective stress it is possible to infer the effect of salts in the sample, since the difference between the mean effective stress in a saturated sample (matrix suction) and the total suction is the osmotic suction. The equilibrium time used by Duran (1987) was 7 days. The filter paper water contents obtained by Duran (1987) (non-contact, then measuring total suction) were directly compared with the mean effective stress applied in the oedometer (matrix suction in a saturated sample). However, it is clear that the suction measured with the filter paper out of contact with the soil cannot be related to the mean effective stress applied in the oedometer, since this value corresponds to the matrix suction generated when the sample is unloaded. By assuming a constant value of osmotic suction for London Clay (*e.g.* 250 kPa) and adding it to the matrix suction generated, the results agree reasonably with the calibration curve obtained by Chandler and Gutierrez (1986) as can be seen in figure 4.6. It is important to point out that the use of soil samples for calibration purpose using non-contact technique is not recommended, since the osmotic component is usually unknown. Hence, Duran's data cannot be used as calibration points for the filter paper.

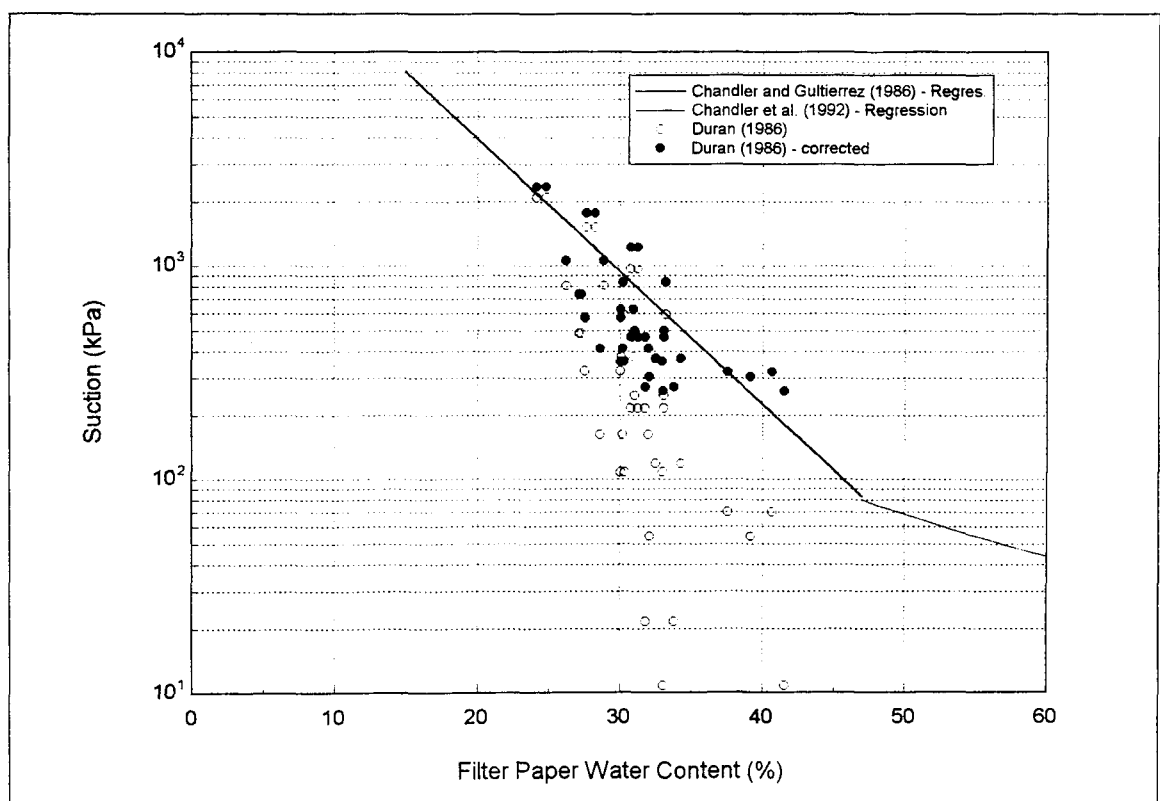


Figure 4.6 - New Interpretation of the results obtained by Duran (1987)

The ASTM "Standard test method for measurement of soil potential (suction) using filter paper" (D.5298-92) describes the filter paper method and presents two calibration curves, one for Whatman N° 42 and another for Schleicher & Schuell N° 589. The two calibrations are based in results obtained by Fawcett and Collis-George (1967) and McQueen and Miller (1968), respectively. Their data were statistically analysed by Greacen (1987) and the calibration curves obtained adopted by the ASTM (see figure 4.7). For comparison, the calibration suggested by Chandler and Gutierrez (1986) and Chandler *et al.* (1992) are also represented in figure 4.7.

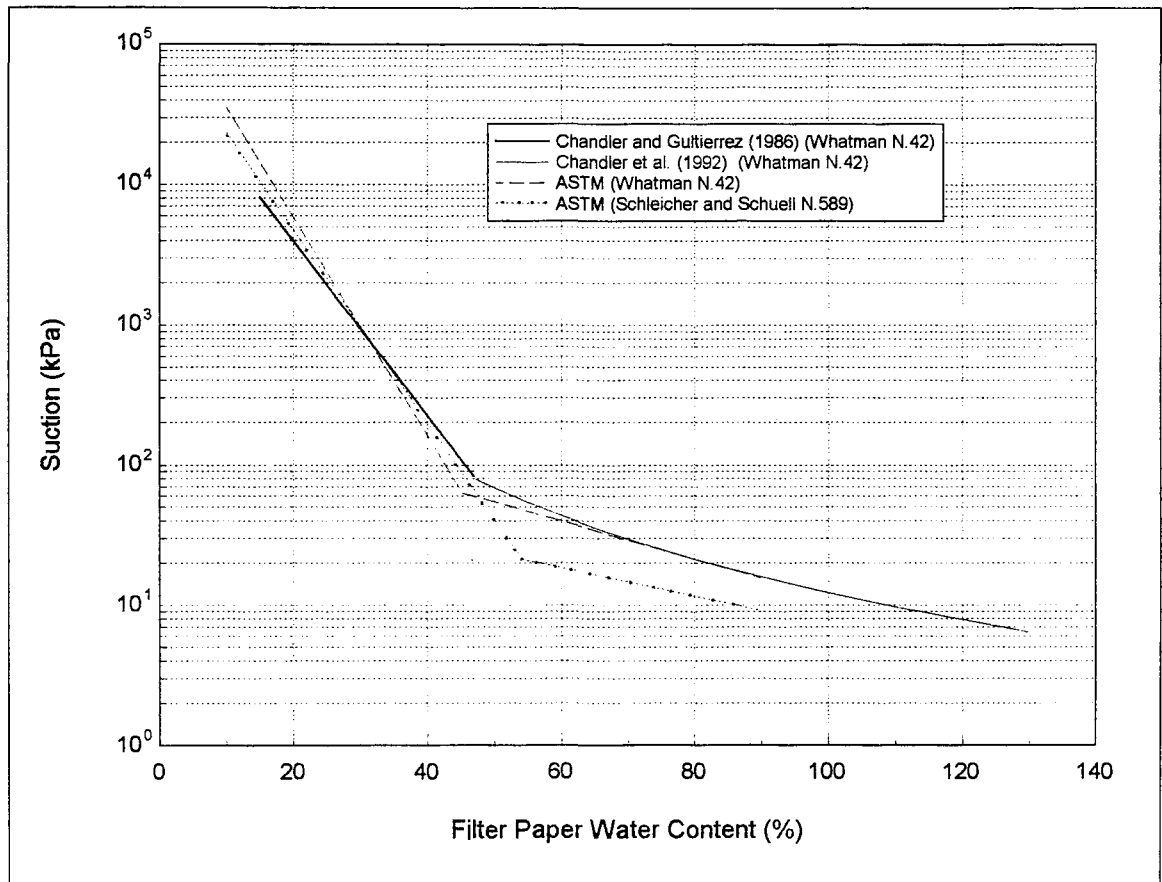


Figure 4.7 - Calibration curves adopted by the ASTM for Whatman N° 42 and Schleicher & Schuell N° 589.

4.2.3 - Important Aspects of the Filter Paper Method

4.2.3.1 - Moisture Flow

All suction measurement techniques require an exchange of water between the soil and the measurement system. The system can absorb water from the soil or loose water to the soil. Usually the filter paper method is used with the paper absorbing water. The absorption can occur in two ways: by vapour flow (see figure 4.8a) or by capillary flow (see figure 4.8b).

In the vapour flow situation the molecules of water have to escape from the soil by overcoming the capillary forces in the soil and also the eventual osmotic forces that act due to the presence

of dissolved salts (see section 2.1.4). The air space left between the soil water and the filter paper provides a barrier to the salts, allowing only water vapour to flow (*i.e.* pure water).

Capillary flow occurs through the soil particles and filter paper fibres, without the water breaking its continuity. The capillary flow implies an interaction between the filter paper and the soil pore water (*i.e.* with salts *etc.*).

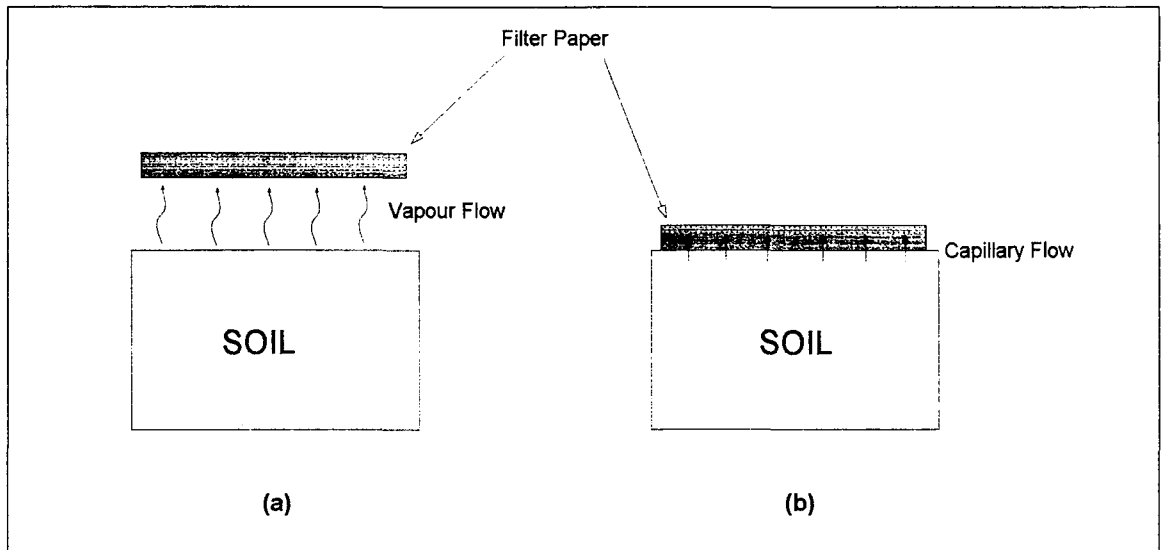


Figure 4.8 - Types of water flow from the soil to the filter paper.

If the flow occurs by vapour transfer only, the filter paper measures total suction since it incorporates the osmotic and capillary forces which hold the molecules of water. When the flow occurs by capillarity it is matrix suction that is measured. In this case the osmotic component does not act as an additional holding force to the water in its transfer to the filter paper.

It is common when measuring total suction to place the filter paper over a perforated inert disk to avoid contact with the soil water or with any other solution or solute. The flow of vapour through holes is studied by biologists who are interested in diffusion through pores (stomata) of plants. Figure 4.9 presents a schematic representation of vapour flow through holes. In figure 4.9a (from Noggle and Fritz, 1976), flow lines of water vapour from a circular water surface in an open environment are shown. The flow lines (indicated by arrows) intersect surfaces of equal water vapour concentration. The pattern shown in figure 4.9a is similar to that of vapour coming out from soil pores. In the particular case of a perforated disk, with different hole sizes, the pattern is more complicated, as shown in figure 4.9b (from Coult, 1973). The distance between the disk and a line of equal water vapour concentration, increases with increasing hole size for an open system. If a closed system is considered, the lines of iso-relative humidity should initially follow the same pattern as in the open system, since the relative humidity is usually low inside the equilibration system, and afterwards the relative humidity iso-lines should tend to an equilibrium with time. This time will depend, on factors such as the volume of the environment, initial relative humidity and temperature. When the time duration is less than the

equilibration time for the whole environment, the filter paper water content will depend on its distance from the source of vapour.

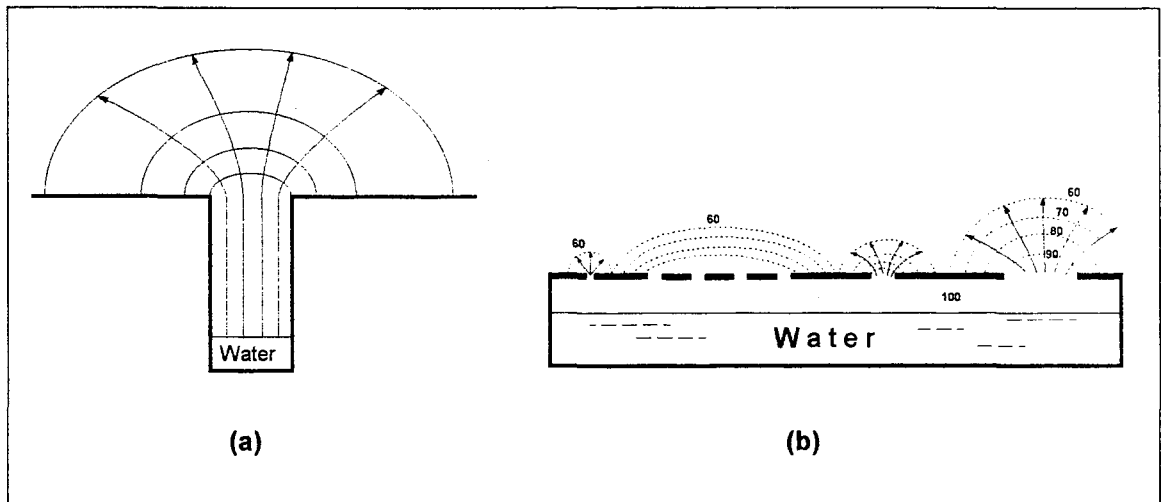


Figure 4.9 - Vapour flow through holes

4.2.3.2 - Contact and Equilibrium Time Effects

The contact between the filter paper and the soil sample is mentioned by several authors as one of the major problems of the filter paper method (e.g. Al-Khafaf and Hanks, 1974; Schreiner, 1988; Crilly *et al.*, 1991; Crilly and Chandler, 1993; Fredlund and Rahardjo, 1993).

Usually calibration curves are obtained using several methods to generate the suction. These techniques can be divided in two groups depending on whether there is contact between the filter paper and the water. At high suctions the filter paper is usually calibrated using techniques that do not allow contact between the filter paper and the water and this is referred to as a non-contact technique. At low suctions the filter paper is normally calibrated using a contact technique. It will be seen that the degree of contact effect is greatly influenced by the time of equilibration.

Greacen *et al.* (1987) presented a test where a strip of filter paper (Whatman N° 42) was allowed to absorb water from a source of water subjected to a suction by a suction plate. In figure 4.10 the results obtained by Greacen *et al.* (1987) are presented. It can be seen that the absorption rate is dependent on the suction; for higher suctions longer times are required for the water to flow a certain distance. This may therefore show that the existence of one contact between the filter paper and the soil water may be enough for the filter paper to absorb water.

For filter paper in contact with the soil water at low suction, Greacen *et al.* (1987) showed that most of the water is absorbed in the first minutes and then slows down and reaches an equilibrium in approximately 7 days. Figure 4.11 illustrates this behaviour and shows that the time of equilibrium is essentially independent of the level of suction for low suctions (<50kPa).

For non-contact filter papers McQueen and Miller (1968) presented some results showing the influence of the suction level on the equilibrium time (see figure 4.12). It can be observed that the lower the suction, the longer seems to be the equilibrium time for this non-contact method.

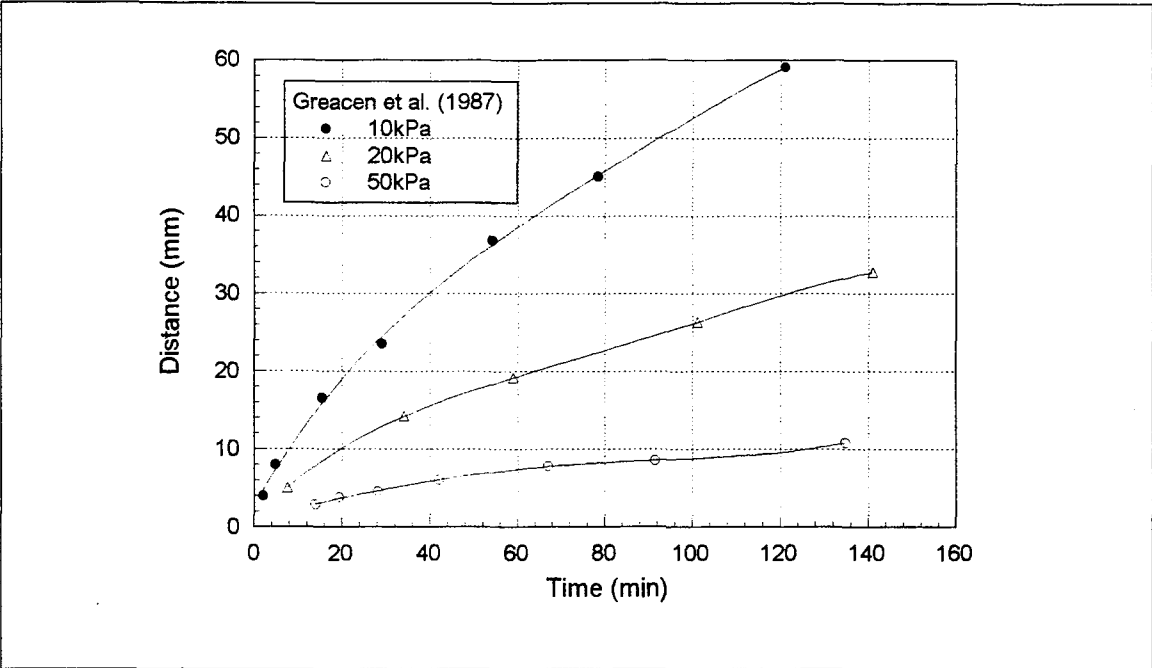


Figure 4.10 - Advance of wetting front at different suctions for Whatman N° 42.

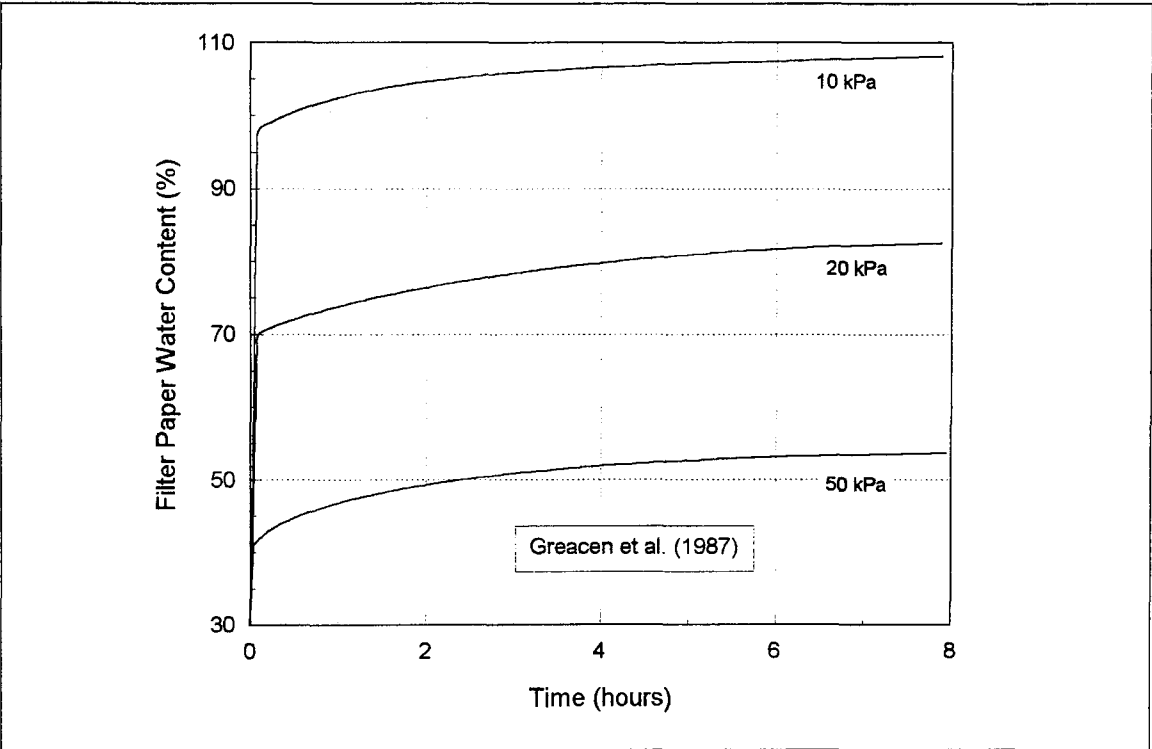


Figure 4.11 - In contact filter paper water content as a function of the equilibrium time for three different suction levels (Whatman N° 42). (from Greacen et al. ,1987)

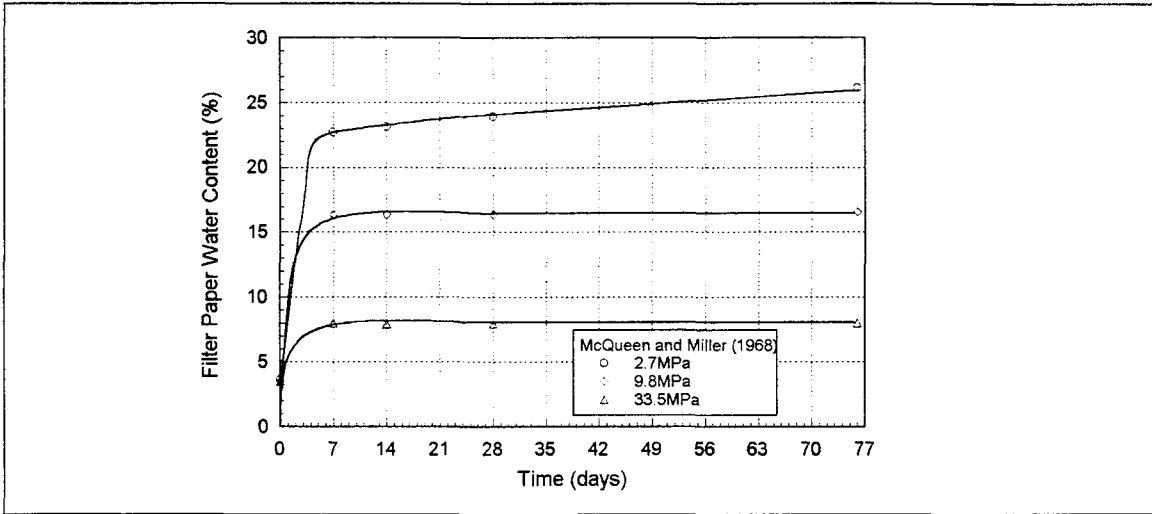


Figure 4.12 - Non-contact filter paper water content as a function of the equilibrium time for three different suction levels (Schleicher & Schuell N° 589).

Al-Khafaf and Hanks (1974) conducted a series of experiments to evaluate the effect of contact between the filter paper and the soil water. A comparison was made with filter paper without contact, filter paper with "uncertain contact" and filter paper in "good contact". Figure 4.13 illustrates how each of the contact conditions were obtained. The actual state of the filter papers at "uncertain" and "good contact" is very difficult to quantify. Al-Khafaf and Hanks (1974) seem to have used an equilibration time of only two days. Even though the equilibration time was short their calibration curve (see figure 4.1) indicates that for equal suction values their filter paper absorbed more water than those indicated by the calibration curves obtained by others (see section 4.2.2.3). Schreiner (1988) suggested that for total suction measurement, one week is not an adequate equilibrium time.

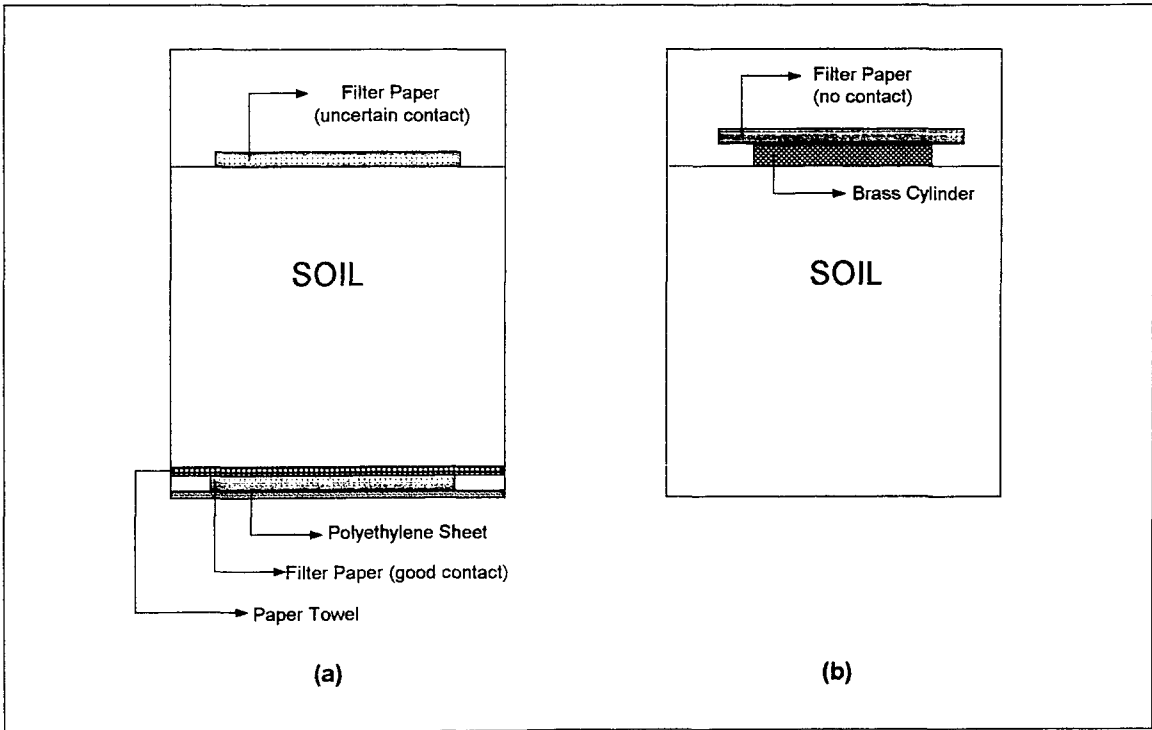


Figure 4.13 - Contact conditions for the filter paper (from Al-Khafaf and Hanks, 1974)

Lee and Wray (1992) questioned the use of the same calibration curve for total and matrix suction with the filter paper method. They suggested that the calibration curve determined using the non-contact technique is different from that of the contact technique. In their experiment, matrix suction was generated using a pressure plate. The measurement of total suction was made using the filter paper method and a thermocouple psychrometer. The tests were performed on soil specimens of known matrix suction, and the equilibrium time used was two weeks. The results of Lee and Wray presented in figure 4.14 suggest that the filter paper technique overestimates the suction when compared with the psychrometer. If the psychrometer results are considered, it could be concluded that the soil tested has no osmotic suction, since the matrix and total suction are similar. It is important to point out that the applied pressure was obtained using the pressure plate, thus generating matrix suction. The results between suction generated and measured would not be expected to agree unless the soil tested had no salts. The filter paper results suggest the existence of osmotic suction. The results indicate that there is a tendency towards agreement between psychrometer and filter paper results when the suction approach e.g. 500kPa. The equilibrium time used may not have been appropriate for the filter paper measurement of total suction. The results presented by Lee and Wray are not conclusive regarding to the possible restriction of the use of the calibration curve for total suction in the low range of suction.

Ridley (1993) also questioned the validity of the calibration curve at low suctions (below 1.5MPa) for non-contact filter paper measurement (total suction). Filter papers were left to equilibrate over salt solutions together with a thermocouple psychrometer. The water content obtained from the filter papers were compared with the calibration curve of Chandler and Gutierrez (1986) and the results indicate that the water content for an equivalent suction was lower than that given by the calibration curve. Ridley (1993) used a different equilibrium time for each experiment and also different distances between the source of vapour and the filter paper. In figure 4.14 it can be observed that the relation between the suction generated with the salt solution and the suction measured, diverge greatly from the line of equality. The suction obtained using the psychrometer was always higher than the suction determined with the filter paper. One reason for this may be that the distance between the psychrometer and the vapour source was 4.5 times higher than the distance between the filter paper and the vapour source. Although the results between filter paper and psychrometer differ, the tendency of both methods is to diverge from the equality line with the suction measured being approximately 2.5 times that of the suction generated. The results seem to be inconclusive about the general use of the calibration curve for filter paper measurement of total suction, since the suction generated was not measured either with the psychrometer or with the filter paper.

In relation to the equilibrium time the ASTM (D 5298-92) states the following, *"it must be recognized that the equilibrium time process is dependent upon the initial suction of the soil, initial relative humidity of the air, soil mass, and space in the container."*

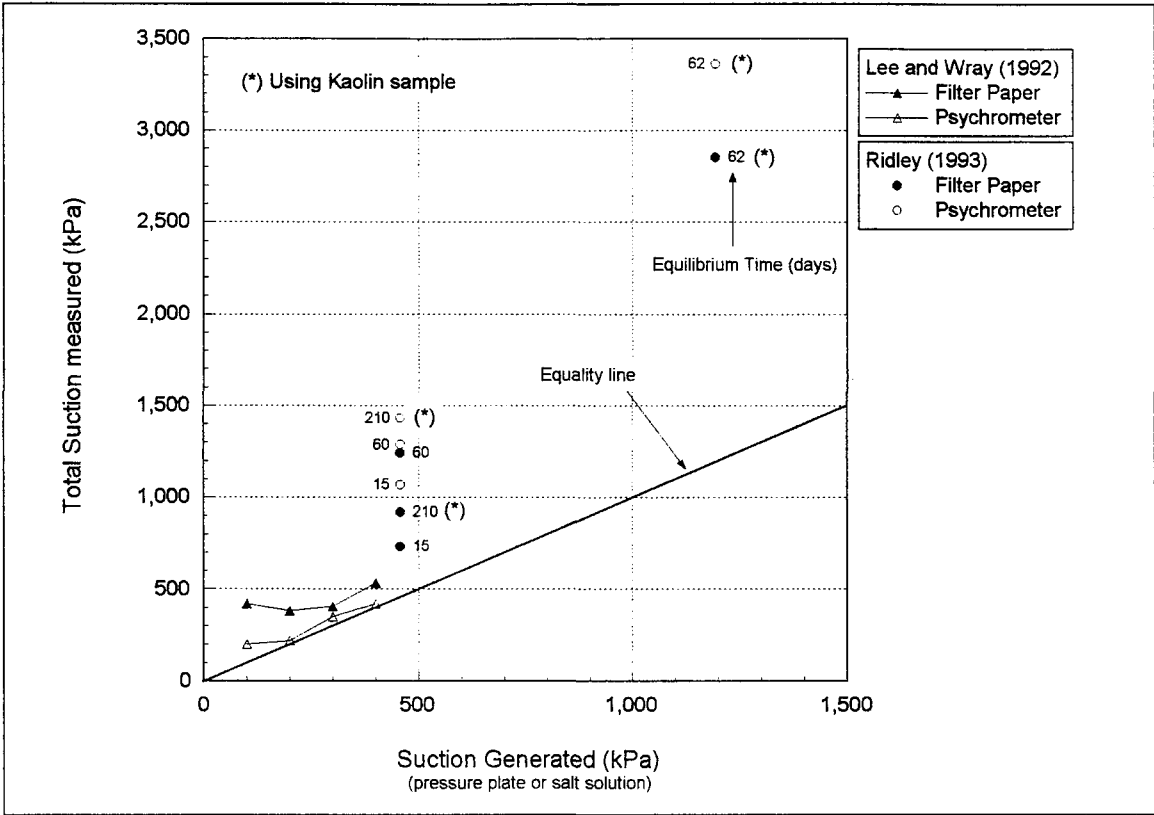


Figure 4.14 - Comparison between total suction measurement using the psychrometer and filter paper.

The contact aspect becomes more important when trying to measure matrix suction. The placement of a filter paper over the soil, with apparent physical contact between the filter paper and the soil, is not a guarantee that there is a contact between the soil water and the filter paper to allow capillary flow. This contact may depend on the soil type and suction level (which is a consequence of the degree of saturation). In order to investigate the contact effect during matrix suction measurement, Greacen *et al.* (1987) prepared samples at different water contents from two different soils (a surface loam and washed sand) mixing them with salt (NaCl) solution (approx. 0.56molar - 2.6MPa). The suction was measured using the filter paper method with the paper in contact with the soil, thus measuring matrix suction. At the end of the suction measurements the amounts of salt in the soil and in the filter paper were determined. The results presented by Greacen *et al.* are plotted in figure 4.15a and 4.15b. At high suction levels in the sand, the NaCl concentration in the filter paper was well below that in the soil. For the loam sample the salt concentration in the filter paper and on the soil remains similar. This behaviour was explained by Greacen *et al.* as being a vapour flow of the water associated with the sand at high suction, and a capillary flow in the loam over the whole range of suction measured. In figure 4.15b it can be observed that the relationship between water content and suction, for the soils with and without salt, agree very well. The initial osmotic suction (approx. 2.6MPa) is too high to be identified at the low water content of the sand. The sensitivity of the suction to the water content for the sand is very high. The results with the loam indicate that matrix suction was measured over the whole range tested.

In relation to the equilibration time item 7.1.1.3 presents suggestions for the equilibrium time to be used for total suction measurement with filter paper.

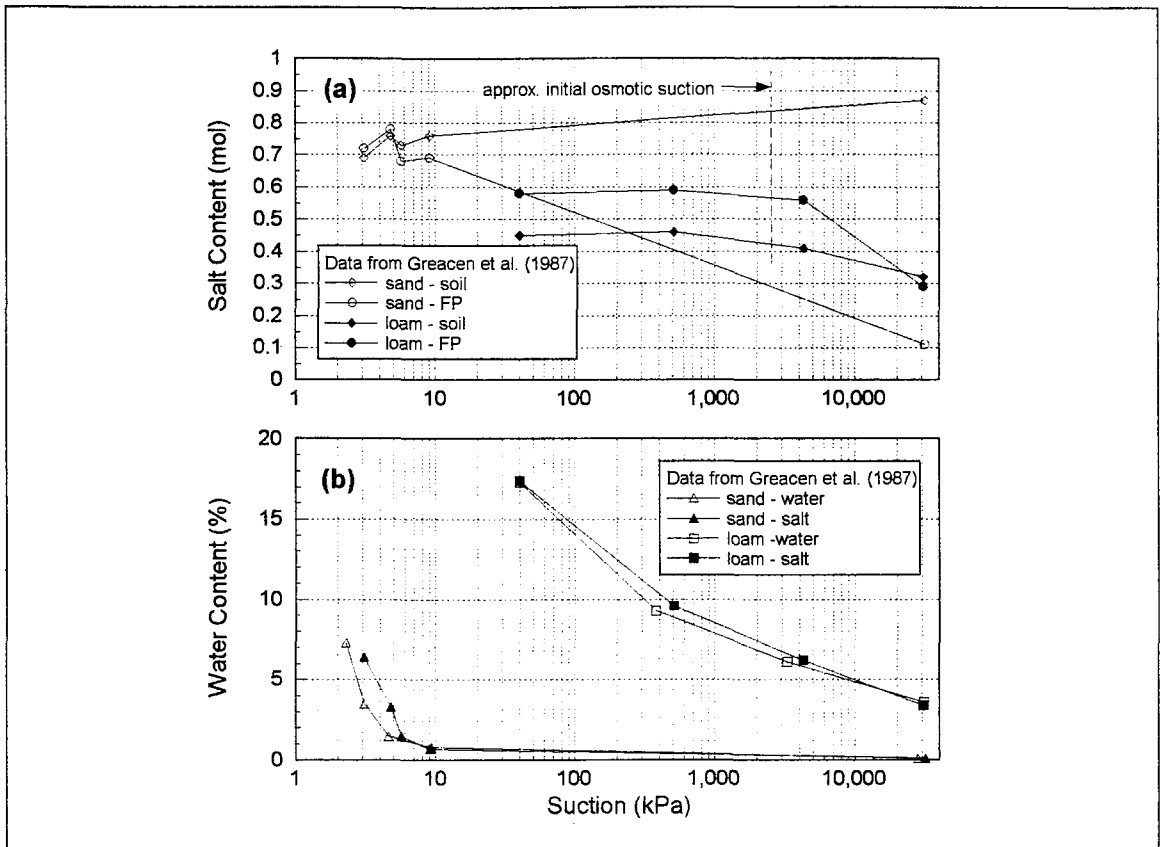


Figure 4.15 - Contact effect (a) Salt content in the filter paper (in contact) and in the soil after equilibrium is reached (b) Relationship between water content and suction..

4.2.3.3 - Temperature Effect

The effect of temperature variation on the relationship between relative humidity and suction is very small as can be seen in figure 4.16. Al-Khafaf and Hanks (1974) concluded that the absolute temperature (15° to 32°) does not affect the equilibrium water content of the filter paper. However, the effect of temperature changes has been recognized as having a great effect on the equilibrium water content of the filter paper. It was observed that for changes in temperature of 2°C, condensation occurs, and this problem is particularly important for suction below 1.5MPa. A variation within 2°C has been shown to be satisfactory for an adequate laboratory control of temperature for the measurement of suction using the filter paper method (e.g. Crilly and Chandler, 1993). The ASTM standard suggests a maximum variation of 3°C at a nominal temperature of 20°C.

Greacen *et al.* (1987) pointed out that the material of the container in which the soil is to equilibrate has an important role in the condensation phenomenon. Using a material with different heat characteristics to the soil induces condensation, since the fluctuation of temperature between the soil and the container will be out of phase. Greacen *et al.* suggested that the filter paper only has contact with the soil. In this case, the more appropriate technique is the one used by Fawcett and Collis-George (1974), Chandler *et al.* (1992) and Crilly and

Chandler (1993) in which the filter paper is placed between soils slices having only contact with the soil.

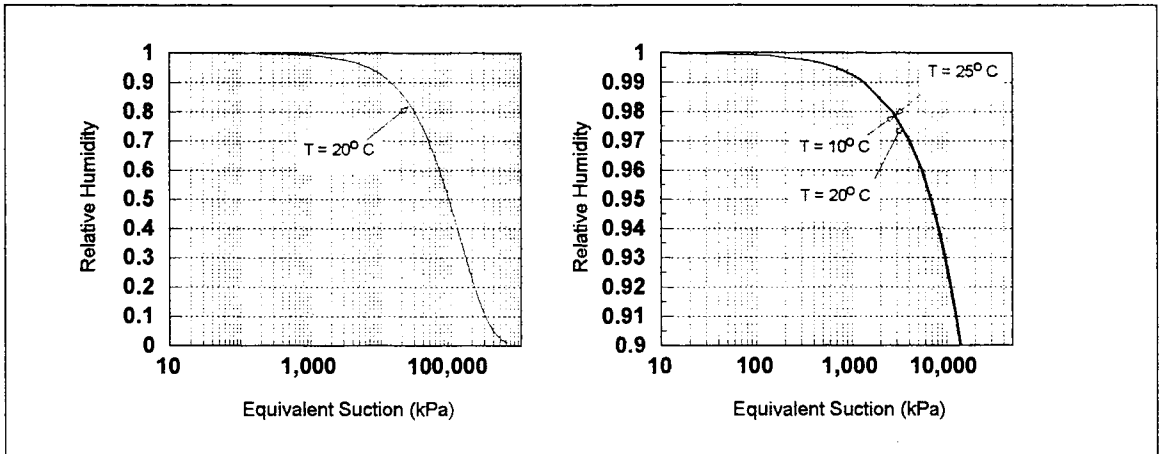


Figure 4.16 - Relationship between relative humidity and suction for different temperatures.

The problems associated with condensation are also related to the hysteresis of the filter paper. The filter paper can absorb the condensed water and then reach a water content higher than that at equilibrium. The paper then has to lose moisture to reach equilibrium. Greacen *et al.* (1987) suggested that the filter paper can be covered with a thin plastic film and insulated with 20mm of foam plastic, providing the temperature fluctuations are small (approx. 0.2°C).

There are suggestions that the calibration of the filter paper changes with the absolute temperature and therefore it would be necessary to calibrate the filter paper according to the operation temperature (*e.g.* Crilly *et al.*, 1991). This may be particularly important for field measurement in arid or semi-arid regions or in specific high temperature environment.

4.2.3.4 - Effect of the Number of Papers.

In order not to contaminate the filter paper with soil, a paper between the soil and the filter paper sensor is used when matrix suction is to be measured. Al-Khafaf and Hanks (1974) used a paper towel to protect the filter paper against the attachment of soil to it (see figure 4.13). Hamblin (1981) observed that the equilibrium time of filter paper in contact with soil depends on the number of paper used. She suggested the use of a single paper, considering that the error due to soil attached to the filter paper at the end of the process is smaller than would have occurred by using a longer equilibrium time or if attempts are made to clean the filter paper. In the latter case evaporation will take place. Gardner (1937) suggested weighing the filter paper before use in order to be able to subtract the amount of soil attached to the filter paper.

Crilly *et al.* (1991) presented a field suction measurement probe in which the filter paper method is used. Due to the difficulty in assuring a good contact between the filter paper and the soil, they used a non-contact method, measuring total suction. The equilibrium time for one filter

paper was observed to be the same as for two papers (see figure 4.17) although the final water content were different. The equilibrium water contents for the three experiments presented in figure 4.17 give suctions of 3MPa (one paper) and 4MPa (two papers), approximately. This suggests that the calibration curve does not apply if more than one paper is used. The level of suction is important for establishing the equilibrium time, as seen in section 4.2.3.2. Tests with one, two and three filter papers at low suction (300kPa) showed that the equilibrium water content were 37.5%, 36.36% and 35.72%, respectively, when the equilibrium time for the experiments increased to two months. This emphasises that different calibrations are required for different numbers of filter papers. In figure 4.18 the relationship between the final filter paper water content and the number of papers used is shown. It can be observed that the number of papers used in the system has a great influence on the final water content of the filter paper. The equilibrium times used on each test presented in figure 4.18 were diferent.

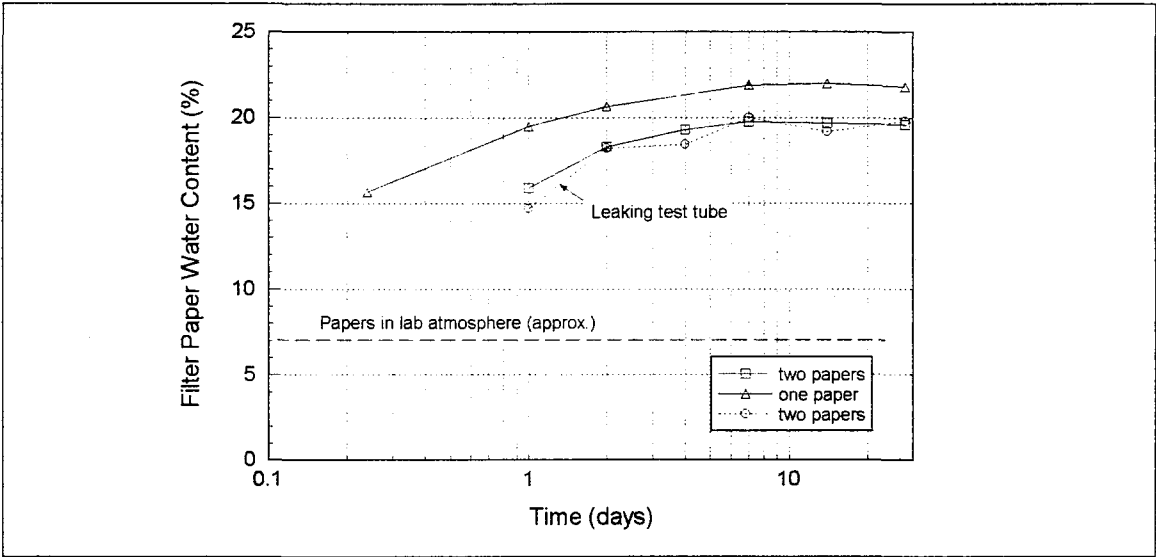


Figure 4.17 - Filter paper water content against equilibration time (from Crilly et al., 1991).

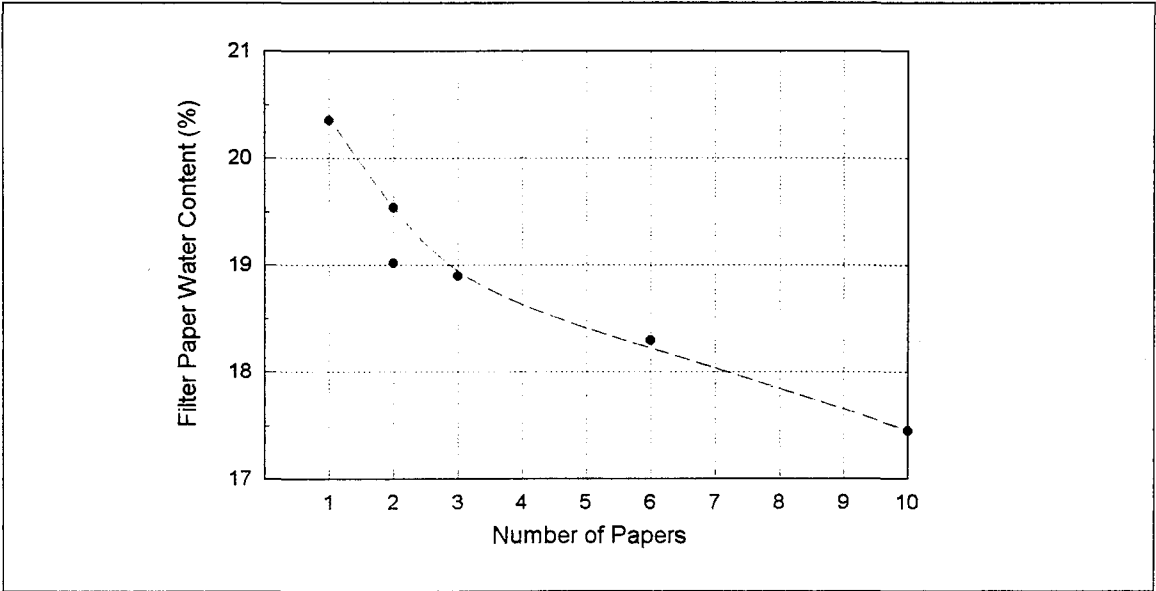


Figure 4.18 - Variation of equilibrium water content with number of filter paper (from Crilly et al., 1991).

4.3 - Comparison with Other Methods

The calibration curves obtained by many authors, at different times and using different methods for generating suction are a good indication that the filter paper method compares reasonably well with other methods of suction measurement (see figures 4.1 and 4.2). However, it is useful to compare suction measurements made using the filter paper method with suction measurements made with other methods.

Daniel *et al.* (1981) [referred to by Fredlund and Rahardjo (1993)] presented a comparison between suction measurement using the filter paper method (measuring total suction) and a psychrometer. A compacted silty sand was used, and measurements were obtained at different water contents. Good agreement was obtained as can be seen in figure 4.19.

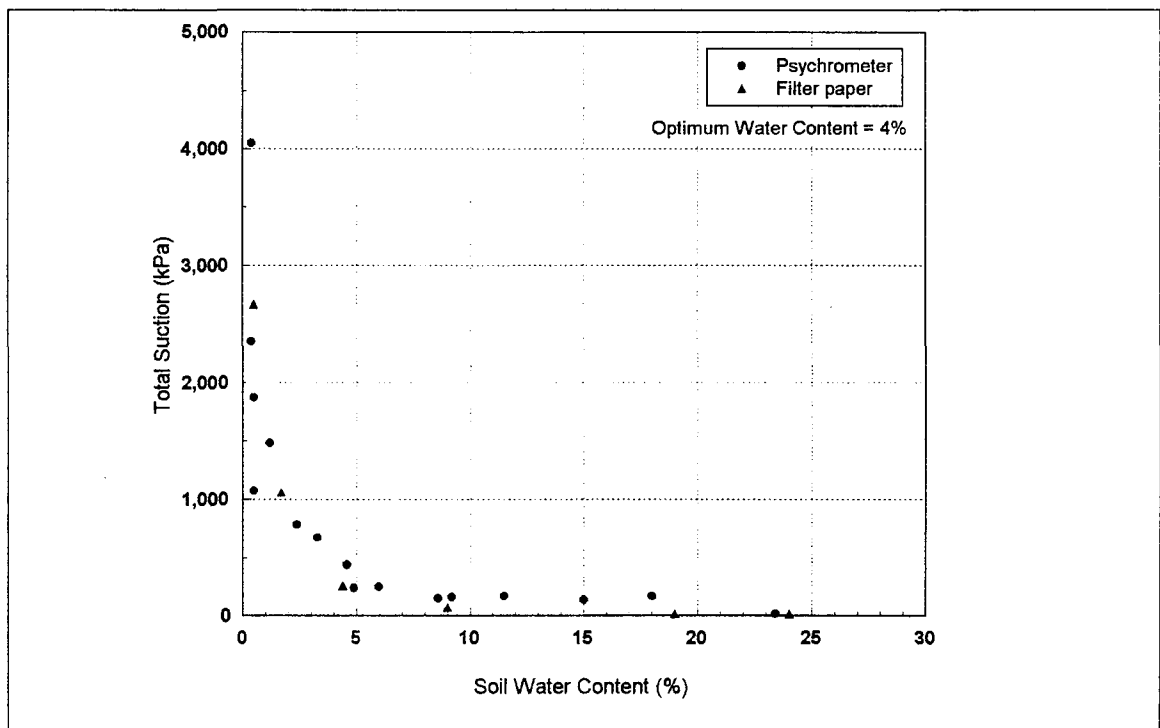


Figure 4.19 - Comparison of independent measurements of total suction on a compacted silty sand (from Daniel *et al.*, 1981).

Using soils from different locations, McKeen (1981) obtained a relationship between total suction measured with the psychrometer and total suction obtained with the filter paper method. The equilibrium time used for both method was 7 days. The results are presented in figure 4.20 and these show good agreement in the range tested, which was approximately 500kPa to 10MPa. Another example, McKeen (1981), of a good agreement between the psychrometer and the filter paper method is presented in figure 4.21 for a heavy clay from Texas (Dallas/Fort Worth Airport site). McKeen pointed out that the filter paper measurement had more accurately depicted the actual suction distribution in the profile, showing low suction at the sand seams. The psychrometer did not reach equilibrium when the samples with sand were used.

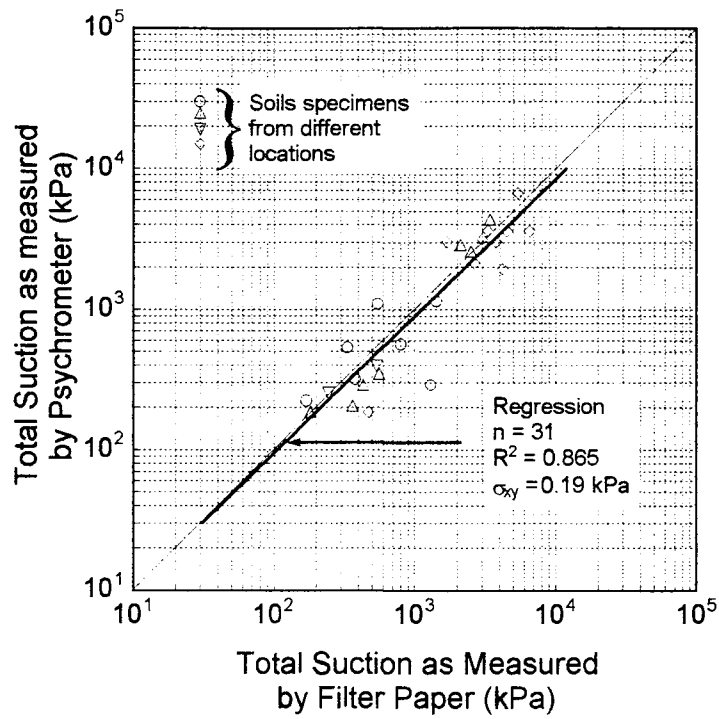


Figure 4.20 - Comparison of total suction measurements obtained using the filter paper method and psychrometer (from McKee, 1981).

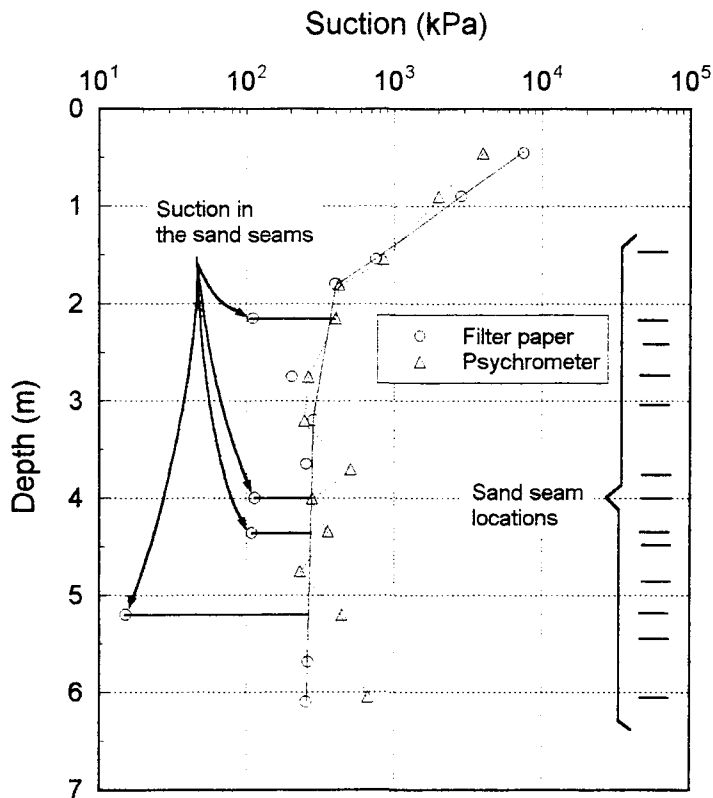


Figure 4.21 - Total suction profiles as determined using the filter paper method and psychrometers (from McKee, 1981).

Van der Raadt *et al.* (1987) presented laboratory measurements of total and matrix suction on soil samples from various depths. They used filter papers for measuring matrix and total suction

and a psychrometer for total suction measurement. The equilibration time used was one week. Figure 4.22 shows the results obtained as suction measurement against depth. A very good agreement is obtained for the total suction measured between filter paper and psychrometer. It can be seen that there is no difference between the matrix and total suction for the first 5 metres. This was explained as a lack of contact between the soil water and the filter paper when measuring matrix suction. It was reported that evaporation may have occurred after the filter paper was removed. Van der Raadt *et al.*(1987) also measured matrix suction using a thermal conductivity sensors, though the results were inconclusive for comparison with the filter paper results. It is important to note that if a soil has high matrix suction and the osmotic suction is relatively small, the difference between the total and matrix suction is likely to be imprecise.

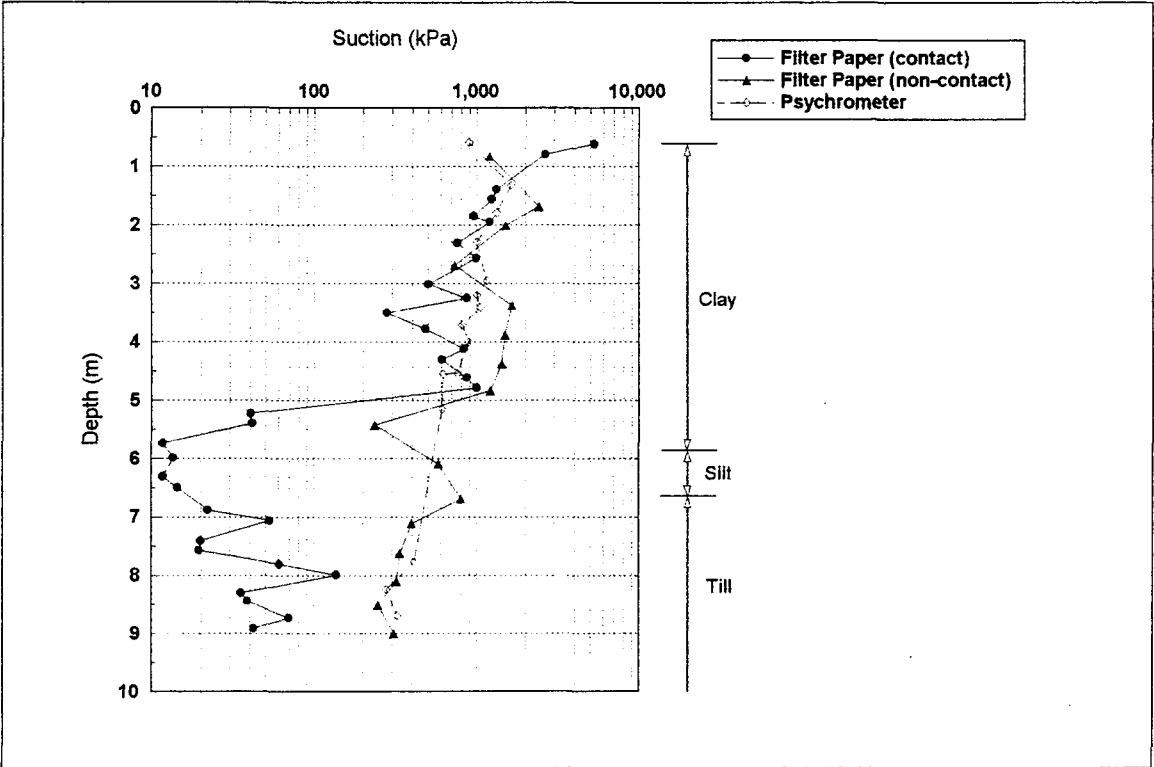


Figure 4.22 - Suction profile versus depth obtained using psychrometers and filter paper method (from van der Raadt *et al.*, 1987).

Schreiner (1988) observed a good agreement between the filter paper method (using Whatman N° 42), pressure plate and psychrometer. His results are presented in table 4.3. The osmotic suction presented was obtained by subtracting the matrix suction from the total suction.

		Suction (kPa)				
Soil	Sample	Pressure Plate (matrix)	Filter Paper (matrix)	Filter Paper (total)	Psychrometer (total)	Osmotic Suction
Nairobi-Mombasa Road Site	1	360	398	-	1050	690/652
	2	365	-	1100	-	735

Table 4.3 - Comparison of different suction measurements (from Schreiner, 1988).

Lee and Wray (1992) presented an evaluation of many soil suction measurement methods. They used Schleicher & Schuell N° 589 filter paper for comparison with pressure plate and psychrometer measurements and allowed an equilibrium time of two weeks. The results obtained are shown in figure 4.23. Not very much detail was given about the set-up of the filter papers, but it seems that two filter papers were placed together in contact with the soil, for matrix suction measurements. The results show a reasonable agreement with the suction generated with the pressure plate. A comparison between filter paper and psychrometer is presented in section 4.2.3.2.

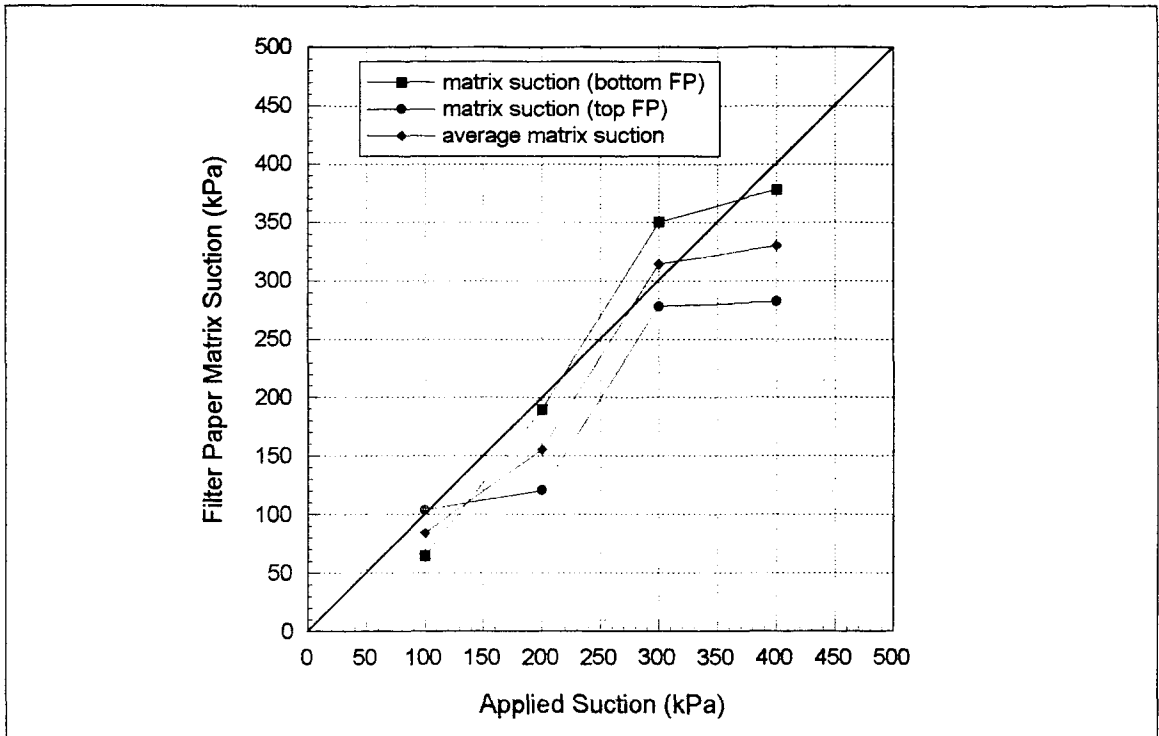


Figure 4.23 - Comparison between matrix suction from contact filter paper method and pressure plate (from Lee and Wray, 1992).

Ridley (1993) compared matrix suction measured with a pressure plate apparatus and with the filter paper method. The sample was prepared by consolidating a slurry of Kaolin at 150% initial water content. The maximum consolidation pressure applied was 1MPa. The sample was unloaded to 100kPa and then removed from the oedometer under undrained conditions. Two filter papers were placed on the top and bottom of the sample to measure matrix suction. The equilibrium time used was 7 days. After removing the filter papers the sample was weighed and placed on the pressure plate. When the suctions were obtained another two filter papers were placed for new filter paper measurements. The procedure was repeated every seven days as the sample dried. Figure 4.24 shows the results obtained from the average filter paper water content and using the calibration curves given by Chandler *et al.* (1992). The tendency of the pressure plate was to give lower suctions compared with the filter paper measurements. This was explained by the fact that the filter paper method increases the suction in the sample, since the sample loses water to the paper, whilst in the pressure plate the sample absorbs water reducing its suction (Ridley, 1993). He also obtained some results using the psychrometer, for

comparison with the filter paper method measuring total suction. Even though his results suggest that the psychrometer gives higher suctions than the filter paper method, the trend is good. The results are plotted in figure 4.25. However, if the suction generated is considered there is a disagreement between the suction generated and the suction measured for both filter paper and psychrometer. The numbers in brackets in figure 4.25 represents the suction generated.

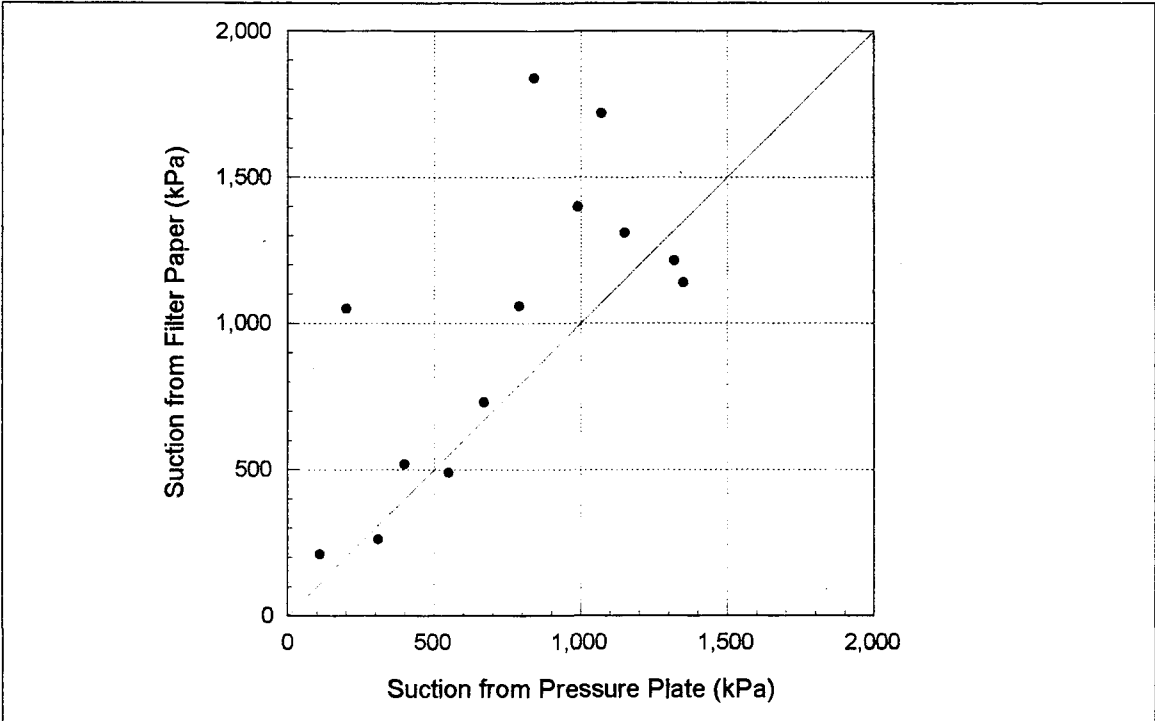


Figure 4.24 - Comparison between filter paper method and pressure plate (from Ridley, 1993).

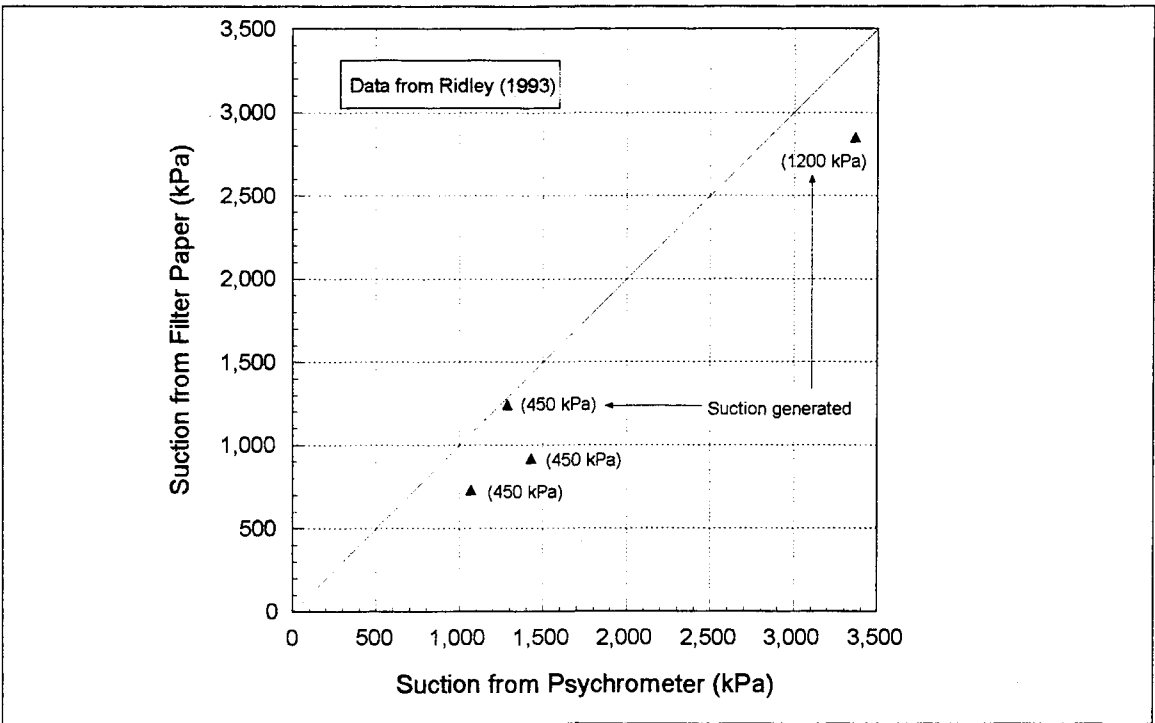


Figure 4.25 - Comparison between filter paper method and psychrometer (from Ridley, 1993).

CHAPTER 5

Soil Shrinkage

5.1 Introduction

The shrinkage behaviour of soil has been studied since the 19th century (*e.g.* Schübler, 1838; Wolly, 1897) . However, it was at the beginning of the 20th century that soil shrinkage studies started to yield models for the phenomenon. The most important developments in this subject were made between 1912 and 1925, and this chapter presents a selective review of these and other findings concerning soil shrinkage. The historical review presents the research done by the soil scientists in order to show the position of the soil mechanic in the studies of soil shrinkage. The concepts and definitions presented in this chapter will be used for interpreting the data in chapter 7.

5.2 Historical Review

Most of the early studies were concerned with agricultural aspects of soil shrinkage; consequently, most of these were published in agricultural journals. For soil mechanics the first relevant work was by Tempany (1917). Using compacted soils he investigated the relationship existing between shrinkage and water loss, and the influence of the amount of clay particles on the shrinkage behaviour. He was the first to suggest the existence of a shrinkage phase, where, for fully saturated samples, the volume change of the sample is equal to the water volume evaporated. This phase exists for contraction without restriction by internal friction between particles. With continuing contraction a point is reached at which the soil starts to develop interparticle friction, resisting the shrinkage. The water content at which the soil stops contracting is the shrinkage limit. The shrinkage limit and the total volume change were observed by Tempany to be a function of the amount of colloids in the soil. Figure 5.1 presents results obtained by Tempany (1917).

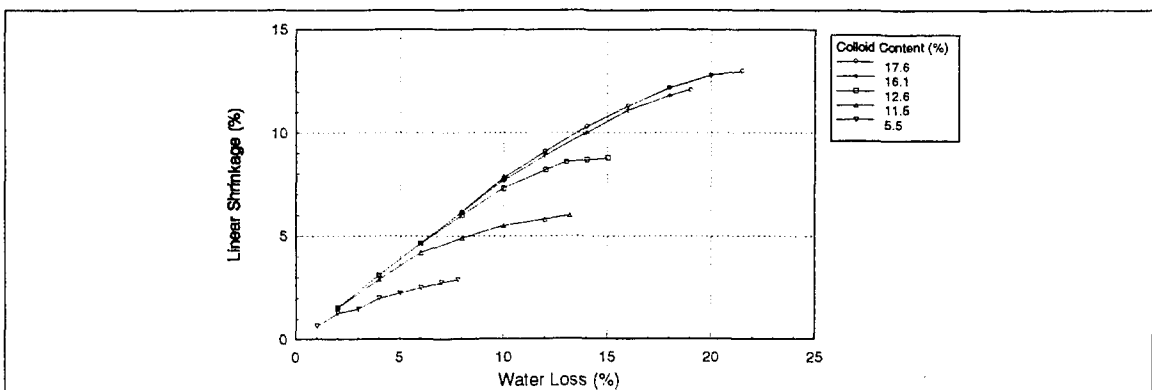


Figure 5.1 - Linear shrinkage versus Water loss for different soils (from Tempany, 1917)

In 1923, Haines presented a complete interpretation of the shrinkage phenomenon. Plotting volume of the sample versus volume of water, Haines observed that the shrinkage curve (see figure 5.2) consists of two straight lines. Point C represents the starting point of drying. Segment CB (normal shrinkage) corresponds to the stage where the volume of water evaporated is equal to the reduction of the total volume of the sample. This implies that the segment CB is a line at 45° in this particular plot. The second phase BA (residual shrinkage) represents the stage where part of the water lost is replaced by air. Haines commented on the importance of the residual shrinkage. *"It can vary a good deal in amount, and can be defined with fair accuracy since the point of inflexion is usually sharp"*.

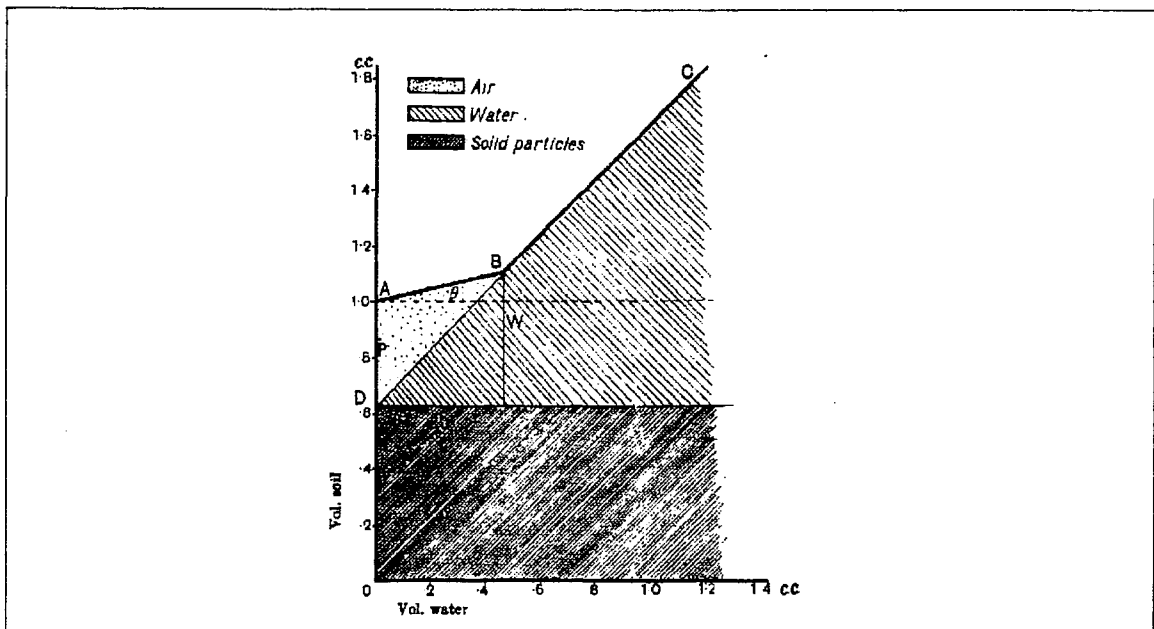


Figure 5.2 - The shrinkage curve (Haines, 1923)

Terzaghi (1925) was the first to review shrinkage from an engineering point of view. He realized that the only difference between the artificial compression under load, and the natural shrinkage due to drying, is that compression can be carried almost indefinitely, whilst for shrinkage due to evaporation a point is reached beyond which the volume of a clay remains constant. He stated that: *"It is astonishing that nobody seems to have felt the necessity of investigating the physical causes of this identity"*. In describing the mechanism of shrinkage Terzaghi defines the suction at the shrinkage limit as a *transition pressure*, which is the limit at which the soil passes from the semi-solid to the solid state. One can observe that the identity between mechanical compression and shrinkage due to evaporation exists only during the normal shrinkage phase.

Lauritzen and Stewart (1941) and Lauritzen (1948) studied the shrinkage behaviour of undisturbed samples observing a phase prior to normal shrinkage. This phase is only present in soils with a specific kind of structure, later termed structural shrinkage by Stirk (1954).

In the same way that Tempany (1917) observed a relationship between shrinkage and amount colloids, Stirk (1954) showed that there is a correlation between the proportion of particles smaller than $2\mu\text{m}$ and the suction at commencement of the end of shrinkage (Terzaghi's transition pressure). Figure 5.3 presents the results obtained by Stirk (1954).

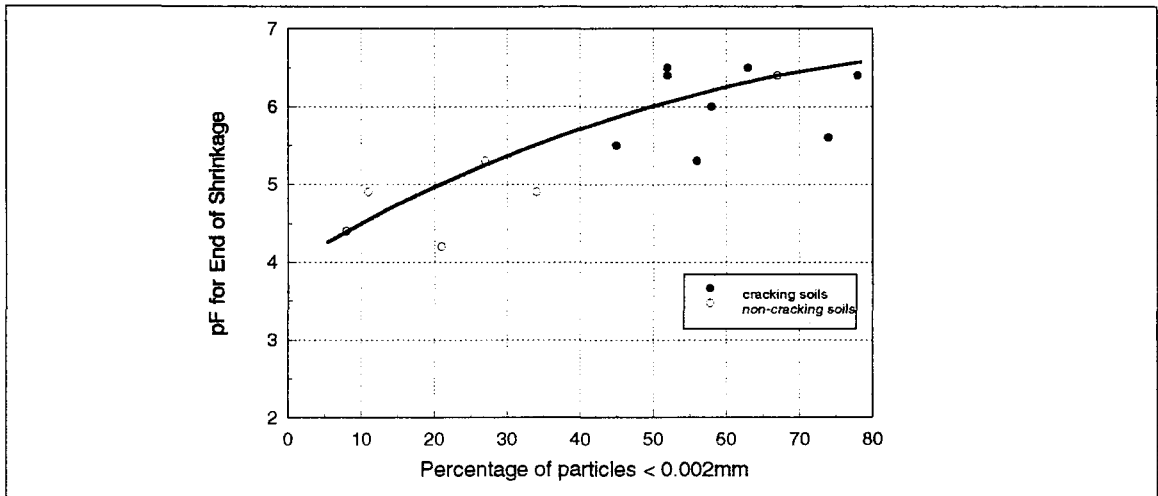


Figure 5.3 - The influence of clay content on the pF at the shrinkage limit. (from Stirk, 1954).

De Jong and Warkentin (1965) studied shrinkage phenomena in soils using mixtures of clay and glass beads. Their conclusions can be generalized as follows. The water content at the shrinkage limit should depend only on the proportion of clay in the mixture. This is valid since the coarse fraction of the soil holds no water. However, if the coarse particles touch during shrinkage the water content at the shrinkage limit will depend on the quantity of coarse particles and how they are arranged in the soil. De Jong and Warkentin (1963) observed that in samples with more than 30% clay, soil shrinkage increases approximately linearly with the percentage of clay. Samples with more than 50% clay show a linear relationship between water content at the Shrinkage limit and percentage of clay.

Dumbleton and West (1970) presented a study where soil mixtures were used to investigate the influence of soil composition on the suction and strength. It was observed that the strength, measured using a vane test, increased approximately proportionally with the suction for a given sample. Addition of round particles, up to 50%, had no effect on the strength for a given suction. On the other hand, addition of angular grains increased the strength for a given suction.

Acar and Nyeretse (1992) investigated the relationship between total suction and the soil composition. They suggested that the total suction at the optimum water content can be estimated based on the plasticity index of the soil. The total suctions at the optimum water content obtained by Acar and Nyeretse were extremely high, suggesting the presence of a high osmotic suction. Figure 5.4 presents a compilation of results found in the literature (Fry *et al.*, 1993; Ho *et al.*, 1992 and Cruz and Ferreira, 1993) showing the relationships between matrix suction at optimum, liquid limit, clay content and water content. It can be seen that there is no

clear relation between the suction at the optimum water content and liquid limit or clay content.

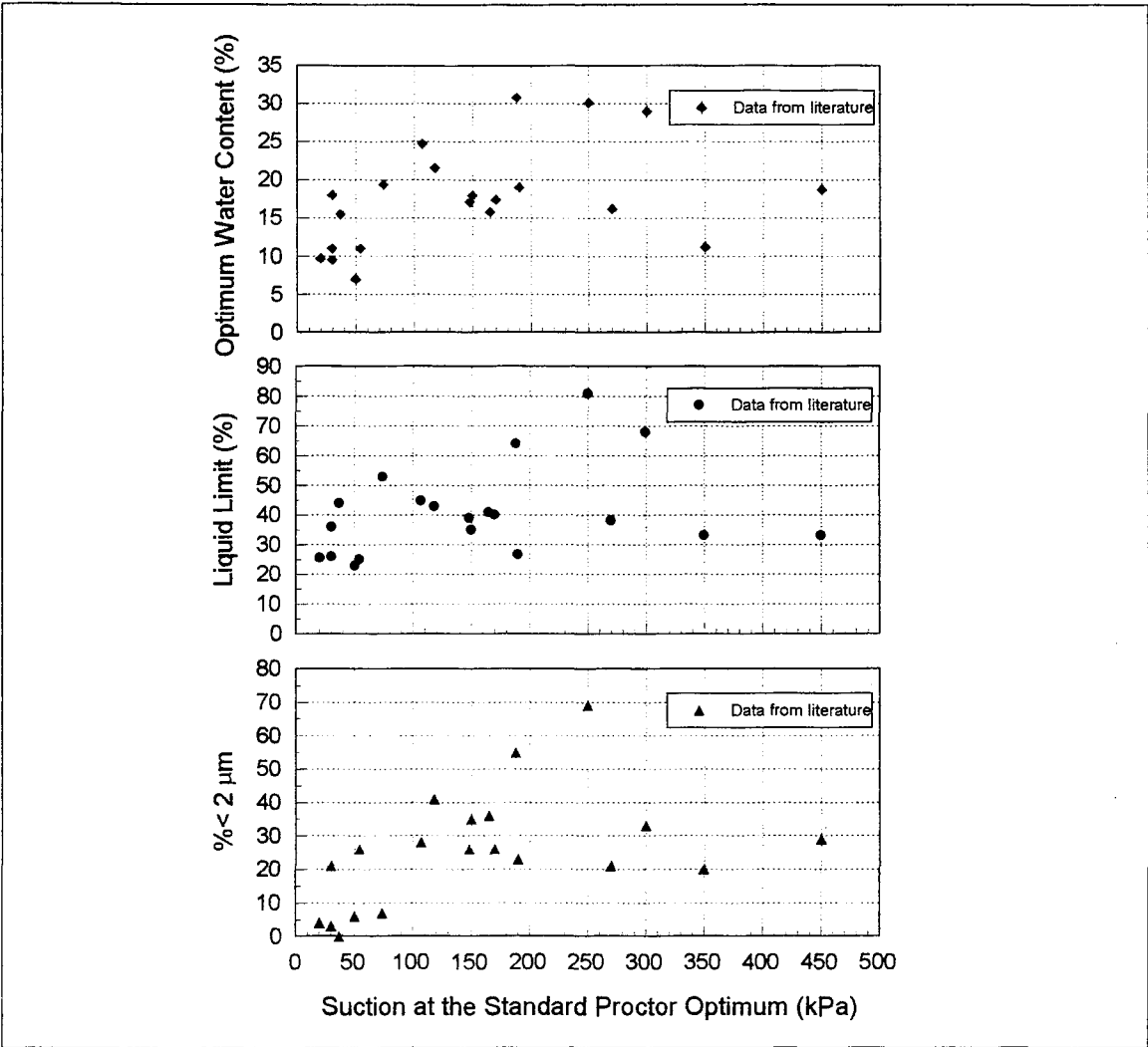


Figure 5.4 - Suction at the standard proctor optimum versus the clay content and liquid limit.

The first model of the soil shrinkage in terms of soil suction was given by Poulovassilis (1970). The concept of soil shrinkage was presented in terms of volume of water in the soil and suction, as shown in figure 5.5. The curve defined during the drying of a soil from saturation up to the maximum suction (dry condition) is called saturation boundary drying curve (AGRB). The curve BEC is the ultimate boundary wetting curve and CDB is the ultimate boundary drying curve. Between the ultimate boundary wetting and the saturation boundary drying curves there are primary wetting (*e.g.* GHM , RN) and drying curves (*e.g.* MG, NFR).

Poulovassilis drew attention to the fact that the difference between the water contents of two zero suction states reached via two different primary wetting curves (*e.g.* GM and RN), which have their origin at two different suctions (*e.g.* G and R) on the saturation boundary drying curve, represents the volume of entrapped air in pores draining in the suction interval defined by their origins (G and R).

Rao and Sartyadas (1985), using statically compacted Black Cotton clay, showed very clearly

the point at which, during drying, air starts to enter the sample in significant quantity. This observation was achieved by plotting degree of saturation versus volumetric or linear shrinkage.

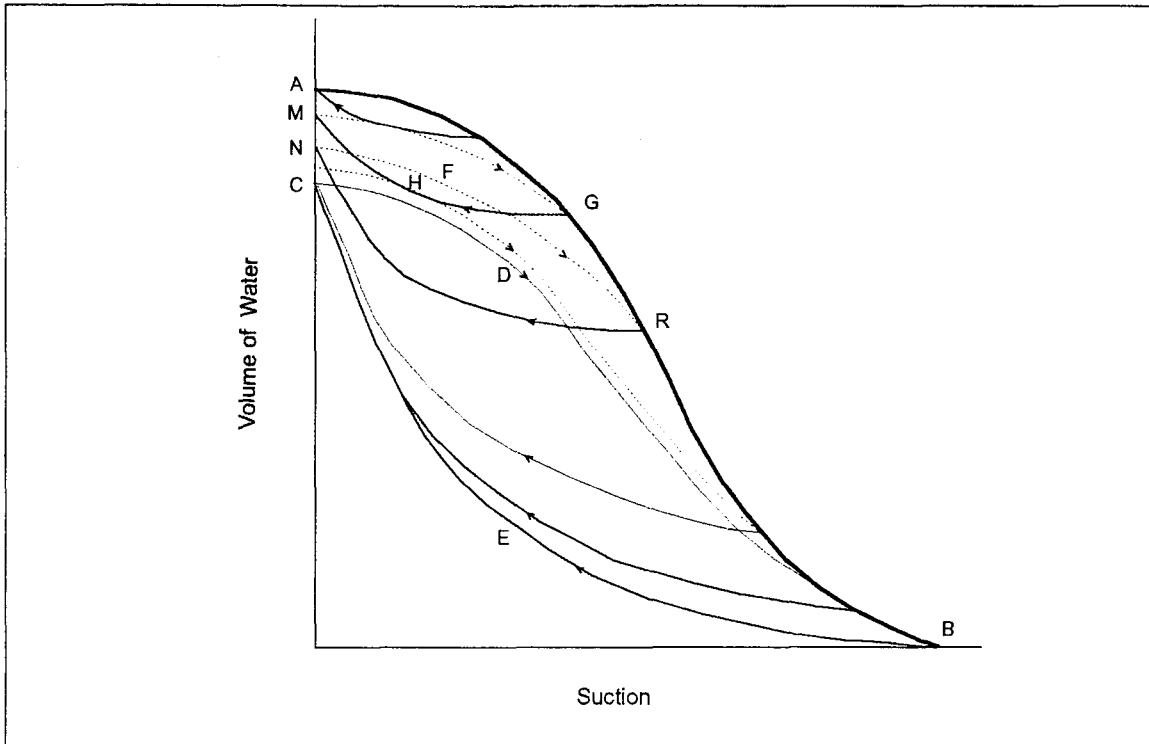


Figure 5.5 - Representation of the drying and wetting behaviour of soils (from Poulovassilis, 1970).

Toll (1988) described the desaturation phenomenon in a similar way to Poulovassilis (1970), but from an engineering point of view. Figure 5.6 represents the desaturation concept suggested by Toll (1988). The point A in figure 5.6a, is the starting point of a saturated soil in a normally consolidated condition, undergoing drying. The segment AB represents the normal shrinkage phase. At B the soil desaturates. In terms of void ratio (e) a point is reached where the soil stops reducing in volume (point C). Plotting volumetric representation of water content ($e_w = Gw$) at point B the curve e_w departs from the e curve, defining the virgin desaturation line. If the soil is overconsolidated, then, in a saturated state at the same suction, it will have a lower void ratio. Figure 5.6b presents the behaviour of overconsolidated soils during drying, while figure 5.6c shows an idealization of the drying and wetting cycles for a normally consolidated soil. Toll (1988) postulated that "a unique water content/suction relationship exists for an initially saturated, normally consolidated soil subjected to drying with no external stress applied".

The line defined by the volumetric water content/suction relationship was called the 'virgin desaturation line' (VDL) and a soil on the VDL is a 'normally desaturated' soil. Soil lying beneath the VDL as a result of re-wetting (not due to overconsolidation) is an 'undersaturated' soil. As Toll (1988) pointed out, the virgin consolidation line (VCL) is not unique, but is affected by the initial fabric. It is likely that the 'virgin desaturation line' will be even more sensitive to fabric, and for compacted soils it will be dependent on the compaction conditions.

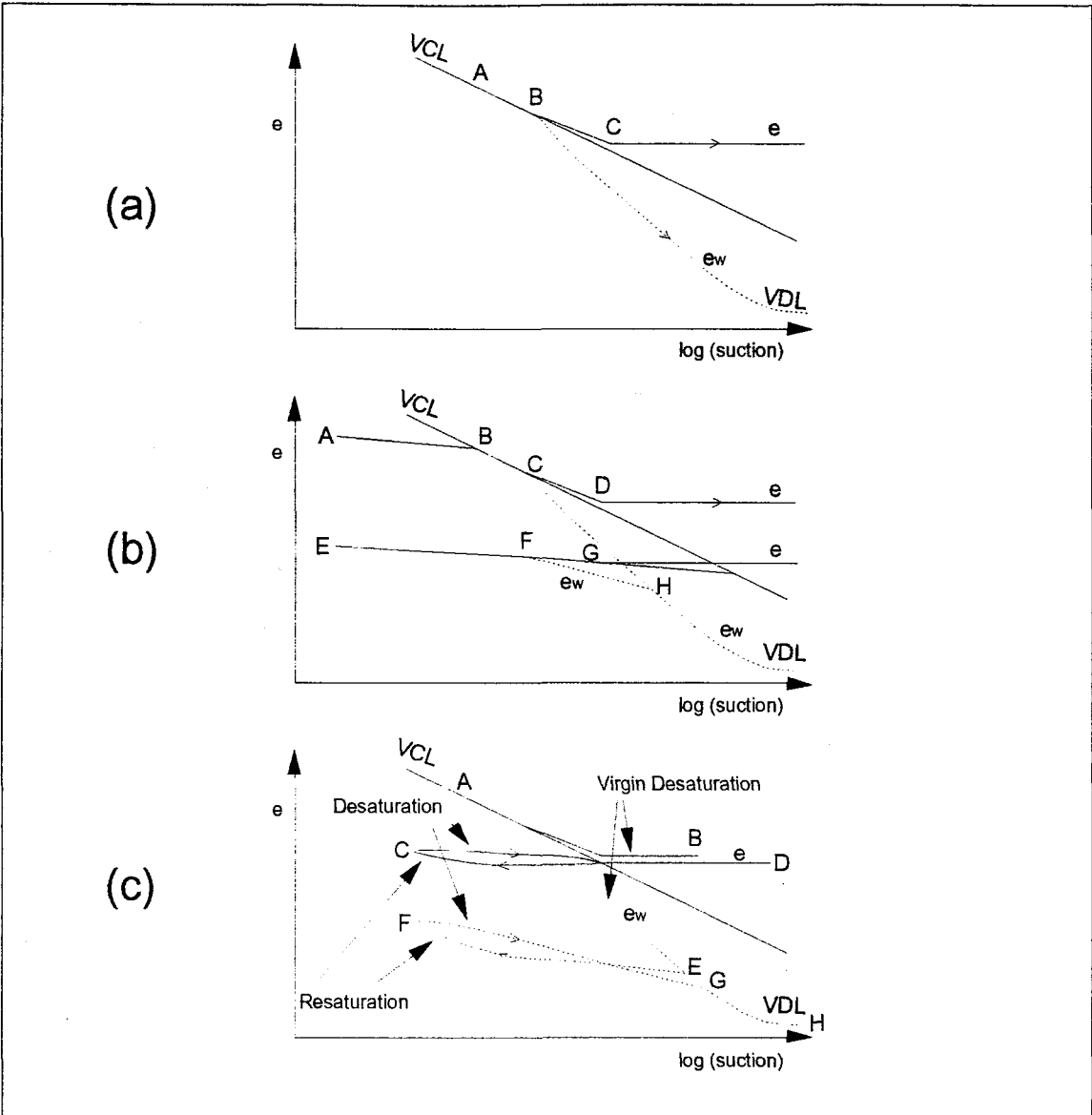


Figure 5.6- (a) Virgin desaturation of a normally consolidated soil (b) Virgin desaturation of an overconsolidated soil (c) A drying-wetting cycle for a normally consolidated soil (from Toll, 1988).

5.3. Aspects of Shrinkage Phenomena

5.3.1 General Concepts

This section presents an overview of the main concepts involved with soil shrinkage. The aim is to characterize shrinkage phenomena using fundamental definitions in order to form a basis for understanding the literature reviewed in the following sections.

The capacity of a soil to shrink depends on the soil type (potentially expansive soils). The amount of shrinkage depends, *inter alia*, on the soil type (*i.e.* mineralogical composition), soil structure and initial and final water contents. *In situ* shrinkage is predominantly caused by water evaporation from the ground surface and by evapotranspiration by plants. The reduction in volume during shrinkage is similar to the reduction in volume due to mechanical compression,

provided the soil remains saturated or near saturation.

Figure 5.7 shows a schematic representation of the several ways in which a clay particle holds water. The five categories shown in figure 5.7 are described as follows (Head, 1980).

1. This layer of water is called adsorbed water and cannot be removed by oven drying at 110°C . It is considered to be part of the soil grain.
2. This water can be removed by oven drying.
3. This water is held by surface tension and can be removed by air drying the soil at standard laboratory temperature. It is called capillary water.
4. This water can be removed by drainage and is called gravitational water.
5. This water is chemically combined with the mineral. It is the water of hydration of the crystal structure. This water is usually not removable, except for gypsum and some tropical clays.

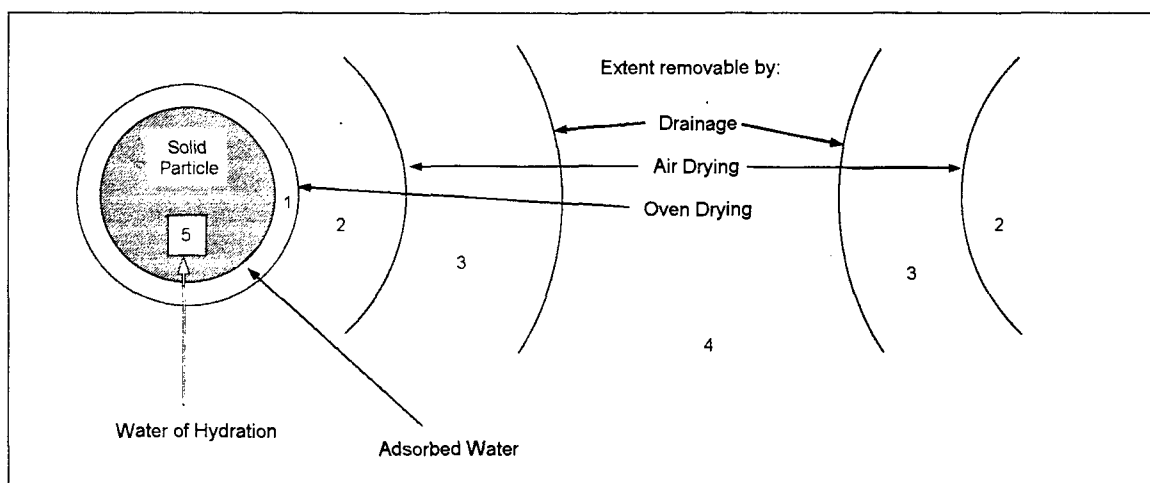


Figure 5.7 - Representation of categories of water surrounding clay particles (from Head, 1980).

A useful way of representing the shrinkage phenomenon is by plotting volume per 100g of dry soil against water content, as shown in Figure 5.8a. This figure also shows theoretical lines of iso-saturation and a shrinkage curve. The segment AB is the normal shrinkage, where the loss of water is equal to the sample contraction in terms of volume. At point B air enters the sample. This point is the desaturation point for an initially saturated sample. The point C represents the shrinkage limit, which by definition (BS - 1377) is the intersection of the line AB and the horizontal line passing through Point D.

Figure 5.8b presents the three basic types of behaviour that an initially saturated sample can exhibit. The type of behaviour will depend on the particle sizes and their distribution and on the stress history of the sample.

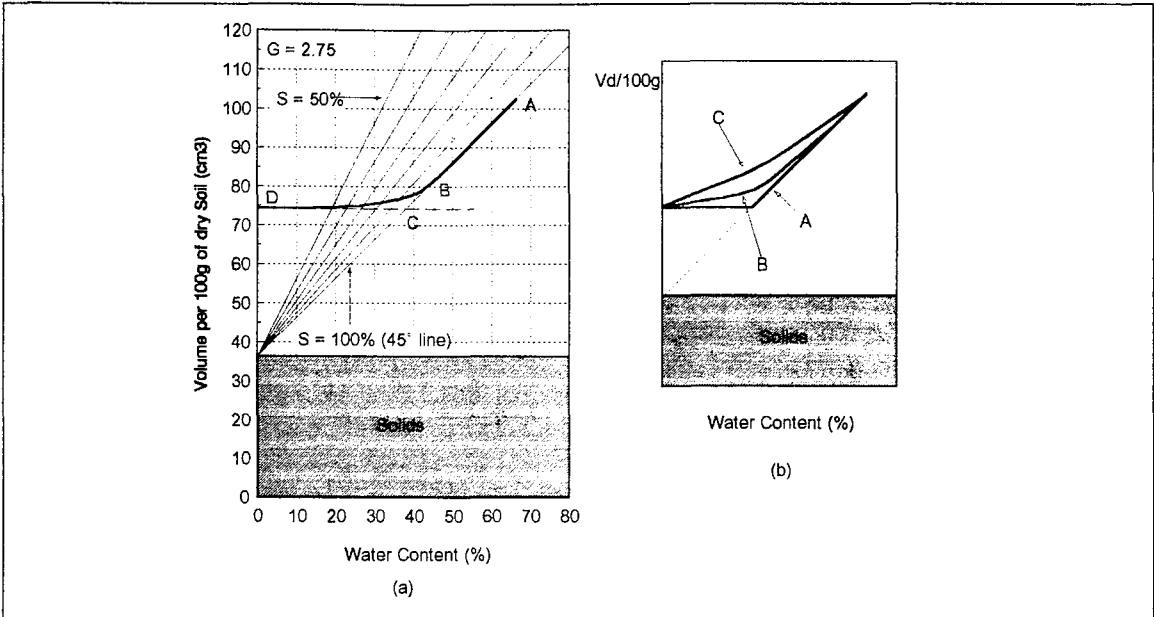


Figure 5.8 - Drying phenomenon - (a) theoretical lines for constant degree of saturation and (b) shrinkage curves.

Figure 5.9a shows the behaviour of an initially saturated sample. For a non-saturated sample two bounding paths can be postulated. One where the degree of saturation remains constant (path AB in figure 5.9b), and other where the degree of saturation reduces during drying (path AC). The latter behaviour can be divided into two types, one where the volume of air in the sample is constant and another where the volume of air increases. For a sample starting from a saturated or unsaturated condition a point is reached where the air starts to enter more rapidly. This point will be called the general air entry point (GAE). It is represented by the water content at which the gradient of the shrinkage curve changes.

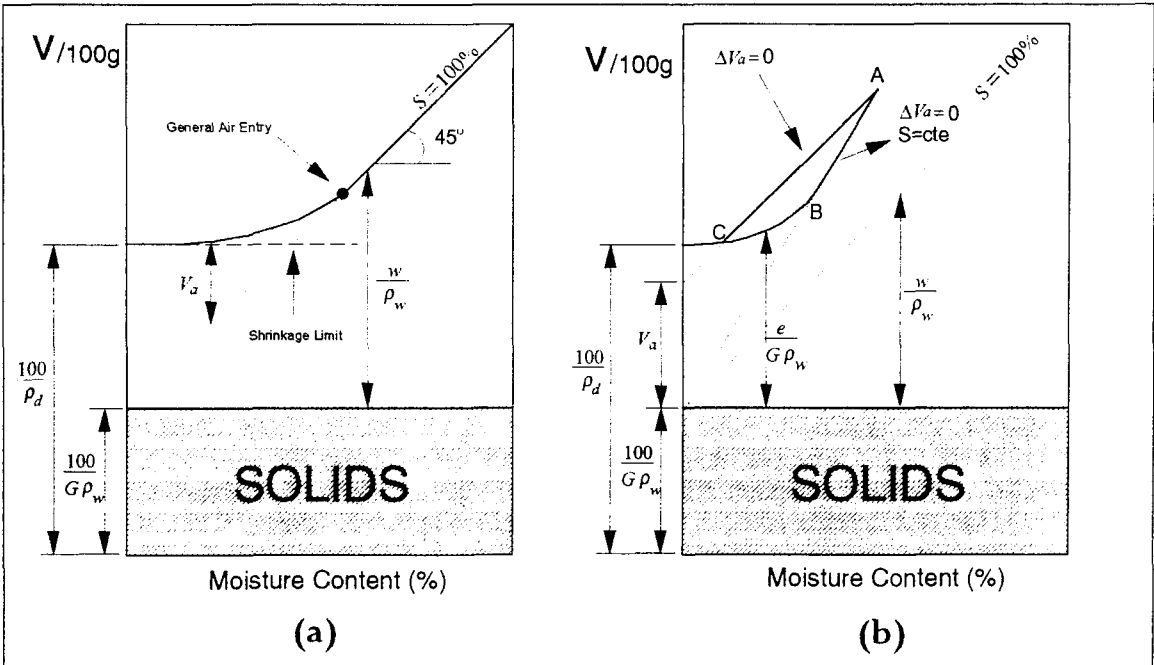


Figure 5.9 - Physical relationships on the drying curve. (a) saturated sample (b) unsaturated sample.

Figure 5.10 shows results collected from the literature showing the relationship between the shrinkage limit, clay content, liquid limit and plasticity index. It can be seen that the shrinkage limit varies between very broad limits, and that it is difficult to identify a consistent relationship.

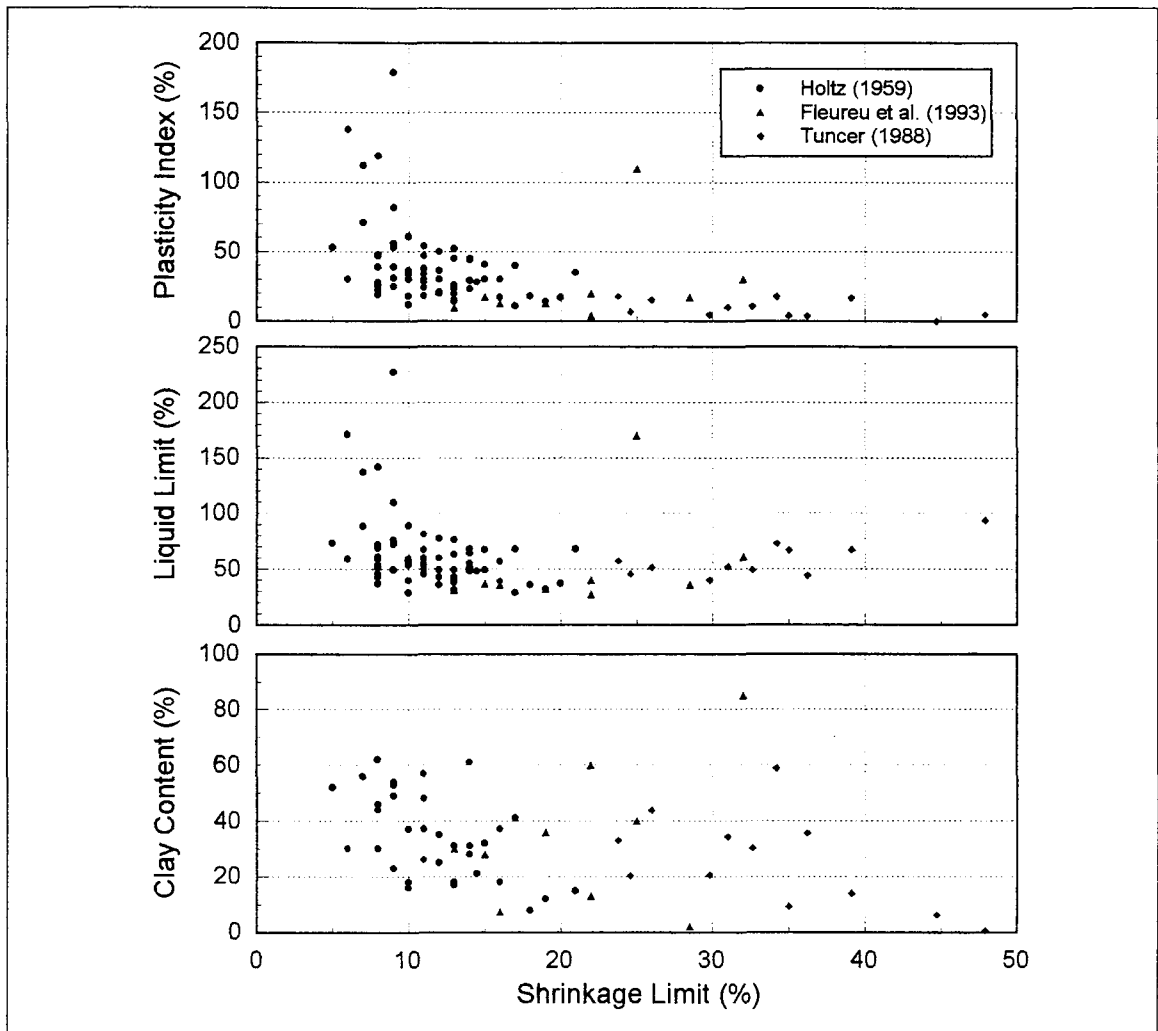


Figure 5.10 - Variation of the shrinkage limit with the clay content, liquid limit and plasticity index.

To visualize shrinkage phenomena it is useful to plot degree of saturation against water content, together with lines of constant void ratio. Figure 5.11a shows the theoretical lines of constant void ratio. In figure 5.11b different types of soil behaviour are shown; curves A, B and C are the same as those shown in figure 5.9b. Curve D represents a sample starting drying from an unsaturated state. The points G are the general air entry points.

In soil science, the relationship between suction and water content is usually called the "curve characteristic" of the soil. The curve characteristic comprises drying and wetting curves. It can vary significantly with the type and structure of the soil (Hillel, 1971).

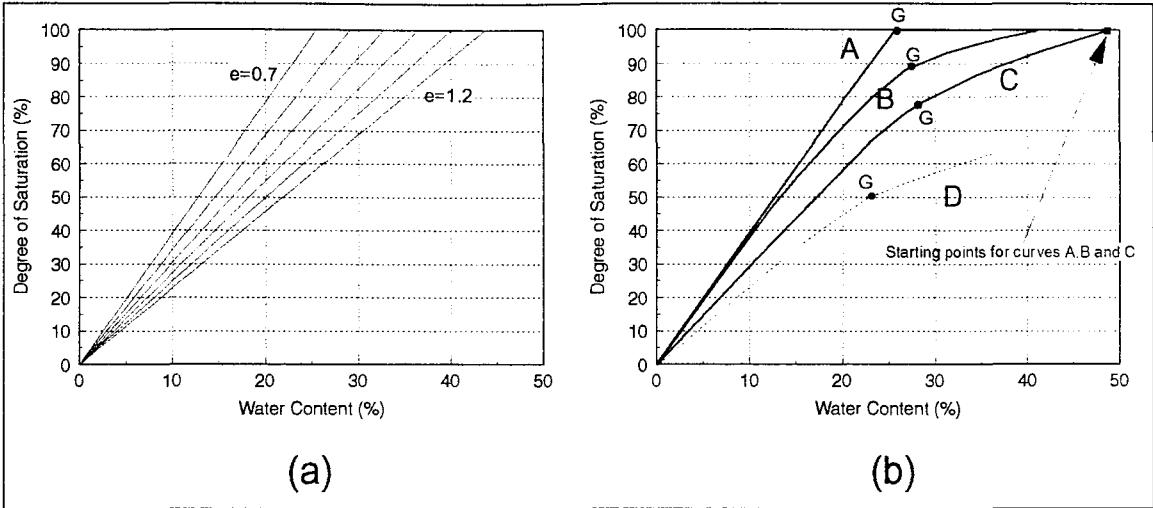


Figure 5.11 - Degree of saturation versus water content showing (a) theoretical lines for same void ratio (b) general behaviour during drying.

For a plastic soil, the drying curve has a well defined linear portion as shown schematically in figure 5.12. The slope of the drying curve¹ will be called the Suction Capacity (C) and is defined as

$$C = \frac{\Delta w}{\Delta \log(\text{suction})} \quad \{5.1\}$$

The drying curve is unique for a particular soil with a given stress history. The effect of overconsolidation on the drying curve is shown in figure 5.12. The suction capacity (C) depends on the soil type.

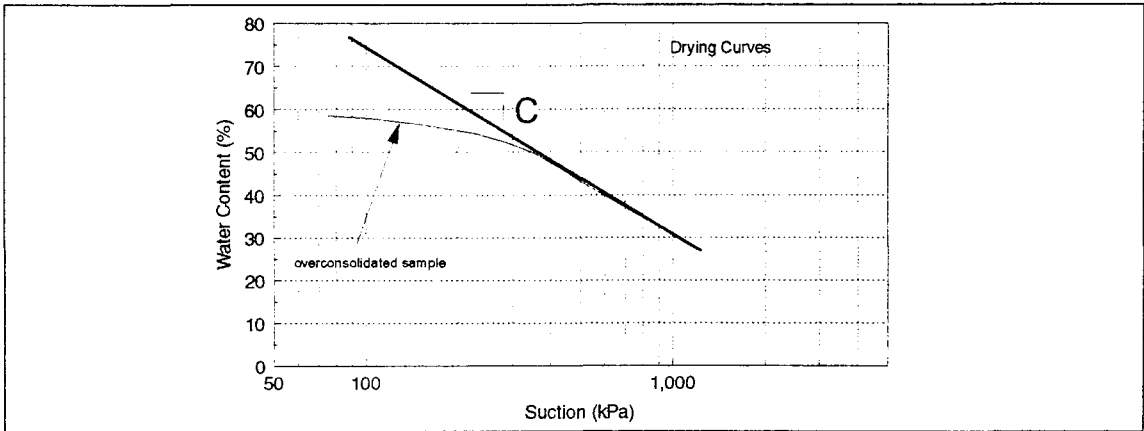


Figure 5.12 - Suction capacity definition and the effect of overconsolidation.

The correlation between C and Liquid Limit seems to be dependent on the stress history of the sample. Figure 5.13 shows results obtained from the literature² showing the effect of stress history on the magnitude of C in relation to liquid limit (the overconsolidated points shown in

¹ This quantity was probably first defined by Richards (1931) as Capillary Capacity, later Mitchell and Avalle (1984) called it Moisture Characteristic; Alonso et al (1987) defined it as Storage Term; Jucá (1990) called it Differential Water Content Capacity; Ho et al (1992) called it Water Content Index and Marinho and Chandler (1993) called suction capacity.

² Croney and Coleman (1954); Olson and Leonard (1965); Dumbleton and West (1968); Skempton (1970); Biarez et al (1987); Jucá (1989); Burland (1990); Ho et al (1992) and Fleureau et al (1993).

figure 5.13 are from the present work).

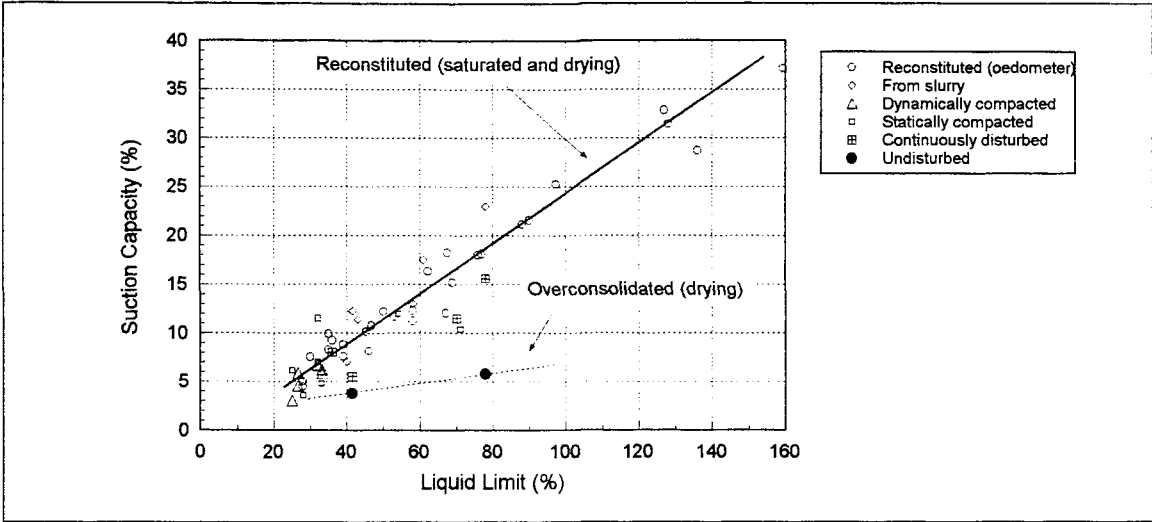


Figure 5.13 - Relation between suction capacity and liquid limit (data from literature).

In terms of volume change as a function of increasing suction, the behaviour is similar to mechanical compression. The processes are comparable until the "effectiveness" of the suction is reduced. This reduction in effectiveness of the suction is probably associated with the non-uniformity of the stresses inside the sample. Figure 5.14 shows the path followed by a drying sample. The increase in suction, due to water content reduction, corresponds to a decrease in void ratio. If the sample is initially saturated, the point B defines the desaturation point. If not it defines the GAE point. At B, the "effectiveness" of the suction is reduced as air penetrates the sample, with a corresponding reduction in the overall volume change. The dashed line in figure 5.14 represents the mechanical isotropic consolidation line .

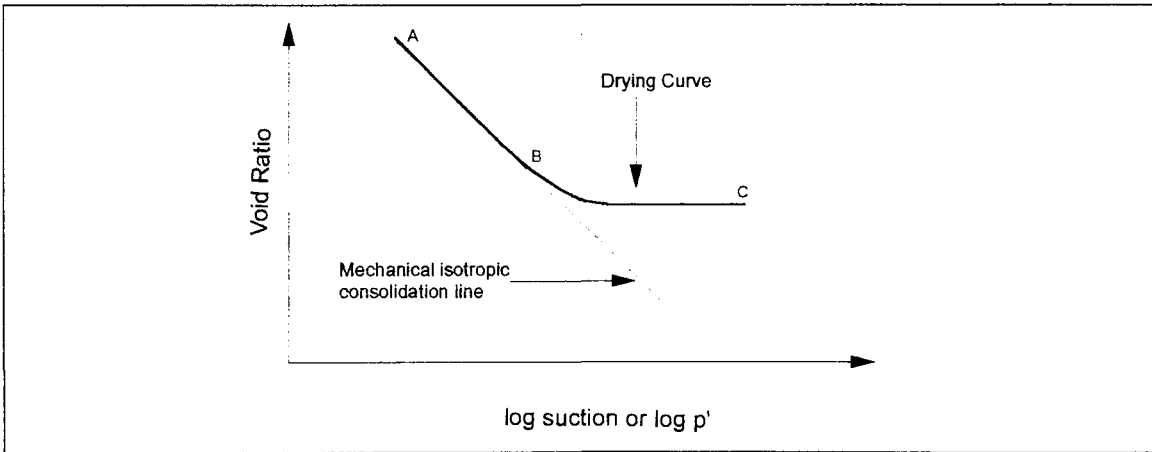


Figure 5.14 - Correlation between drying pressure and mechanical pressure.

The results presented in figure 5.13 show the similarities between mechanical compression and drying for saturated samples. Blight (1965) showed that the volumetric shrinkage produced by mechanical pressure, suction and gravitational head are equivalent when the soil is saturated. The results obtained by Blight are shown in figure 5.15. Biarez *et al.*(1987) also reached a similar conclusion: the relationship between void ratio and pressure was obtained by drying

(suction), using an oedometer and applying an isotropic pressure. It was shown that isotropic mechanical compression gave similar paths to the drying, but that the results from the oedometer were different, since it controls the vertical pressure only. Further data related to this comparison can be found in Soemitro (1994).

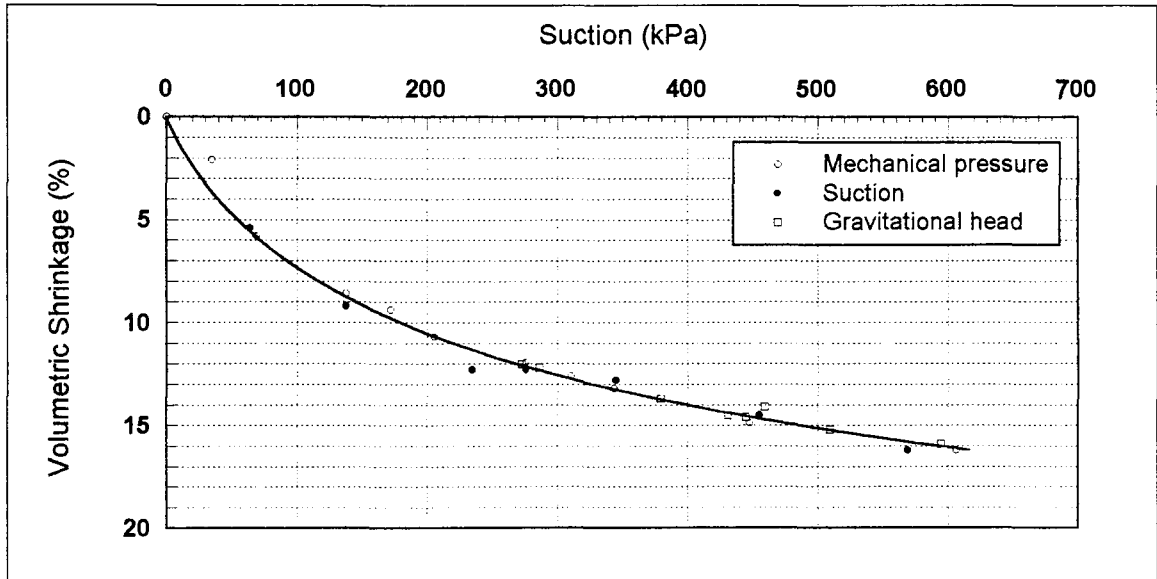


Figure 5.15 - Relationship between volumetric shrinkage and isotropic effective stress for a remoulded saturated clay, showing the equivalence in the saturated range of effective stresses produced by mechanical pressure, suction and gravitational head. (from Blight, 1965).

5.3.2 The Air Phase in Unsaturated Soil

The air in unsaturated soils can exist in two states: connected and occluded. The air pressure for the connected state is usually atmospheric pressure. The air in the occluded state can have a positive pressure (greater than atmospheric). It is well recognized that the presence of air within the soil increases its compressibility and decreases its permeability to water (*e.g.* Fredlund and Rahardjo, 1993a).

Olson (1963) suggested that the optimum point in the compaction curve is associated with the occlusion of the air. He also observed that the air permeability when the air is occluded is zero. Marsal (1979) pointed out that the occlusion is not dependent on the optimum water content since the latter depends on the energy and procedures used for compacting the soil. He suggested that occlusion is more appropriately associated with the degree of saturation (*e.g.* de Mello, 1958; Sandroni, 1985). Testing samples with a continuous air phase, Sandroni and Barbosa da Silva (1988) and Lins and Sandroni (1994) used the degree of aeration (ratio of the volume of air to the total volume of the sample), to relate to the occlusion point. Occlusion was reached by increasing the confining stress. Lins and Sandroni gave a theoretical model for representing the development of pore-air and pore-water pressure during compression at constant water content tests. Figure 5.16 illustrates this model. In this figure the air in the

sample at the beginning of the test is connected and subjected to atmospheric pressure. At this stage the sample has a suction. The air is allowed to drain, and, as the sample compresses, the degree of saturation increases and the suction reduces. Lins and Sandroni (1994) suggested that after occlusion, the pore-water pressure may be positive or negative, depending on the relative magnitude of the capillarity tension and pore air pressure. They defined the *positivation pressure* as the pressure where the suction is zero, and concluded that, for the soil tested, there is a unique degree of aeration at which positivation occurs. The samples were obtained by static compaction of a residual soil (LL=78%, PL=32%).

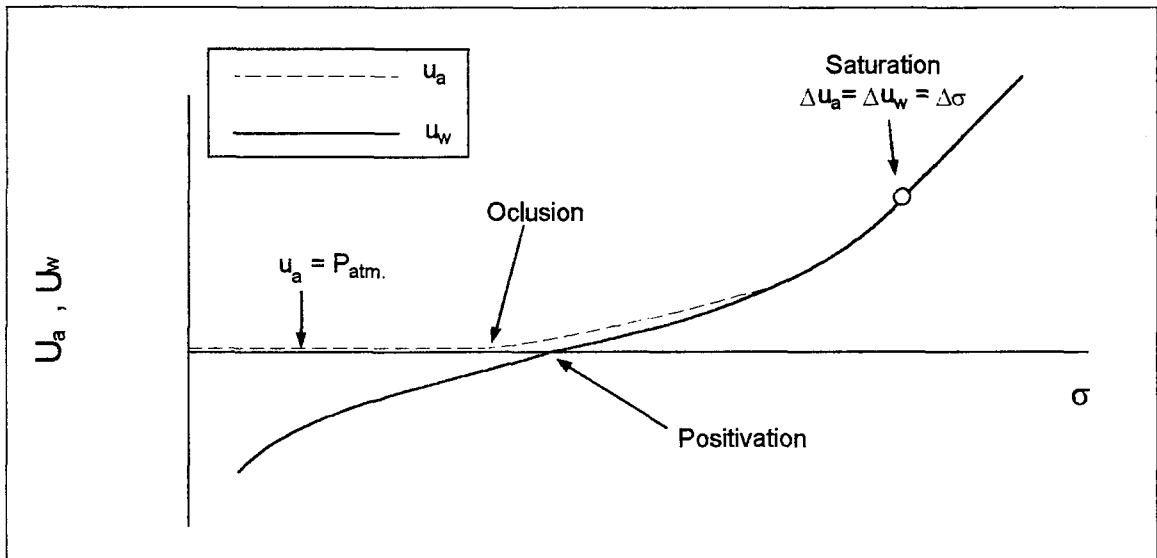


Figure 5.16 - Theoretical model for occlusion and positivation (from Lins and Sandroni, 1994).

For compacted soils the air can be occluded or continuous depending on the degree of saturation. The air phase is normally continuous at a degree of saturation of about 80% or lower. This means that when compacted, the air will be trapped in the soil mass if the degree of saturation is higher than 80% (e.g. Fredlund and Rahardjo, 1993a). The air state, occluded or continuous, is a function of the path followed to reach a particular degree of saturation, and also depends on the initial degree of saturation.

The soil type may influence the formation of occluded air as suction is increased, since in a granular soil or a soil with clusters of granular material, the increase of suction may allow cavitation to occur within the soil mass.

Another possible mechanism of occlusion of air within the soil mass is described by Chahal (1964) and Peck (1969). When an initially saturated plastic soil undergoes drying, desaturates, the air normally becomes connected. Chahal (1964) and Peck (1969) suggested that during drying, air can be trapped due to the movement of water. In their model, the volume of air trapped varies from zero at complete saturation to a maximum at some intermediate water content, and then, when all the pores have been drained, decreases to zero again. Figure 5.17 illustrates the two models of air state during the drying of initially saturated samples.

Peck (1969) showed that when the air pressure is higher than the water pressure the air bubble is not in equilibrium and it will dissolve. This may reduce the importance of air occlusion in the long term.

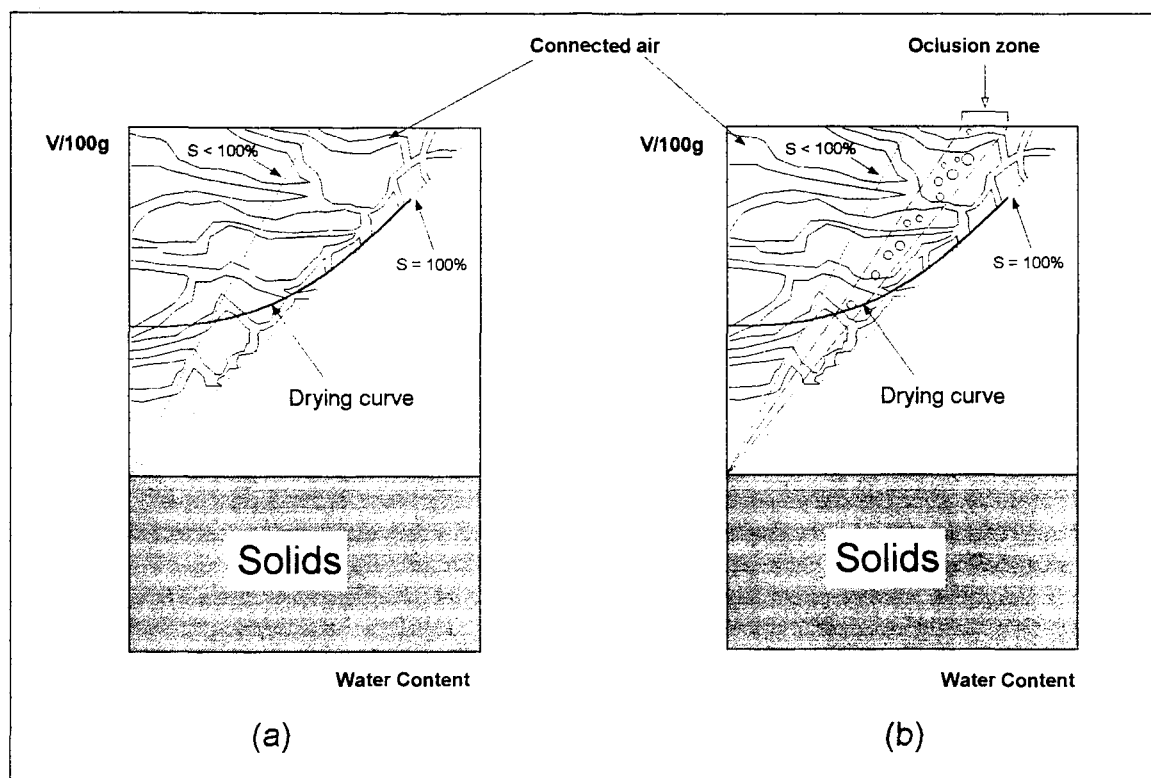


Figure 5.17 - Air states during the drying process a) after desaturation the air is connected throughout b) air become occluded at some stage after desaturation.

5.3.3. Soil Suction and Shrinkage Phenomena

5.3.3.1. Soil Suction and Soil Volume Change

Most of the problems associated with the shrinkage of soils occurs under a constant value of the net normal stress state variable³ ($\sigma - u_a$), while the matrix suction stress state variable ($u_a - u_w$) changes (Fredlund and Rahardjo, 1993a). Matrix suction can be used to predict soil volume changes when *volumetric deformation coefficients* are obtained (Fredlund and Rahardjo, 1993a). There are several formulations which use matrix suction to determine volume change indices. Hamberg (1985) [referred to by Fredlund and Rahardjo, 1993a] gives a compilation of the more important definitions of volume change indices with respect to suction changes. The main references and the description of the indices used are as follows.

Grossman et al.(1968) - Uses the value of linear strain corresponding to a suction change from 33kPa to the oven dry state.

U.S.D.A. Soil Conservation Service (1971) - Use the ratio of the bulk density of the oven dry

³ A stress state variable is defined as the nonmaterial variables required for the characterization of the stress condition. These should be independent of the physical properties of the soil (e.g. Fredlund and Rahardjo, 1993a).

sample and the bulk density of the sample at a suction of 33kPa.

Aitchison and Martin (1973) - Use the slope of the vertical strain versus logarithm of total suction curve.

Jonhnsn (1977) - Uses the slope of the water content versus suction curve.

Lyton (1977); McKeen (1981) - Use the slope of the volumetric strain versus log total suction curve.

Fargher et al (1979)- Use the slope of the vertical strain versus log matrix suction curve.

Fredlund (1979) - Uses the slope of the void ratio versus log matrix suction curve.

Ho *et al.* (1992) gave the following definitions and terminology for the volumetric deformation coefficients in terms of void ratio and water content.

Void ratio:

$$a_t = \frac{\delta e}{\delta(\sigma - u_a)} \quad \text{or} \quad C_t = \frac{\delta e}{\delta \log(\sigma - u_a)} \quad \{5.2\}$$

$$a_m = \frac{\delta e}{\delta(u_a - u_w)} \quad \text{or} \quad C_m = \frac{\delta e}{\delta \log(u_a - u_w)} \quad \{5.3\}$$

Water content:

$$b_t = \frac{\delta w}{\delta(\sigma - u_a)} \quad \text{or} \quad D_t = \frac{\delta w}{\delta \log(\sigma - u_a)} \quad \{5.4\}$$

$$b_m = \frac{\delta w}{\delta(u_a - u_w)} \quad \text{or} \quad D_m = \frac{\delta w}{\delta \log(u_a - u_w)} \quad \{5.5\}$$

These coefficients can be combined as follows:

$$C_t = \frac{a_t(\sigma - u_a)_{ave}}{0.435} \quad \{5.6\}$$

$$C_m = \frac{a_m(u_a - u_w)_{ave}}{0.435} \quad \{5.7\}$$

$$D_t = \frac{b_t(\sigma - u_a)_{ave}}{0.435} \quad \{5.8\}$$

$$D_m = \frac{b_m(u_a - u_w)_{ave}}{0.435} \quad \{5.9\}$$

where $(\sigma - u_a)_{ave}$ is the average of the initial and final net normal stresses increment, and $(u_a - u_w)_{ave}$ is the average of the initial and final suction increment.

5.3.3.2. Soil Suction and the Water Content

The relationship between water content and suction has been extensively studied and more studies are still required (e.g. Fredlund and Rahardjo, 1993b). Much of the early work was performed for agricultural purposes, and Croney and Coleman (1954) were probably the first to study the structure of the soil as affected by change in suction using the water content for soil mechanics applications. Figures 5.18 and 5.19 show results obtained by Croney and Coleman (1954) for two soils, a clay (London clay) and a silty clay. In figure 5.18 the curve A represents the first drying curve of an undisturbed sample. Curve B is the wetting path of the same undisturbed sample and the curve C is the second drying of the same sample. Curve D represents the drying curve of an initially slurried soil. The loops E and F are for initially slurried samples that were wetted after they had reached a certain suction, and then allowed to dry again. Curve G is called the continuously disturbed line. It was obtained with a slurried soil (water content well above the liquid limit). Using the Casagrande apparatus for determination of the liquid limit, the soil was submitted to a number of blows necessary to close the groove and then the suction and water content were determined. In figure 5.18, the number of blows applied to some of the points on curve G are given.

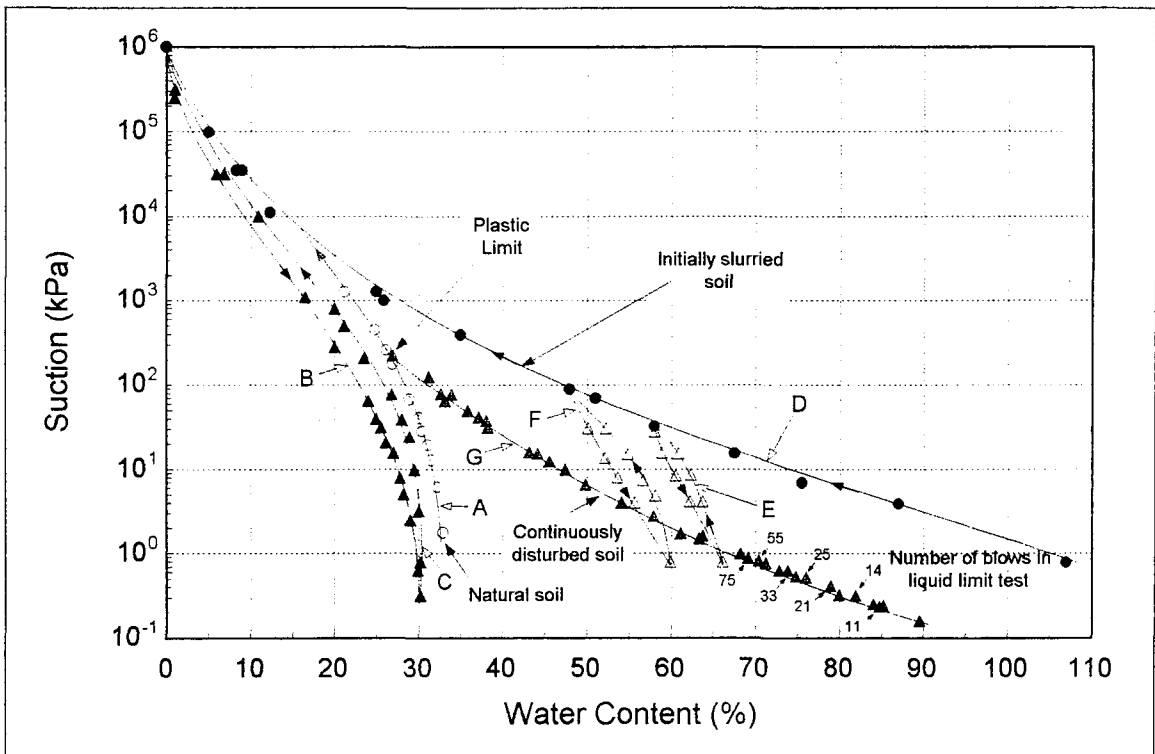


Figure 5.18 - Suction - water content relationships for London Clay (from Croney and Coleman (1954)).

Croney and Coleman (1954) found that if a soil is disturbed without change of water content, it assumes a suction given by curve G at that water content irrespective of its initial suction. The main conclusion stated by them was: "If the suction/water content relationship of the soil is represented by a point above the line G, disturbance causes a decrease in suction to the value

given by the line at the water content of the sample. On the other hand, if the initial suction is represented by a point below the line G, disturbance will be accompanied by an increase of suction." They also pointed out that the curve G "may be of importance as representing the suction of the soil during shearing." It was concluded that the continuously disturbed curve obtained using the liquid limit apparatus, is unique for each soil.

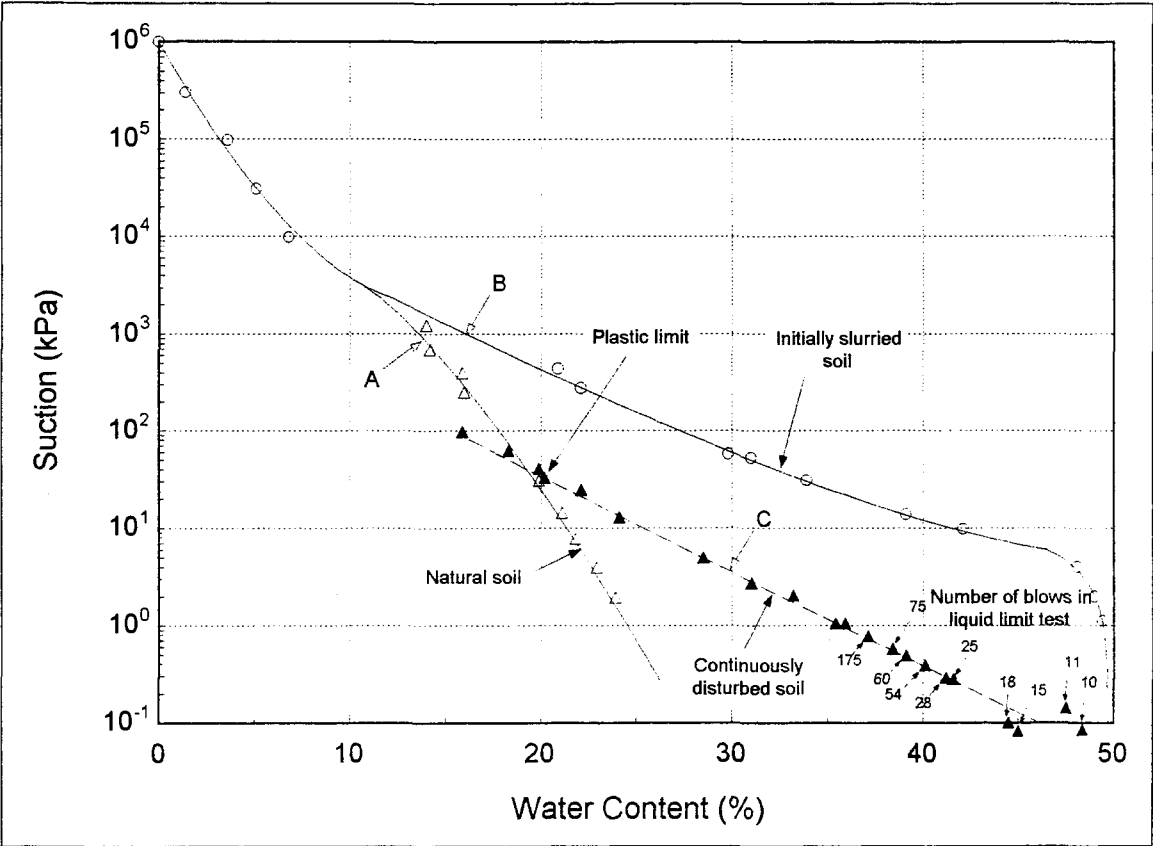


Figure 5.19 - Suction - water content relationships for a silty Clay (from Croney and Coleman (1954)).

In 1961 Croney and Coleman suggested a relationship between unconfined compressive strength and continuously disturbed suction for a heavy clay. Figure 5.20 shows this relationship. The continuously disturbed suctions were obtained from the unique suction curve from figure 5.18 at the same water content as the unconfined strength was determined. The relationship obtained was linear over the range tested. It was observed that the unconfined strength rose only slightly for an initial suction greater than 10MPa; it was believed that this was due to desaturation of the soil.

Bishop *et al.* (1975) performed unconfined compression tests on samples of London clay. They compared the results obtained with two types of samples, having the same water content. One type of sample was consolidated by mechanical compression and then unloaded, and the other consolidated by drying. It was concluded that there is no unique relation between strength and water content for the two types of samples tested, because the samples consolidated by drying seem to desaturate at a much lower water content than the unloaded consolidated samples.

The desaturation water content for the sample undergoing drying was about 25%, which using Croney and Coleman (1954) data (see figure 5.18), gives a suction of approximately 500kPa. Any mechanical compression beyond 500kPa (or the suction at the general air entry value, 2MPa) will give a reduction in void ratio that the drying process is not able to reproduce. When the consolidation pressure is released the soil sample can remain saturated, depending on the soil characteristics, but even if a reduction in the degree of saturation is observed, the degree of saturation will still be higher than that of the drying sample at the same water content. Although the two types of sample may have the same value of suction, the sample consolidated by mechanical compression was submitted to a higher effective stress than the drying process was able to produce.

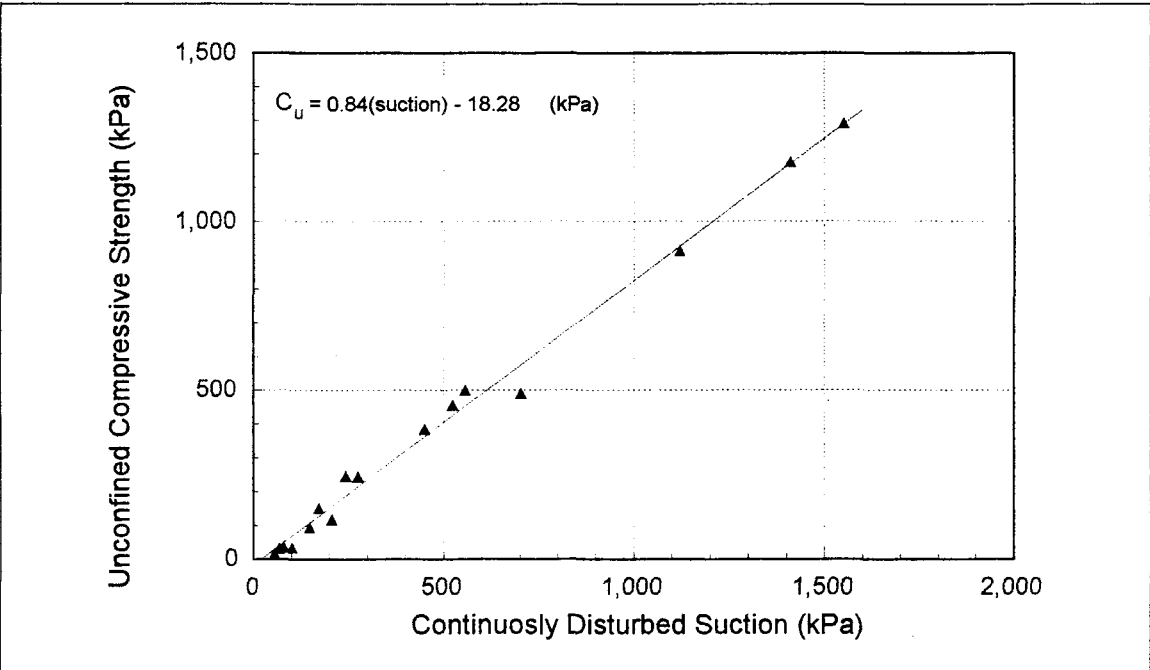


Figure 5.20 - Relationship between continuously disturbed suction and unconfined compressive strength for a heavy clay (from Croney and Coleman ,1961).

More recently Brady (1988) suggested that the continuously disturbed line can be related to the critical state line. Using data from the literature it was shown that there is a close relationship between the critical state and the continuously disturbed state. Figure 5.21 shows what Brady called "*a crude comparison*" between soil suction and critical state data for London clay. He concluded that the continuously disturbed line determined from soil suction tests and the critical state line are identical.

Toll (1990) pointed out that, due to the difficulties involved in defining the effective stresses in unsaturated soils, it is not easy to analyse unsaturated test data within the critical state framework. Toll used a lateritic gravel (LL=56 to 66%, PL = 27 to 31%) to examine the relationship between water content and change in suction during shear. It was observed that samples with initially low suction ($\approx$ 50kPa) showed an increase in suction under shear. For samples having a high initial suction a reduction in suction was observed. This behaviour seems

to agree with the hypothesis presented by Croney and Coleman (1954), described previously, where a soil may increase or decrease its suction depending whether it is below or above the continuously disturbed line.

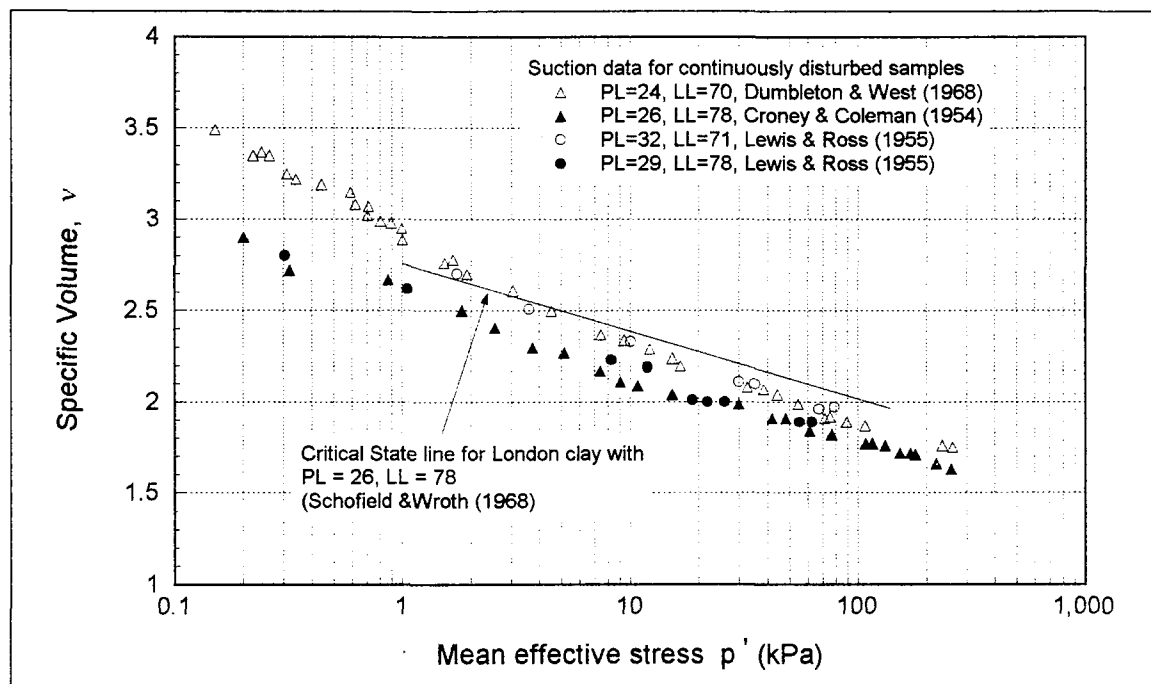


Figure 5.21 - Relationship between specific volume and logarithm of the mean effective stress (from Brady, 1988).

5.3.3.3. Soil Suction and the Degree of Saturation

Since Bishop's seminal lecture of 1955 the degree of saturation has been used as an auxiliary parameter for unsaturated soils. Bishop's parameter χ is a function of the degree of saturation (e.g. Blight, 1961; Jennings and Burland, 1962), though the relationship between degree of saturation and χ is extremely dependent on the soil type and its initial condition. Fredlund *et al.* (1978) introduced the parameter ϕ^b , which is defined as the angle indicating the rate of increase in shear strength relative to matrix suction. Since ϕ^b is related to χ by the equation

$$\chi = \frac{\tan \phi^b}{\tan \phi'} \quad [5.10]$$

ϕ^b is also a function of the degree of saturation.

Blight (1965) gave a relationship between χ and suction for an expansive clay, showing the dependence of this relationship with the mode of water absorption by the soil (e.g. constant volume, constant load, etc.).

When defining a constitutive equation for shear strength or volume change of partly saturated soils, two independent stress parameters are required, $\sigma - u_a$, (net stress), and $u_a - u_w$, (matrix suction) are commonly used (Burland, 1965; Fredlund and Morgenstern, 1977). Soil parameters required for shear strength are c' , ϕ' and ϕ^b , while for volume change the *volumetric*

deformation coefficients may be used (see section 5.3.3.1).

Brooks and Corey (1966) proposed three parameters derived from the relationship between degree of saturation (S) and suction, the residual degree of saturation (S_r), the pore size distribution index (λ), and the air entry value of the soil $(u_a - u_w)_b$. The residual degree of saturation is defined as the degree of saturation at which an increase in matrix suction does not produce a significant change in the degree of saturation. The other two parameters are obtained from the relationship between effective degree of saturation (S_e)⁴ (Corey, 1954) and suction.

$$S_e = \frac{(S - S_r)}{(1 - S_r)} \quad \{5.11\}$$

Figure 5.22a presents the relationship between degree of saturation and suction, showing the residual degree of saturation. In their experiment Brooks and Corey (1966) used an hydrocarbon as test fluid. Hydrocarbon was used, since it gives a more stable structure for the soil than the water. They pointed out that no difficulty was experienced in determining the residual saturation. However, they say that *"it is possible to conceive of media in which it might be difficult to determine residual saturation, particularly if the wetting fluid is water and the medium is clay."*

The pore size distribution index (λ) is defined as the negative slope of the effective degree of saturation versus matrix suction. Soils with uniform grain size distribution (uniform pore size distribution) tend to have large values of λ and soils with a wide range of pore sizes tend to have a small value of λ . Figure 5.22b presents typical values of the pore size distribution index for various soils. The air entry value is defined as the matrix suction value that must be exceeded before air recedes into the soil pores⁵. In figure 5.22b the air entry value for each soil is shown. For matrix suction greater than the air entry value the effective degree of saturation can be expressed by the following equation:

$$S_e = \left\{ \frac{(u_a - u_w)_b}{(u_a - u_w)} \right\}^\lambda \quad \{5.12\}$$

⁴ The effective degree of saturation is sometimes called irreducible saturation in the petroleum literature

⁵ In the petroleum engineering it is called "displacement pressure" and in ceramic engineering "bubbling pressure" (Corey, 1977).

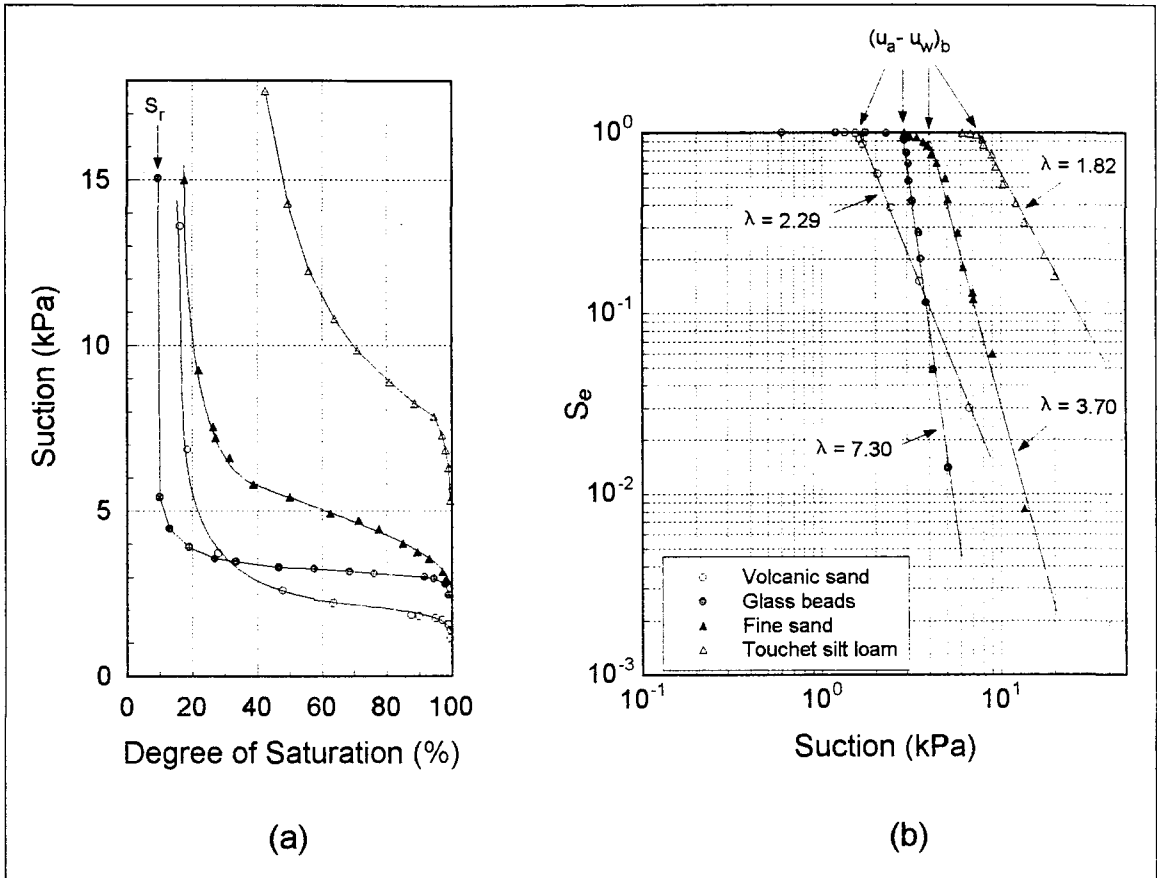


Figure 5.22 - Matrix suction versus degree of saturation curves for various soil (a) matrix suction versus degree of saturation curves, (b) effective degree of saturation versus matrix suction. (from Brooks and Corey, 1966).

Matyas and Radhakrishna (1968) suggested that the void ratio (e) and the degree of saturation (S) can be expressed as stress dependent quantities. Under triaxial state of stress e and S can be expressed by the functions,

$$e = F(\text{mean effective stress, deviatoric stress, suction, } e_o, S_o) \quad \{5.13\}$$

$$S = \phi(\text{mean effective stress, deviatoric stress, suction, } e_o, S_o) \quad \{5.14\}$$

They pointed out that F and ϕ may or may not be unique functions depending on the stress and saturation path followed. Barden *et al.* (1969) also observed that hysteresis between saturation and desaturation processes is the major cause of loading path dependence.

The importance of the initial degree of saturation in controlling the final volume of the shrinkage process was shown by Livneh *et al.* (1971). Using a compacted soil (LL=72%, PL=31%) they determined the relationship between initial degree of saturation and the final porosity, obtaining a linear relationship. Figure 5.23 presents the results obtained by Livneh *et al.* (1971) but in terms of void ratio. It can be seen that there is a very consistent relationship between the initial degree of saturation and the final void ratio. The initial void ratio is also plotted for reference. They concluded that samples tested from a slurry give lower final porosities than compacted samples, even if both samples start from the saturated condition. This is probably a reflection of

the initial fabric. This indication reinforces Toll's (1990) suggestion, that the degree of saturation can be used as an indicator of the soil fabric. Toll referred only to compacted soils prepared under similar conditions.

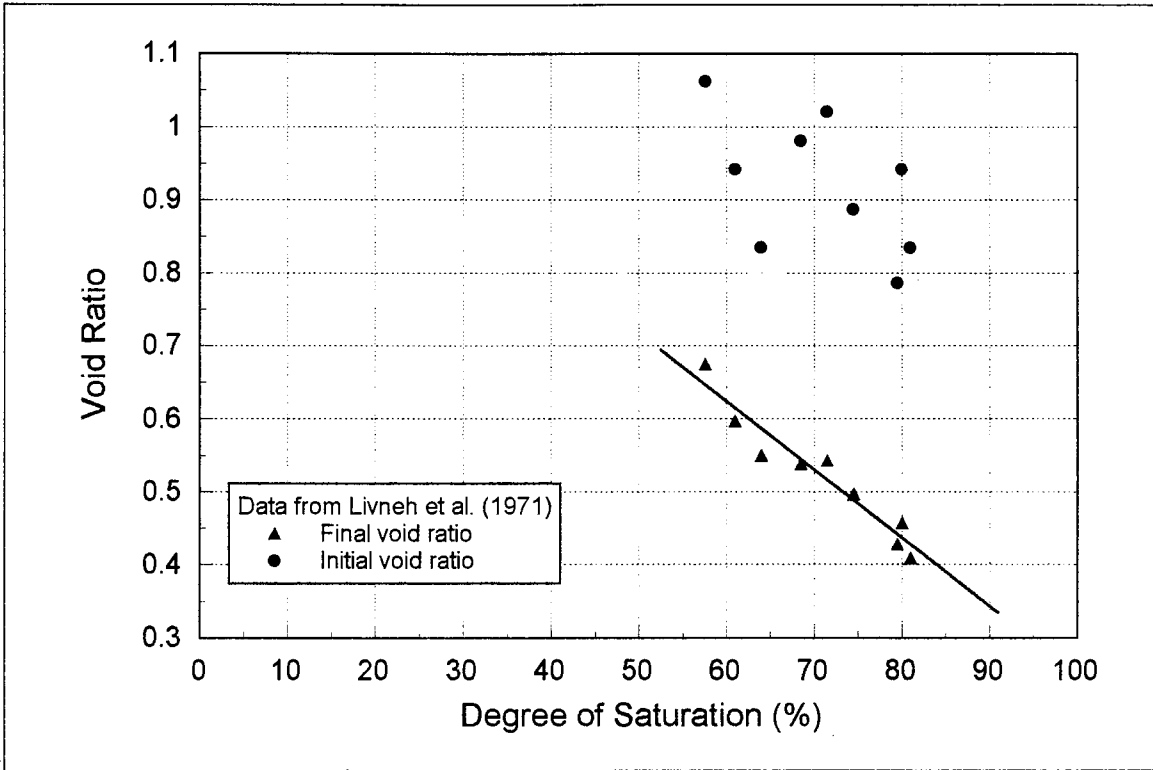


Figure 5.23 - Relationship between void ratio at the end of shrinkage and initial degree of saturation.

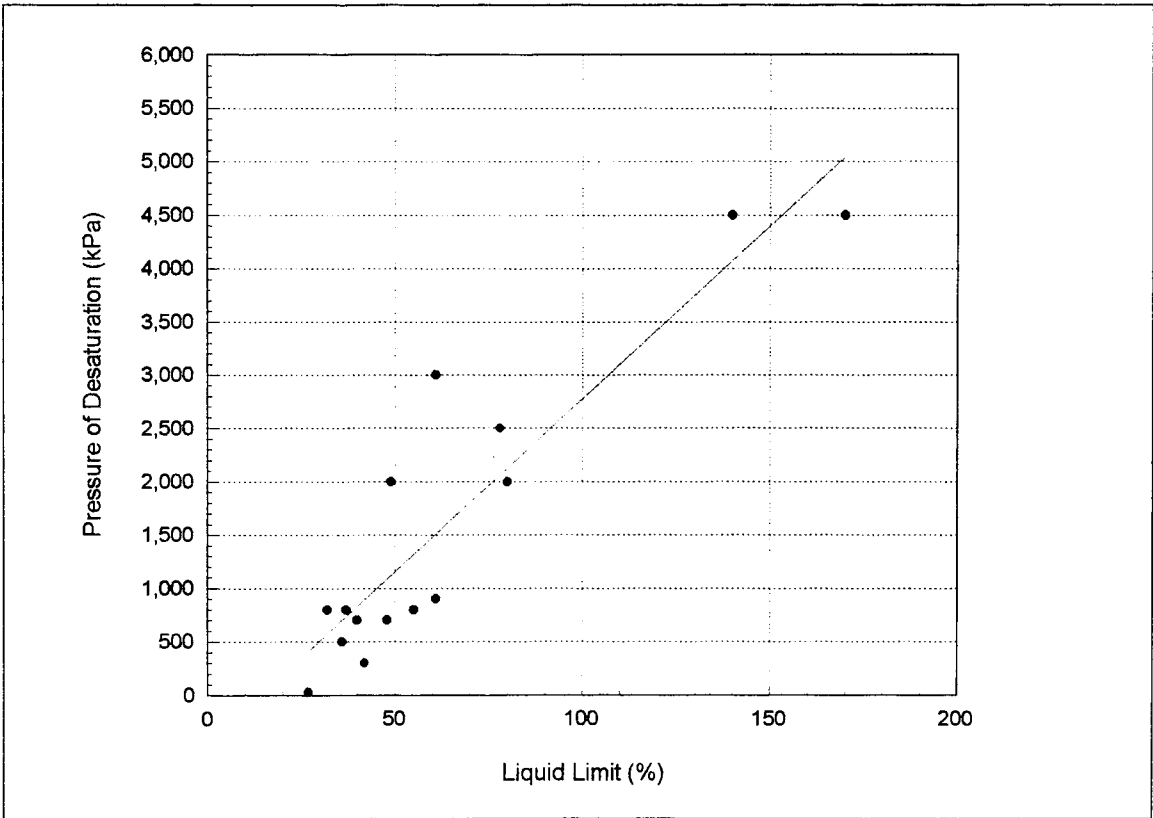


Figure 5.24 - Relationship between the desaturation pressure and the liquid limit (from Fleureau et al., 1993).

Fleureau *et al.*(1993) presented a series of drying and wetting tests using eleven different soils. The samples were prepared in many different ways (*i.e.* slurries, consolidated, compacted and undisturbed). The relationships between degree of saturation and suction were presented for the drying and wetting paths. It was found that the desaturation pressure of a slurry can be correlated with the liquid limit. Figure 5.24 shows the relationship between the desaturation pressure and liquid limit. Fleureau *et al.*(1993) pointed out that the desaturation pressure appears mainly to be dependent on the pore size distribution of the soil, rather than on the liquid limit.

CHAPTER 6

Materials, Techniques and Procedures

This Chapter presents a detailed description of the soils used and the techniques and procedures applied throughout the thesis. These techniques and procedures were used to provide the data which are presented in the following chapters.

6.1 Soils Used

The soils tested in this thesis are of two types: naturally occurring soils and artificially mixed soils. Table 6.1 presents the characteristics of all soils tested. The figures in which the grain size distribution of each of the soils appears are also referred to in table 6.1. The clay used in the clay/silt mixtures was London clay from Chattenden, and for the clay/sand mixture London clay from an unknown place was used. The silt and the sand were industrial materials. The soils LC105 and LC500 are originally London clay that were placed in the oven under a temperature of 105°C and 500°C, respectively, for 24 hours. The specially compressed bentonite is a industrial material commercially available from Rawell Water Control Systems LTD.

6.2. Sample Preparation

Five type of samples were used in this thesis and the following sections describe each of these samples. The samples were classified in undisturbed, slurried, statically compacted, dynamically compacted and continuously disturbed.

6.2.1. Undisturbed Samples

The London clay samples from Chattenden and the Pentre silt sample were obtained from tubes samplers. The blue clay was obtained from an undisturbed block. The Pentre silt sample was kindly given by Miss Fiona Chow.

6.2.2. Slurried Samples

These samples were prepared by mixing air-dry soil with pure water (de-ionised) to a water content between 1.35 and 1.5 of the value at liquid limit (the London clay used was passed through a n°40 sieve). The soil was then left for moisture equalization for a minimum period of 24 hours. The samples were obtained by consolidating the slurry to 100kPa in the oedometer and then unloaded under undrained conditions. This procedure was used for all London clay

samples and mixtures. Only one sample of London clay was prepared by pouring the slurry into a sealed oedometer ring and allowed to dry from this state inside a sealed environment to obtain a slow drying. It was about six months before this sample could be handled, and then used for suction measurement.

The bentonite sample was mixed with water until a fluid state was reached. The fluid material was poured into a specially designed mould, covered internally by filter paper with a very fine sieve at the bottom. The top of the mould was covered to avoid evaporation. The fluid mixture was then allowed to drain freely for approximately two months. The sample was then removed from the mould and kept wrapped in plastic film for about four months.

Soils	Location	Type of sample*	LL (%)	LP (%)	% <2 μ m	G	Grain size distribution figure
London clay	Chattenden	U, SC, SL	89	32	64	2.75	6.1
L105	Chattenden	SC	84	31	66	2.75	6.1
L500	Chattenden	SC	50	34	22	2.75	6.1
Pentre silt	Shropshire	U	30	22	10	2.79	6.2
Kaolin	Commercially available	SC, CD	64	32	63	2.63	6.5
80% Kaolin + 25% silt + 25% sand	mixture	SL	36	17	47	2.63	6.5
Blue Clay	Italy	U, SL	63	27	50	2.75	-
Queenborough clay		U, CD	102	34	56	2.75	6.2
Janga clay	Brazil	SC	73	28	58	2.75	6.2
Chalk	Kent	U					
Boom Clay	Belgium	SC	56	29	57.5	2.71	6.2
Bentonite	Commercially available	SL	402	45		2.8	-
Bentonite	Commercially available	specialy compressed	270			2.8	-
Carsington Clay	Carsington	DC	63	31	53.5	2.7	6.2
Clay/silt = 80/20	mixture	SL	73	29	54	2.73	6.3
Clay/silt = 70/30	mixture	SL	65	26	49	2.71	6.3
Clay/silt = 60/40	mixture	SL	43	22	44	2.7	6.3
Clay/silt = 40/60	mixture	SL	36	19	34	2.68	6.3
London Clay	-	SL	77	29	65	2.75	6.4
Clay/sand = 90/10	mixture	DC	69	24	59	2.74	6.4
Clay/sand = 70/30	mixture	DC	54	19	45	2.71	6.4
Clay/sand = 50/50	mixture	DC	40	17	32	2.69	6.4
Clay/sand = 30/70	mixture	DC	24	18	20	2.67	6.4

* U - undisturbed; SL - slurried; SC - statically compacted; DC - dynamically compacted; CD - continuously disturbed.

Table 6.1 - Characteristics of the soils tested.

The blue clay and Queenborough clay were kindly given by Miss Federica Cotechia and Dr. R.J. Jardine, respectively.

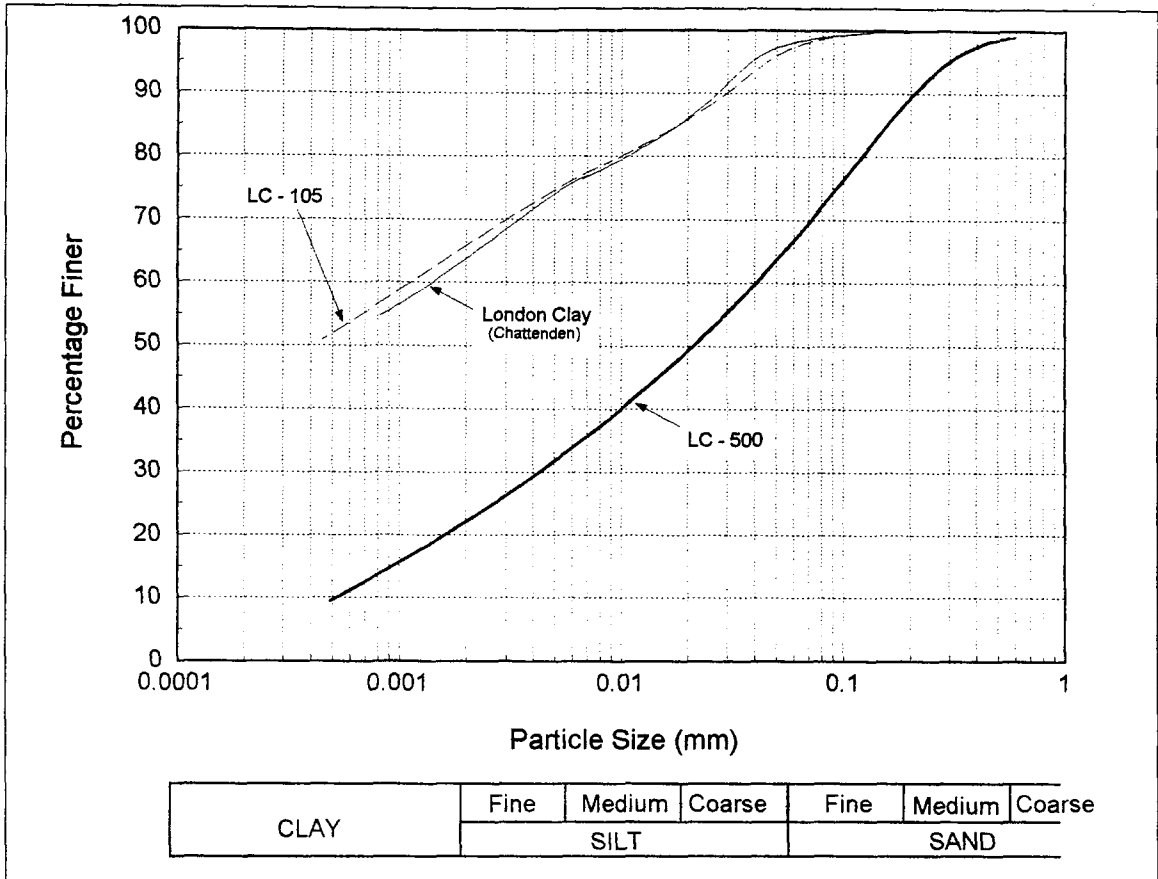


Figure 6.1 - Grain size distribution for London clay, LC-105 and LC500.

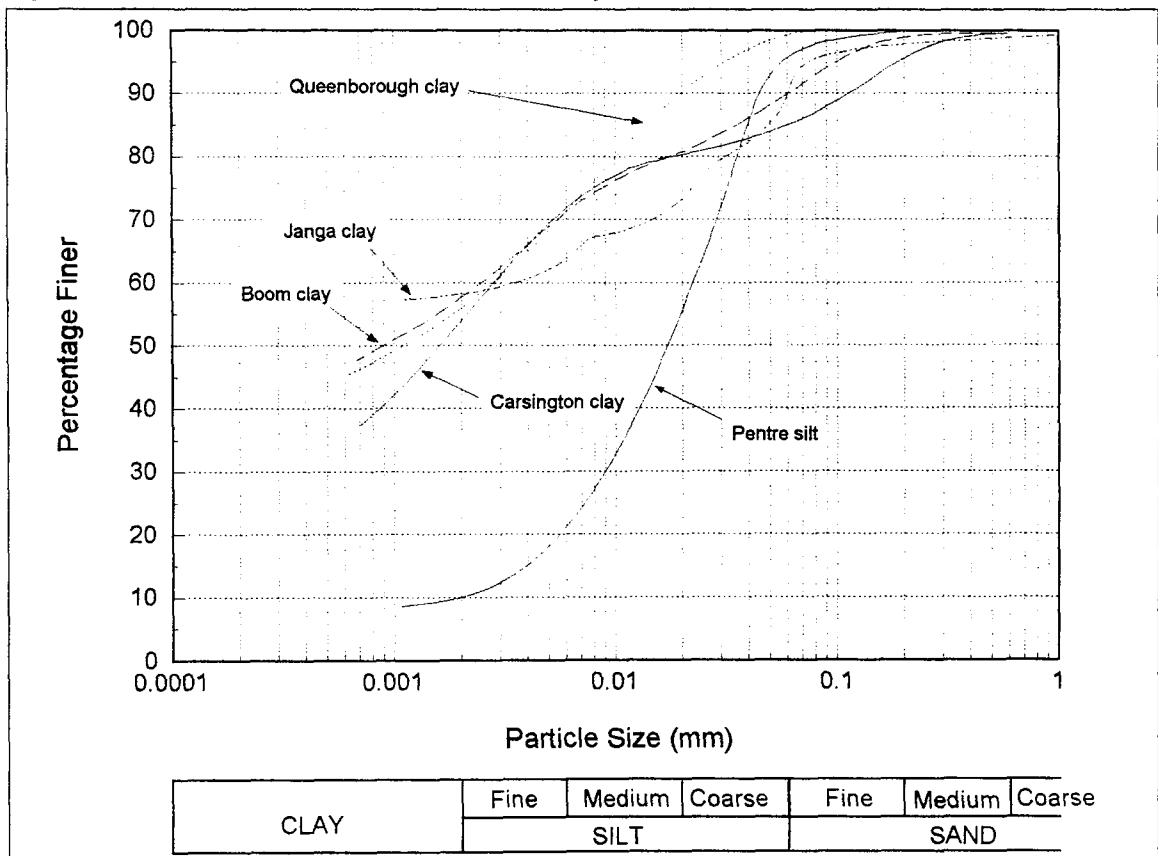


Figure 6.2 - Grain size distribution for Queenborough clay (from Smith, 1993), Janga clay, Boom clay, Carsington clay and Pentre silt (from Chow, 1995).

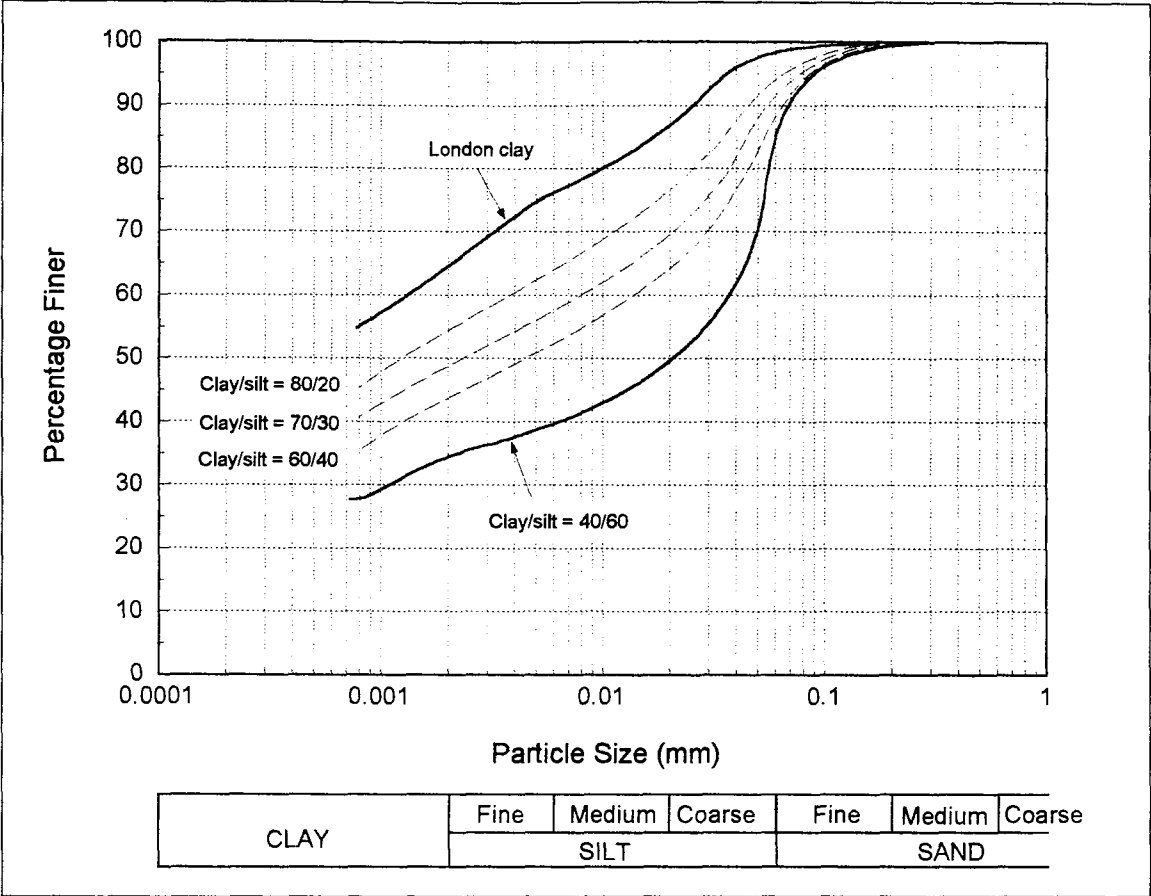


Figure 6.3 - Grain size distribution for the clay/silt mixtures.

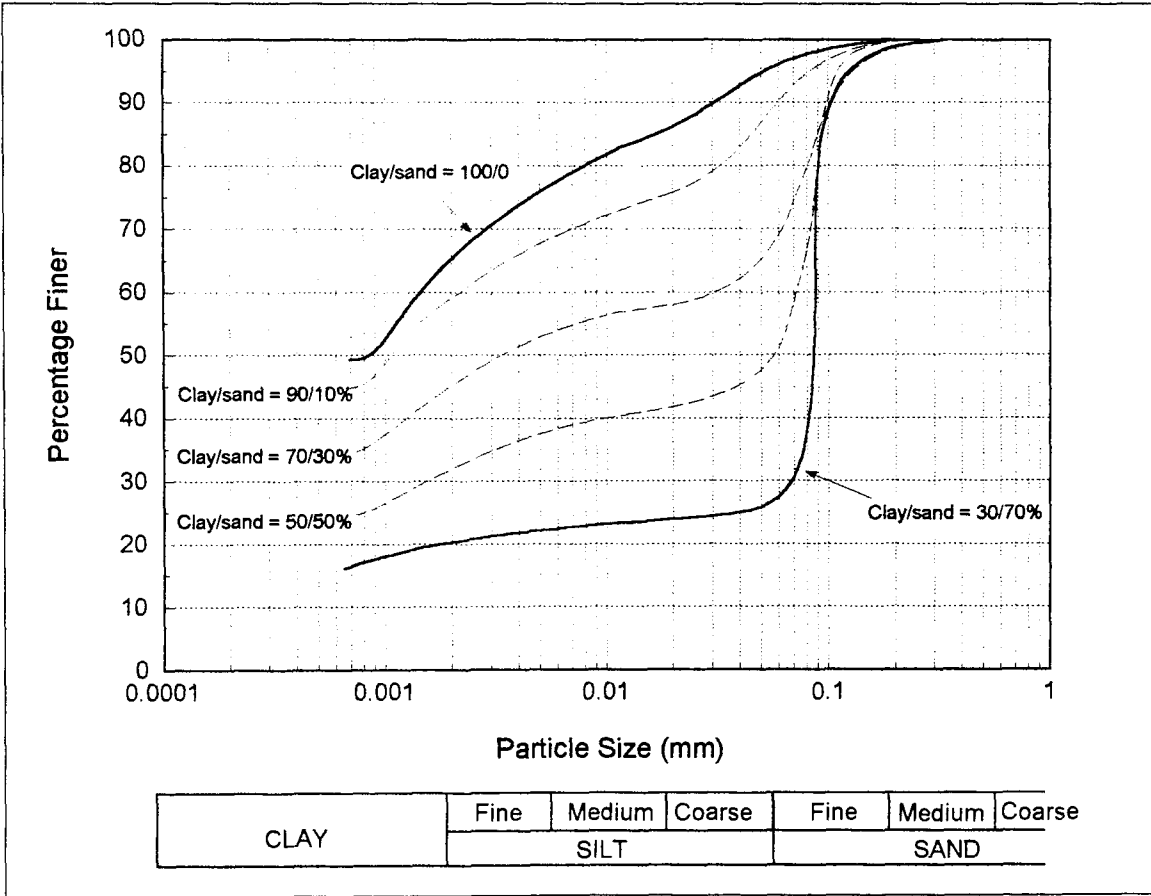


Figure 6.4 - Grain size distribution for the clay/sand mixtures.

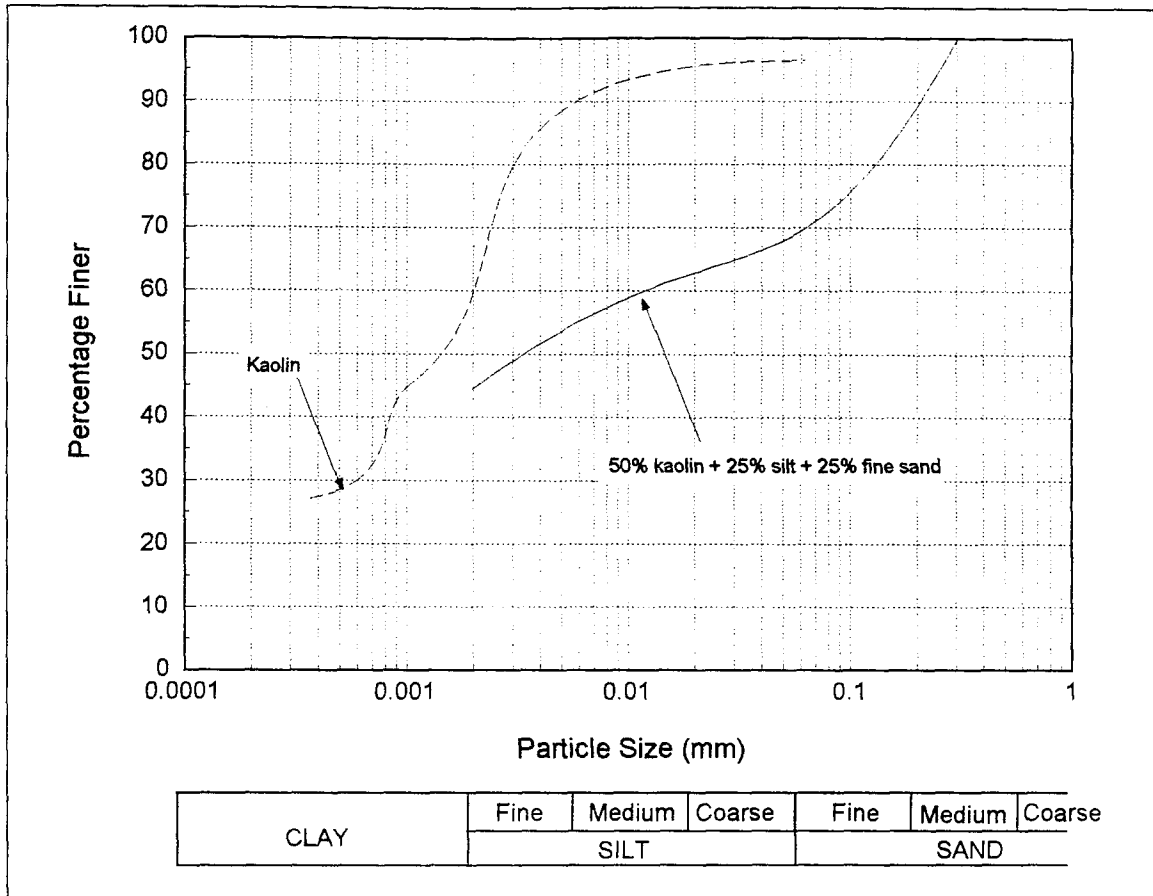


Figure 6.5 - Grain size distribution for kaolin and the mixture kaolin, silt and sand (from Ridley, 1993).

6.2.3. Statically Compacted Samples

In terms of the initial "fabric" of the soil before compaction, two types of samples were prepared. One in which the soil was passed through a n°40 sieve in a powder state, and another where initially "undisturbed lumps" of the soil sample were broken into small lumps having variable nominal diameters. The characteristics (*e.g.* initial water content, initial void ratio, *etc.*) of each sample prepared is given in chapter 7.

Samples prepared from powder.

The soils used for compaction were prepared from an air dried state and then ground and passed through n°40 sieve. Water was added in order to obtain specific water contents. The soil was left for moisture equalization for a minimum period of 24 hours. When mixed with water the soil formed lumps of variable sizes. Samples with uniform lumps sizes were prepared. The majority of samples were compacted into oedometer rings; those used for the bender element tests were prepared in a larger mould in order to increase the wave travel time.

Samples obtained from undisturbed lumps.

Originally undisturbed samples were broken into lumps of different sizes, and samples with uniform lumps sizes were prepared. The water content of these samples was not changed. All

samples were compacted into oedometer rings. This type of sample was prepared using the Janga clay.

The static compaction was performed using a triaxial loading frame, the compression being carried out until a pre-determined void ratio was reached. The samples were left under load for a minimum period of 2 hours. The samples were then unloaded and tested.

6.2.4. Dynamically Compacted Samples

The samples were all compacted in a 38mm diameter cylindrical mould, using a sliding weight of 1000g falling through 305mm. Each sample was compacted in 10 layers, with six blows per layer. This corresponds to a compactive effort, or work done per volume, of 2100kJ/m^3 , which compares to 596 kJ/m^3 for the AAHSTO/BS Standard Compaction Test and 2682 kJ/m^3 for the AAHSTO/BS Heavy Compaction Test. When compacted the samples had a length of approximately 75mm. Subsequent references to optimum water content relate to this particular compaction procedure, which, as can be seen, is quite close to the AAHSTO/BS Heavy Compaction Test.

Some practical difficulties were encountered with the 100/0% clay/sand mixture. When removing samples from the compaction mould the soil adhered to the mould wall strongly, making the removal of the sample difficult. It was also observed that slight cracking occurred between layers on drying.

6.2.5. Continuously Disturbed Samples

Two samples were tested using this technique, Kaolin and Queenborough clay. The technique consists in disturbing the soil before a suction measurement is made. The disturbance was obtained by vigorous and thorough mixing of the soil using a metal rod. Two methods of suction measurement were used: filter paper method and the tensiometer probe. When using the filter paper method the sample was left for equalization with the filter paper for 7 days. When the tensiometer probe was used the soil was also left to equalize for 7 days, after which the suction measurement was made.

After the suction measurement only part of the sample was used for water content determination. This procedure was necessary since due to the process of disturbance some soil is lost and it is not possible to back-calculate the water content at the end of the drying process (see section 6.4).

6.3. Suction Measurement

6.3.1. Filter Paper Method

The filter paper method is the main technique used in this thesis for suction measurement. A comprehensive description of the method is given in Chapter 4.

The procedure used was as follows:

- 1 - The filter paper used is Whatman N° 42.
- 2 - The filter paper were used in the air dry condition as it is in the box.
- 3 - The calibration used are the ones presented by Chandler and Gutierrez (1986) and Chandler *et al.*(1992). These calibrations are valid for total and matrix suction.
- 4 - The equilibrium time used for measuring matrix suction was 7 days, while for total suction a minimum period of 15 days was used. For total suction below 500kPa down to 200kPa, 30 days was allowed for equilibrium.
- 5 - A minimum of two filter papers were used per sample tested.
- 6 - The filter papers were never allowed to overlap. No filter paper or any absorbed material was used between the soil and the filter paper sensor.
- 7 - For total suction measurement a perforated plastic disk was used to separate the soil from the filter paper. An 'o-ring' was used between the disk and the filter paper in order to improve the flow and the distribution of the vapour to the filter paper (see figure 6.6)
- 8 - After the placement of the filter paper the samples were wrapped in two layers of plastic film ("cling film"). Sellotape was used in the second layer of plastic film to hold the filter paper firmly in place. The sample was placed into two sealed plastic bags and then left for equilibrium in a box insulated with polystyrene and located into a room with temperature variations of about $\pm 5^{\circ}\text{C}$.
- 9 - After the equilibrium time was reached, the filter papers were removed and placed in a flat plastic bag. The time between removing the filter paper, placing it into the bag and sealing the bag was approximately 5 seconds.
- 10 - The water content of the filter papers were determined using a balance with a resolution of 0.0005g (readable to 0.0001g). The filter papers were allowed to dry for at least 2 hours in the oven at 105°C .
- 11 - The removal of the filter papers from the oven and their placement in the plastic bags took less than 3 seconds.
- 12 - It is important to point out that extreme care was taken during all stages of the suction measurement. The filter paper was always handled with a pair of tweezers. The plastic bags were carefully labelled. The tin in which the filter papers were dried in the oven was also labelled. The plastic bag was weighted every time it was re-used.

In the majority of measurements taken the diameter of the filter paper used was 7.0 cm. However, there were instances when the size of the sample was small and filter paper

diameters down to 2.5cm were used. Care was taken during the cutting the filter paper to avoid the formation of loose fibres at the edges.

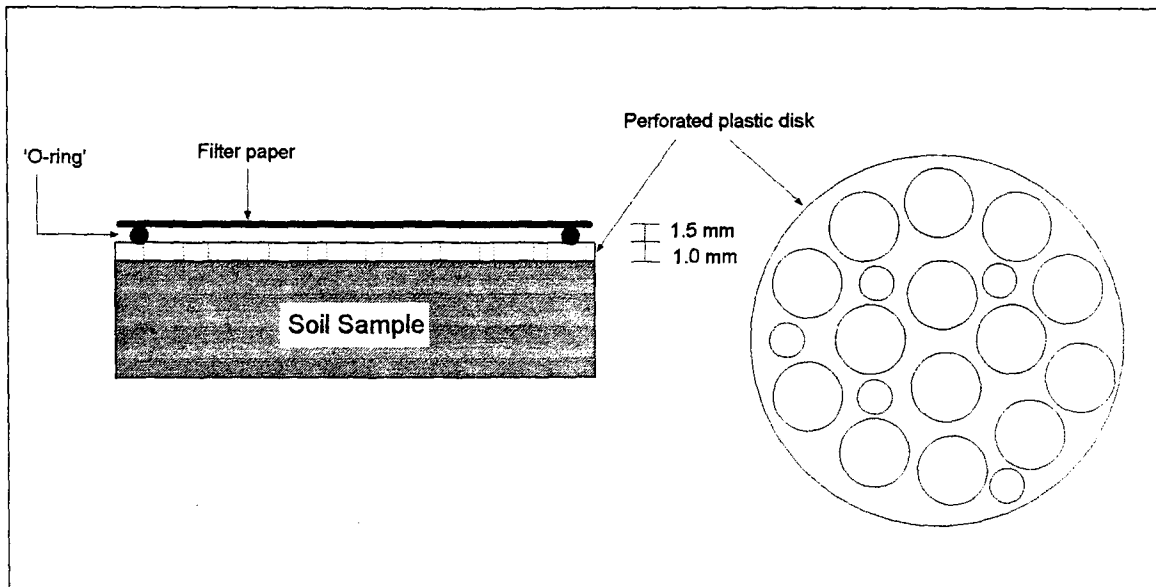


Figure 6.6 - Set up for total suction measurement using the filter paper method.

6.3.2. Pressure Plate Method

This technique was used for comparison with the filter paper method. The equipment used had a porous stone of 5 bars air entry value.

The sample was placed on the porous stone, and a specific air pressure applied to generate a known difference between the air pressure and the water pressure: that is, equal to the matrix suction. The equilibrium time used was 7 days. After this period the sample was removed, weighed, the dimensions measured with a vernier callipers, the volume calculated and the soil sample then replaced on the pressure plate under a higher suction.

6.3.3. Tensiometer

The tensiometer used is that described by Ridley and Burland (1993) and Ridley (1993). It is able to measure negative water pressure up to approximately 1.5MPa (ref. *idem*). Chapter 3 presents a comprehensive description on how it is possible to measure suction higher than the atmospheric pressure, using a tensiometer.

The samples used were simply placed in contact with the tensiometer which had previously been super-saturated at a high water pressure. The sample and the tensiometer were covered with plastic film to avoid eventual evaporation of the sample or/and porous stone. Care was taken to obtain a "good contact" between the soil and the porous stone of the tensiometer. An equilibrium time of 15 minutes was generally sufficient to obtain the measurement.

6.4. Drying Tests

The drying test is an extremely simple test in which a soil sample is allowed to dry, under unconfined conditions, by losing water to the atmosphere. To obtain information about the phenomena involved during the process of drying of soil samples, the suction, water content, and the volume of the samples were measured at intervals as they dried.

The drying test is therefore a shrinkage test in which the suction is also measured. The soil suction was measured using the filter paper method, described in section 6.3.1. The dimensions of the samples were measured using a vernier callipers, reading to 0.01 mm, enabling the volume of the samples to be calculated.

The test procedure was as follows.

- 1 - The samples were allowed to dry naturally in the laboratory atmosphere for approximately 3 hours.
- 2 - The samples were positioned in such a way that the maximum surface area was exposed to the air. In this way it is assumed that the drying process was isotropic.
- 3 - The drying process is then interrupted for seven days for the suction to be measured. At this stage the sample is weighed and dimensions taken. Knowing the specific gravity (G) of the soil, and the weight and volume of the sample, the degree of saturation, void ratio and water content may be calculated.
- 4 - The sample is allowed to dry for further three hours, and another set of filter papers placed on the sample, and the suction and dimensions again determined.
- 5 - The process is repeated up to a suction of about 10MPa.

Since no soil is lost during the drying process, the water content is accurately back calculated using the oven dry mass at the end of the test. The sample at the end of each drying stage has a moisture gradient from the centre (higher water content) to the edges (lower water content). It is presumed that this gradient reaches equilibrium during the seven days required for the filter paper suction measurement.

6.5. Swelling Tests

Some of the samples submitted to the drying test were also re-wetted, to examine the path followed as the soil wets-up and swells. Most of the soils used were potentially expansive and at the end of the drying process the sample is highly expansive, since the water content is low and the density very high. In this state the swelling process is very difficult to control when the confining stresses are lower than the swelling pressure. Usually cracks form as the wetting front progresses into the sample.

The permeability of an unsaturated soil is much lower than a saturated soil at the same water content and void ratio. In fact the highest permeability a soil can have is in its saturated state. It was considered that the permeability to vapour flow is higher than that of liquid flow, and the gradient associated with the wetting front is lower when vapour is used to wet the sample. The formation of cracks due to the wetting process is then reduced.

To allow the soil to absorb moisture, it was placed in a vacuum desiccator glass chamber with its lower part filled with boiling water. The sample was placed in a wire mesh located in the upper part of the chamber. The time required for each increase in suction depends on the soil type and the initial suction.

Although the method requires improvement it was observed that it allows the expansive soil to absorb moisture without apparent cracks appearing.

CHAPTER 7

Results and Discussion

7.1. Suction Measurement

7.1.1. Filter Paper

7.1.1.1. The Precision of the Method

The suctions quoted throughout this thesis are the average value between measurements made using the filter paper method. Each soil sample used for suction measurement had at least two filter papers, giving two independent suction measurements. If there were no dispersion, the measurements made on one soil sample would be equal. However, some scatter of results is observed and in order to evaluate the scatter and then to infer the precision of the filter paper method the relationship between the suction measured (two or more) versus the mean of these suctions are plotted in figure 7.1. The type of plot induce the coefficient of the regression line to be approximately one. However, these data show that the scatter of the data is small. The standard deviation of the regression is 20kPa.

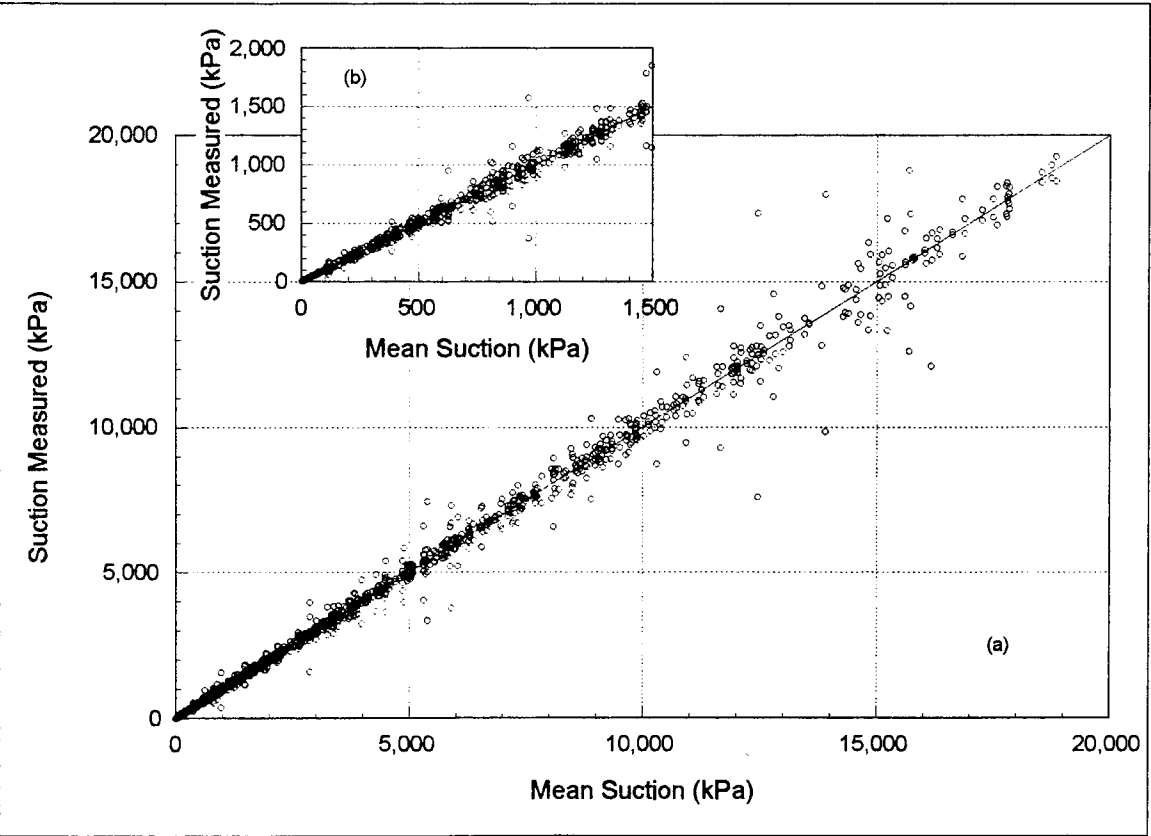


Figure 7.1 - Relationship between suction measured and the means of the suctions using the filter paper technique.

7.1.1.2. Contact Effects

As mentioned in section 4.2.3.2, the contact between the filter paper and the soil water is an important factor in defining which suction has been measured.

An interesting observation was made on a sample of Carsington clay used for suction measurement during drying. The sample was prepared by adding pure water to a field sample composed of small aggregates, which was then compacted. On drying the samples, the suction was measured using the filter paper method. It was observed that after the filter paper had dried in the oven, it became completely brown. As the drying process continued, with increasing suction, the dried paper became marked with brown areas, the rest of the paper remaining white. The highest suction measured in which the filter papers were completely coloured brown was about 800kPa. The following suction was 1600kPa, and in this case the papers were marked with brown areas. The marks on the paper were probably due to some reaction between the soil water or soil itself and the filter paper. It was thought that this may have been an indication of the degree of contact between the filter paper and the soil. In order to investigate the phenomenon another sample was prepared using the same soil, but this time the soil was air dried and passed through a number 40 sieve before adding the water. The sample was statically compacted with an initial water content of 29%, and on one side of the sample a little hole was created as shown in figure 7.2. The area of the hole represented about 10% of the filter paper area. The aim of this was to reduce the contact by a small amount and to compare the suction measurement made with the filter paper with good contact, *i.e.* the other paper apparently in complete contact with the other side of the soil sample.

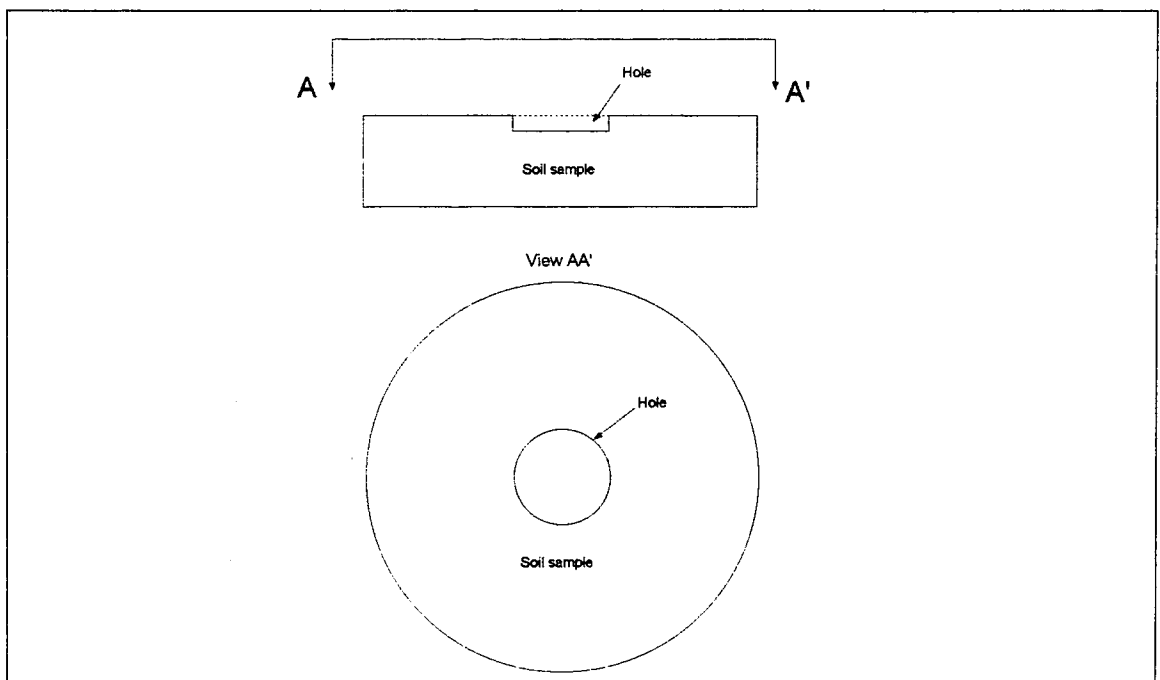


Figure 7.2 - Schematic view of the sample used for evaluate the contact effect of the filter paper with the soil.

Figure 7.3 presents the results obtained with the statically compacted sample. The results show that the suction measured with the filter paper in complete contact where essentially the same as the suction measured with the filter paper having only 90% contact. In this test the phenomenon observed in the previous test with the same material was not observed so clearly. The paper became uniformly light brown, and did not show any difference between the area in contact and the area not in contact. As the suction increased the colour faded. Tests were also carried out on a sample of bentonite, prepared from slurry, which also stained the filter paper brown. Even where 3mm cracks occurred during drying the staining was continuous

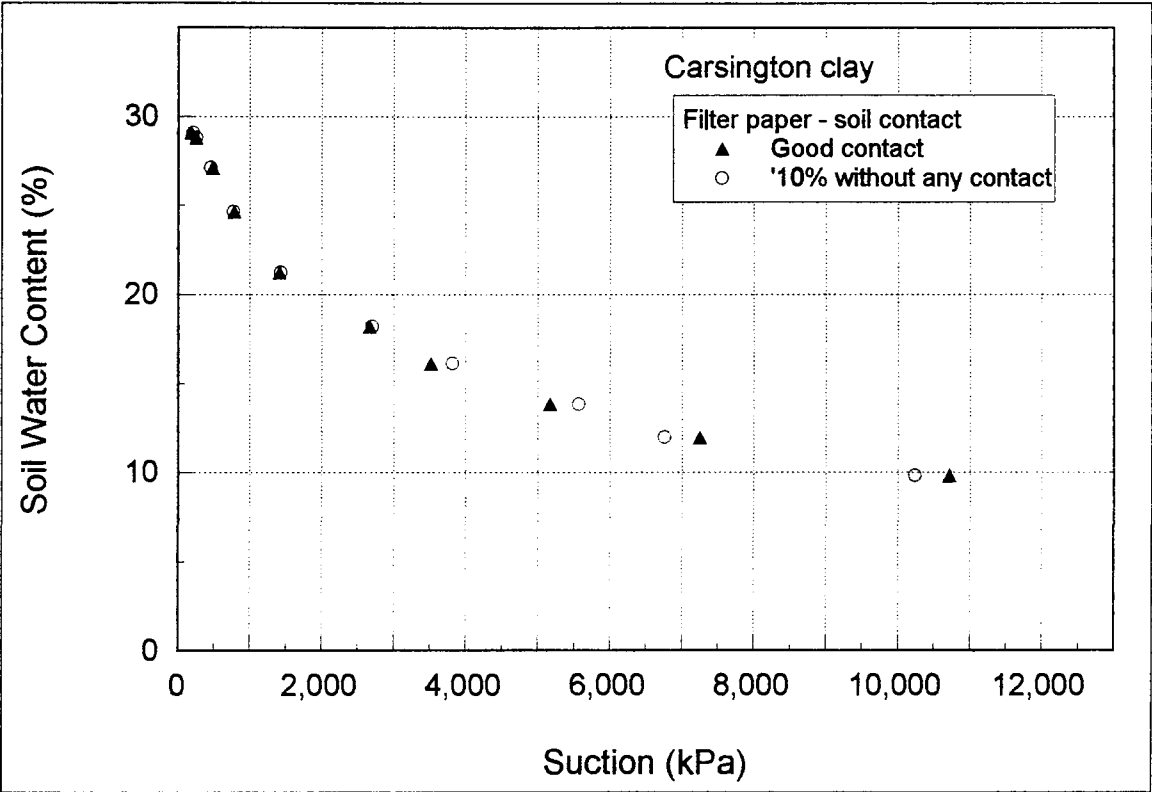


Figure 7.3 - Water content versus suction relationship for Carsington clay with the suction measured with one filter paper with good interaction and the other with 10% not in contact.

These results suggest that if part of the filter paper is in physical contact with the soil, capillary flow will occur throughout the filter paper. The equilibrium of this flow will depend on the equilibrium time.

To investigate this behaviour in another soil, two samples of undisturbed London clay, both obtained from the same depth, were prepared. In both samples a hole was made, as before, in one side of the sample. In one sample total suction (no contact) was also measured. Figure 7.4a and 7.4b presents the results obtained in terms of water content versus suction. It can be observed that there are no differences between the suctions measured using the filter paper in full contact or partial contact. The total suction measurement demonstrates the presence of salts in the sample and emphasizes that the partial contact, between the filter paper and the soil, do not necessarily leads to total suction measurement.

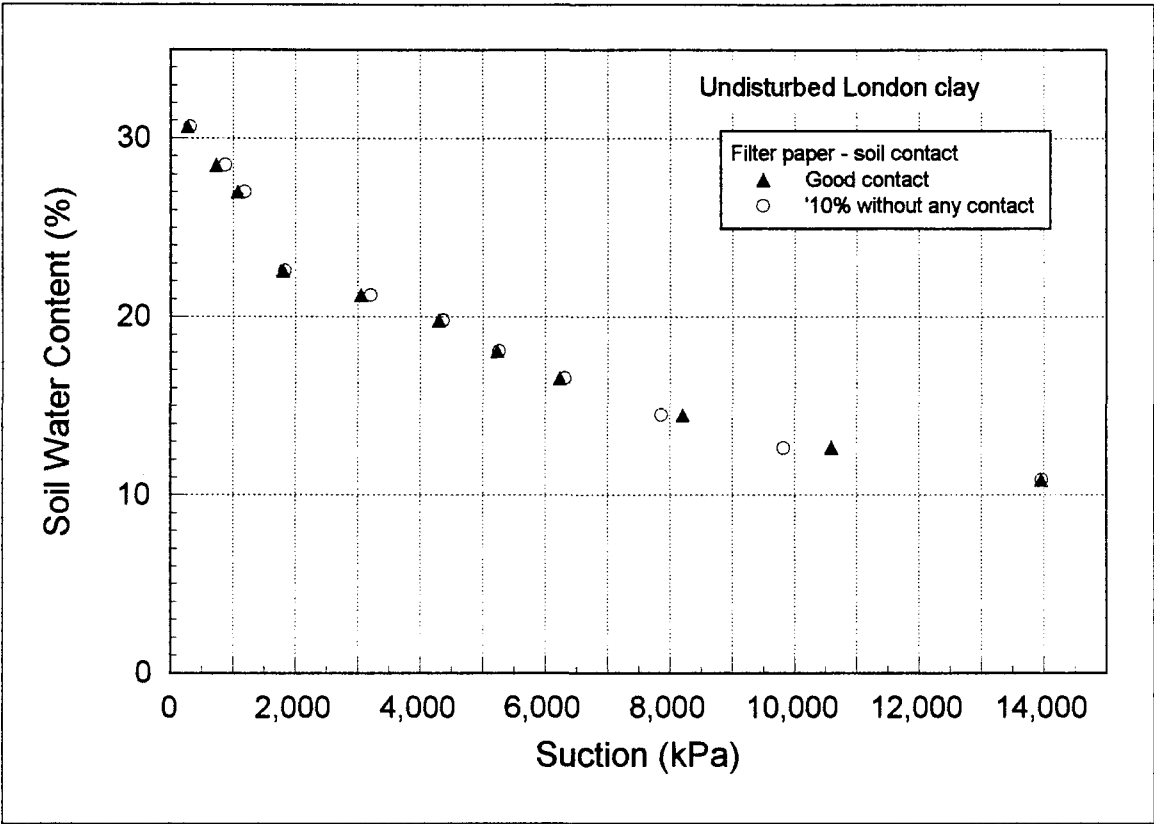


Figure 7.4a -Water content versus suction relationship for a sample undisturbed London clay. The suction was measured with one filter paper with good contact and one with 10% of the paper out of contact.

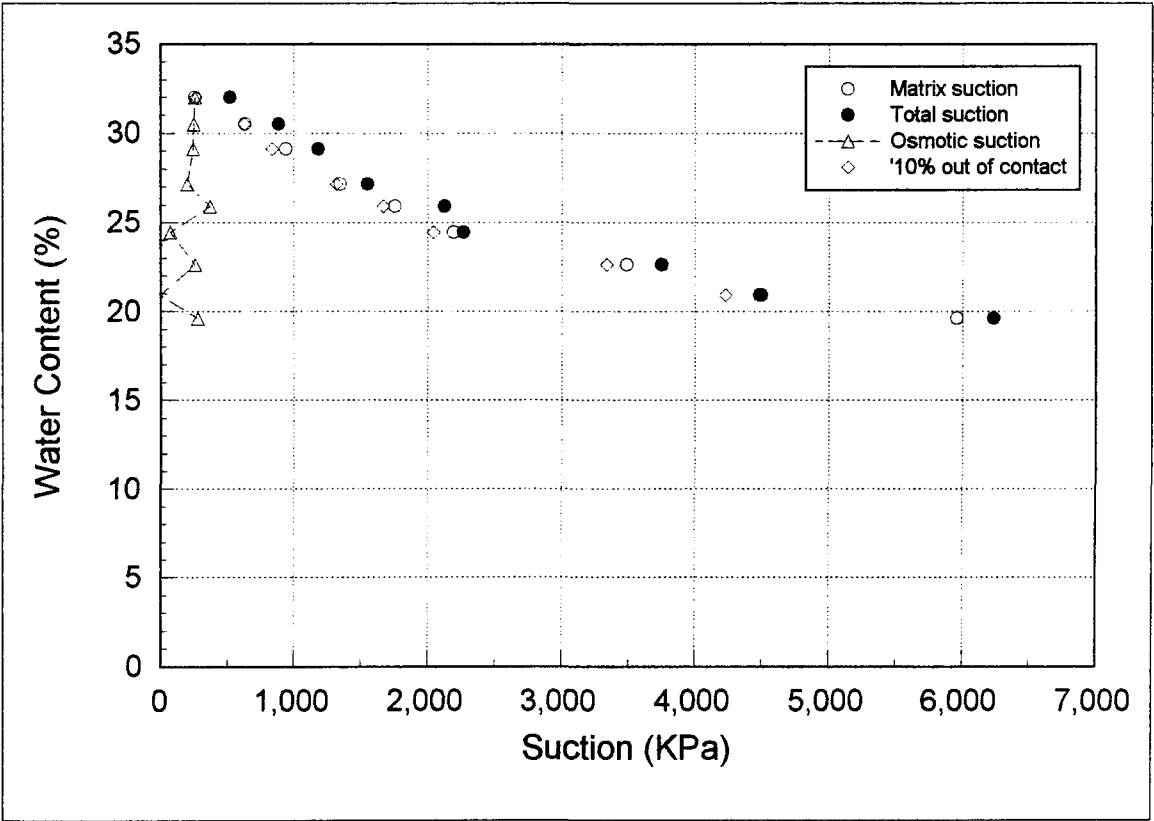


Figure 7.4b -Water content versus suction relationship for a sample of undisturbed London clay. The suction was measured with one filter paper with good contact, one with 10% of the paper out of contact and another measuring total suction.

7.1.1.3. Evaluation of the Calibration for Non-contact Filter Paper

As seen in section 4.2.3 the equilibrium time seems to be a key factor in measuring suction, particularly when using the non-contact technique to measure total suction. A series of experiments was carried out to examine the phenomena involved.

Initially a qualitative study was planned to investigate the effect of the distance between the source of the water vapour and the filter paper and also to investigate the size of the enclosed environment. The study is regarded as qualitative since the insulation of the system was not ideal. However, if any temperature effect occurred it affected equally all the experiments, since for each equilibrium time they were all tested together.

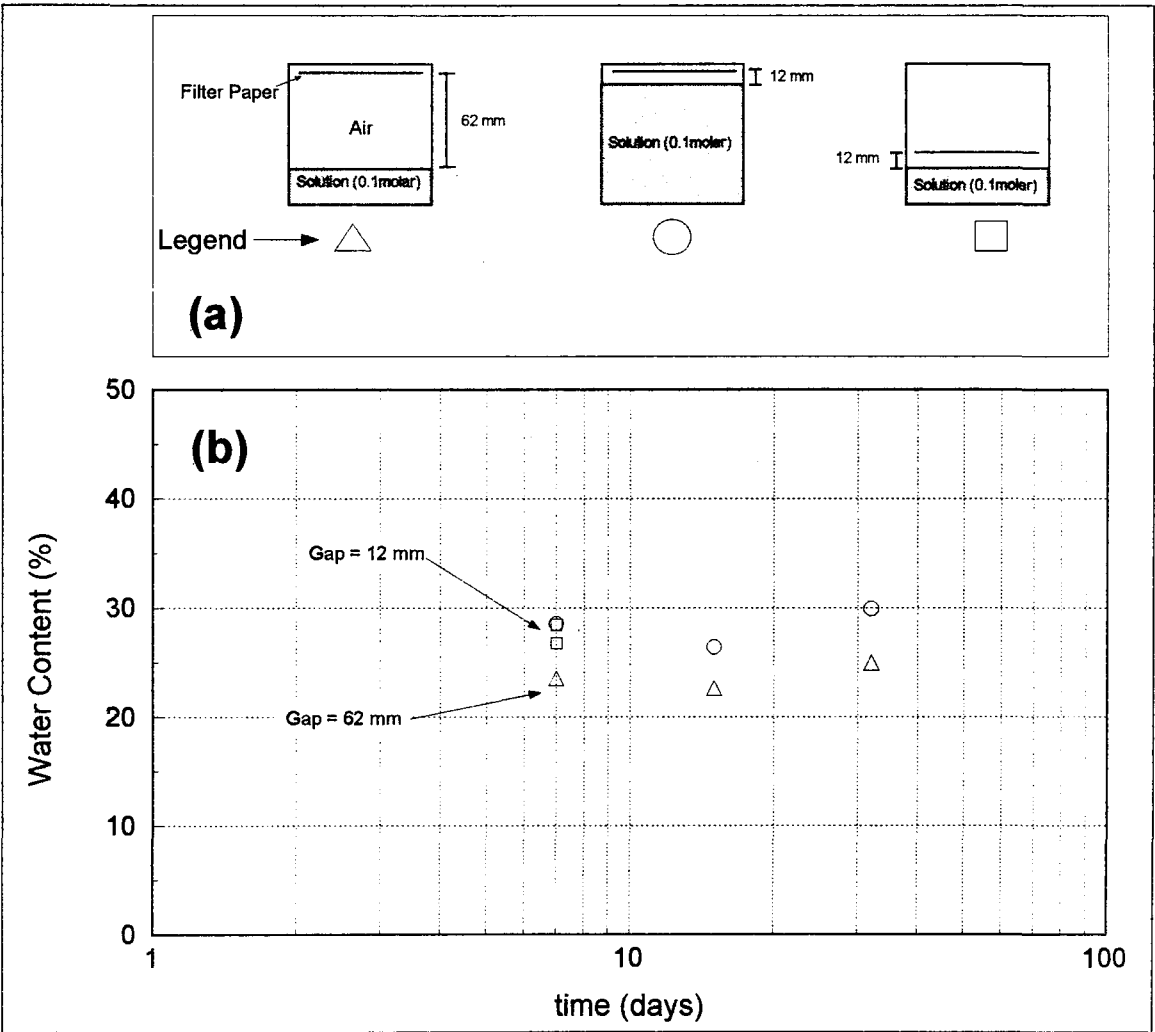


Figure 7.5 - Filter paper water content as a function of the time using two different gaps between the filter paper and the vapour source (no temperature control).

Three plastic containers were manufactured to hold the filter paper at a certain distance from the vapour source, as indicated in figure 7.5a. Figure 7.5b shows the relationship between the water content of the filter paper and the length of test. The results suggest that the gap between the filter paper and the vapour source has an influence on the filter paper water content for a

given equilibrium time. In this experiment was not possible to define the ideal equilibrium time for the gaps tested.

Figure 7.6 presents the relationship between the filter paper water content and the time allowed for equilibration, for different levels of generated suctions. It can be seen that there is a tendency for higher suctions to require a shorter equilibrium time. With pure water, generating zero suction, an equilibrium time far greater than 28 days is required. An attempt at longer tests was not completed.

To reduce the effect of temperature variation, a PVC container with a surrounding insulation box were constructed. The PVC container was placed inside the insulation box whose sides were 20cm of polystyrene sheets which were covered with wood. The whole system was placed in a "temperature controlled" room ($\pm 5^{\circ}\text{C}$). The objective was to investigate the equilibrium time required for the non-contact technique

The filter paper was placed on a perforated plastic disk, similar to the one described in section 6.3.1. The gap between the filter paper and the vapour source was 8mm. The volume of liquid used was always 500ml. Only one filter paper was used per test; the suction was generated using NaCl solutions.

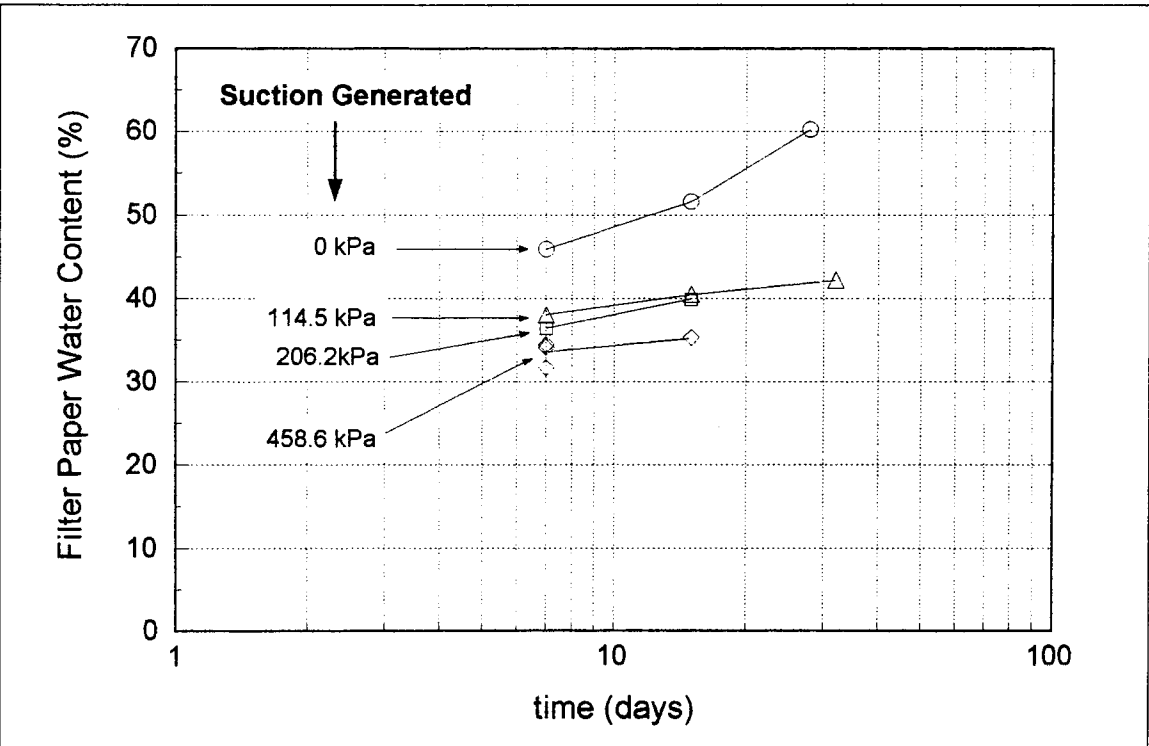


Figure 7.6 - Change in the filter paper water content as a function of time and suction level.

For comparison, the results are plotted together with a calibration for Whatman N° 42 (see figure 7.7). Three "envelopes" are determined, based on the test period used. It may be seen

that there is a consistent increase of the filter paper water content with the time towards the calibration curve presented by Chandler and Gutierrez (1986).

The results suggest that the calibration curve presented by Chandler and Gutierrez (1986), can also be used for measuring total suction, provided the equilibrium time is adequate. Table 7.1 presents a suggestion for equilibrium time as function of the level of total suction.

Total suction range (kPa)	Equilibrium time suggested
0 - 100	not determined, but certainly larger than 30 days
100 - 250	30 days
250 - 1000	15 days
1000 - 30000	7 days

Table 7.1 - Suggested equilibrium time for total suction measurement as a function of the suction level.

For instance, London clay which has an osmotic suction of approximately 250kPa, requires an equilibrium time for measuring total suction of at least 15 days.

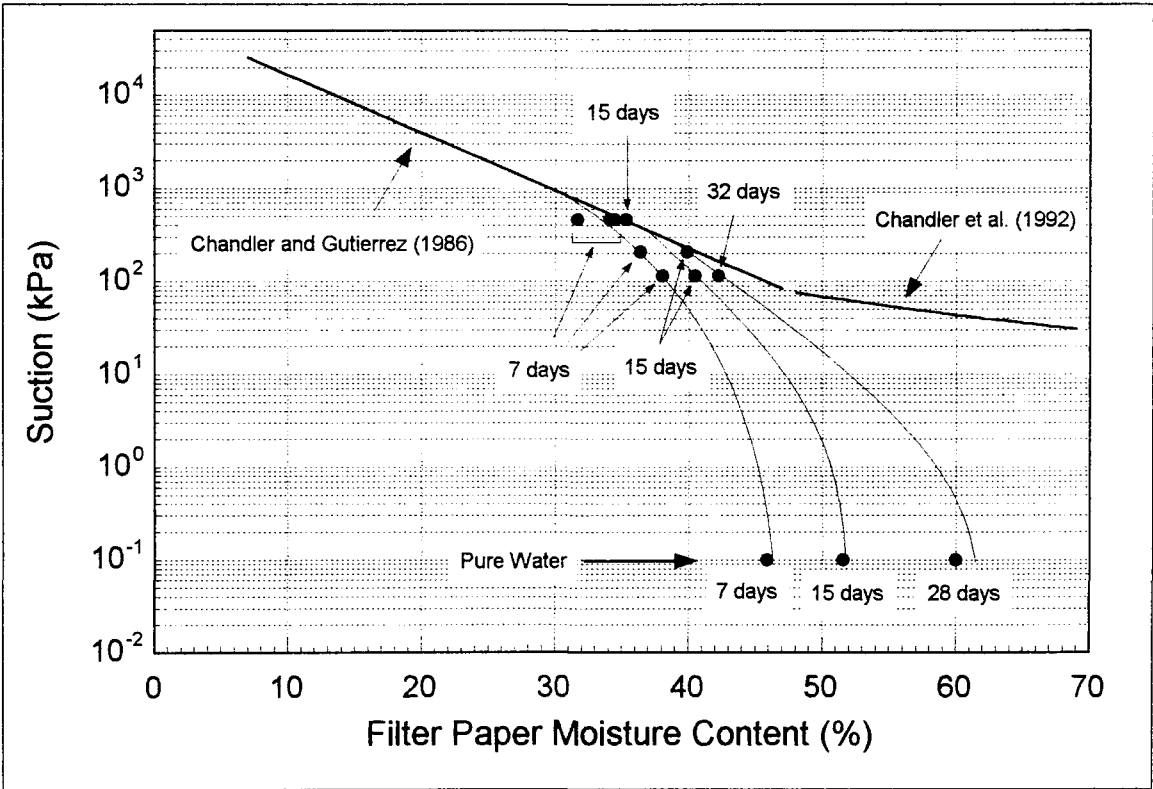


Figure 7.7 - Relationship between filter paper water content and suction showing the increase in the former with the equilibrium time, for total suction measurements.

7.1.1.4. Osmotic Suction

Statically compacted samples were prepared by mixing the soil with NaCl solution. This procedure was used in order to increase the osmotic suction of the soil and then observe its effect on the measurement of matrix and total suction using the filter paper method.

The main objective of the study was to investigate how the matrix and total suction measurements vary as the suction increases. The results may also reflect the degree of interaction between the filter paper and the pore water.

Total suction was measured following the procedures described in section 6.3.1. The results obtained using London clay are presented in figure 7.8a, in terms of soil water content versus suction. Matrix and total suctions measured are shown. It can be seen that at the beginning of the tests (low suction) the difference between matrix and total suction was about 700kPa for the two samples with added salt. The solution used has an osmotic suction of approximately 460kPa. The osmotic suction of the sample mixed with pure water was about 400kPa, which may explain the high values found for the two samples with added salt.

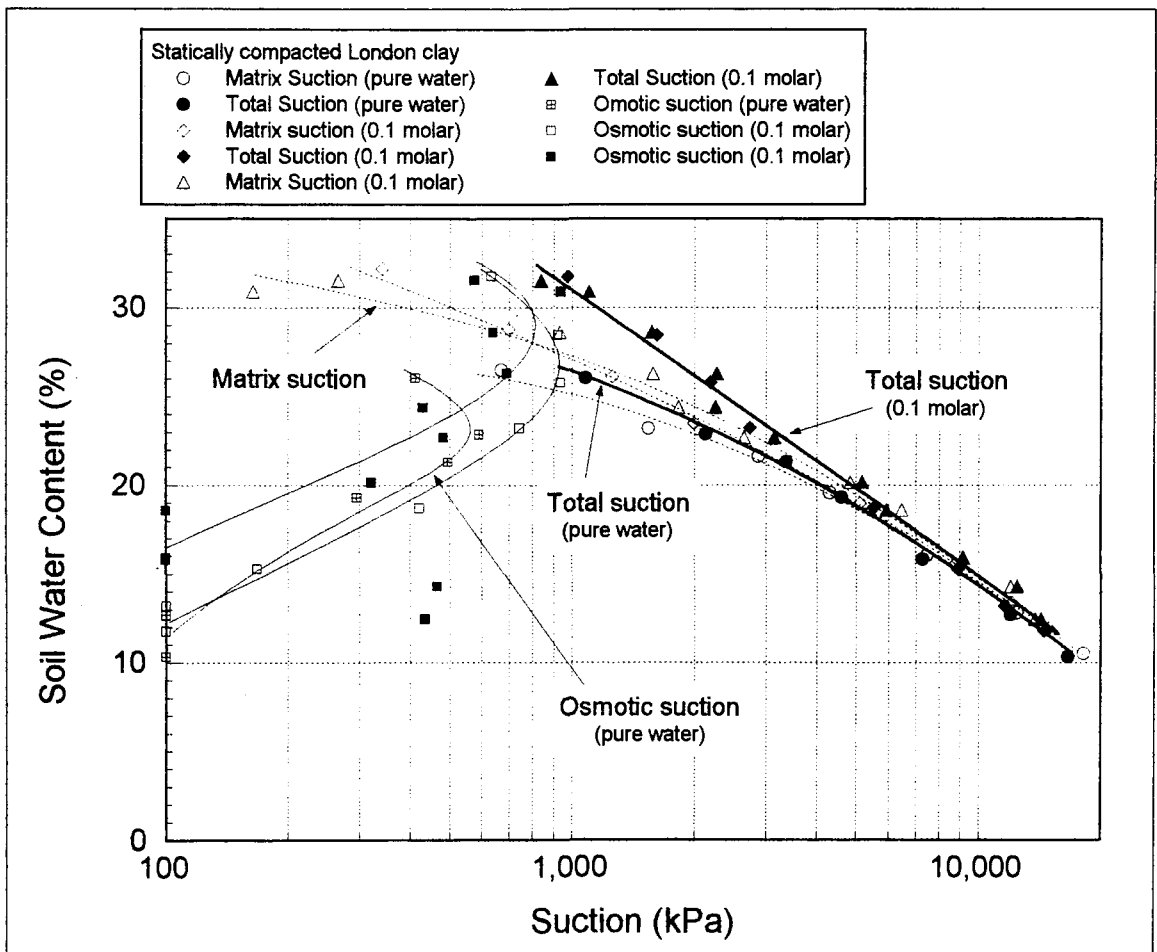


Figure 7.8 a- Total, matrix and osmotic suction measurement in a statically compacted London clay mixed with pure water and salt solution.

As the suction increases the difference between total and matrix suction increases, since the salt content remains constant though the concentration increases due to the lost of water during the drying process. A point was reached where the osmotic suction starts to reduce, at about 1MPa of matrix suction.

The results of another pair of statically compacted samples in which osmotic suction was measured are shown in figure 7.8b. An air dried powder of London clay was placed in an oven at 500°C for 24 hours. The originally brown London clay (IP = 57%) became a red low plasticity clay (IP= 16%). One sample was prepared by mixing the soil with pure water, and the other using 0.1 molar of NaCl solution.

The linear behaviour of the total suction is again observed in figure 7.8b. The initial osmotic suction for the sample with added salt is 600kPa and for the sample mixed with pure water is 350kPa, which gives a difference that does not exactly represent the osmotic suction of the solution added (460kPa)

It can be observed that the osmotic suction for the sample with added salt remains constant up to a matrix suction of about 2.5MPa, while for the other sample it starts to change at a matrix suction of about 1.5MPa.

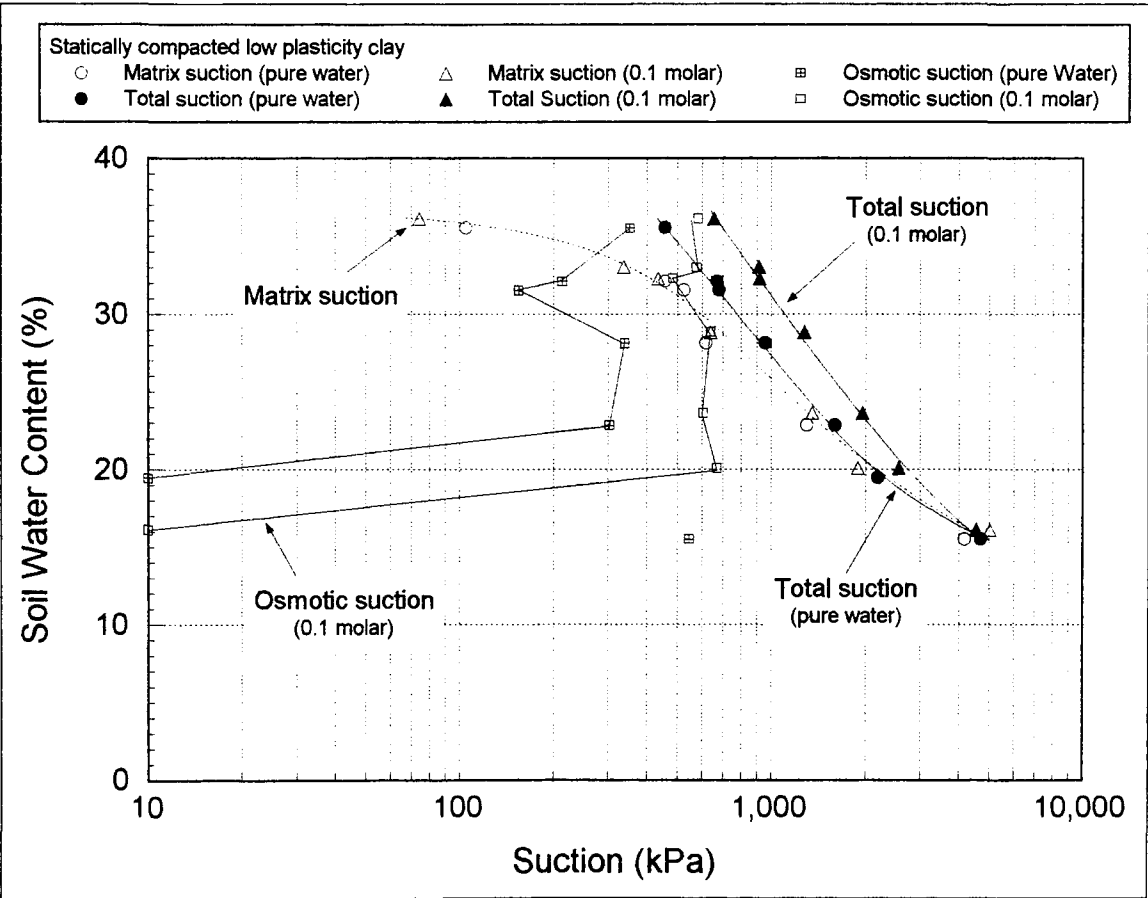


Figure 7.8b - Total, matrix and osmotic suction measurement in a statically compacted low plasticity clay mixed with pure water and salt solution.

Figure 7.8c presents the results of matrix and total suction measurements using two undisturbed samples of London clay. The initial osmotic suctions obtained varied from 100kPa to 250kPa.

The phenomena involved with the osmotic process are complex, but, the reduction in osmotic suction can be explained, since above a certain of suction the filter paper technique measures a combination of total and matrix suction which reduces the difference between the "matrix" and total suctions. The process is associated with the loss of contact between the filter paper and the soil pore water, combined with the test time used. This suggests that the measurement of high matrix suctions requires longer equilibrium time. As seen in section 4.2.3.2, the existence of one point of contact may be enough for capillary flow to occur. At high suctions the rate of flow is very slow, since the gradient between the filter paper and the soil is small. An illustration of this is the wilting point of plants. Plants wilt, not necessarily because there is no water available, but because the rate of flow to the plant is not sufficient in comparison with the evaporation from the leaves (*e.g.* Shull, 1916).

The matrix and total suction curves join at approximately 5MPa. When the matrix suction is high ($> 5\text{MPa}$) the precision of the method does not allow the detection of small osmotic suctions.

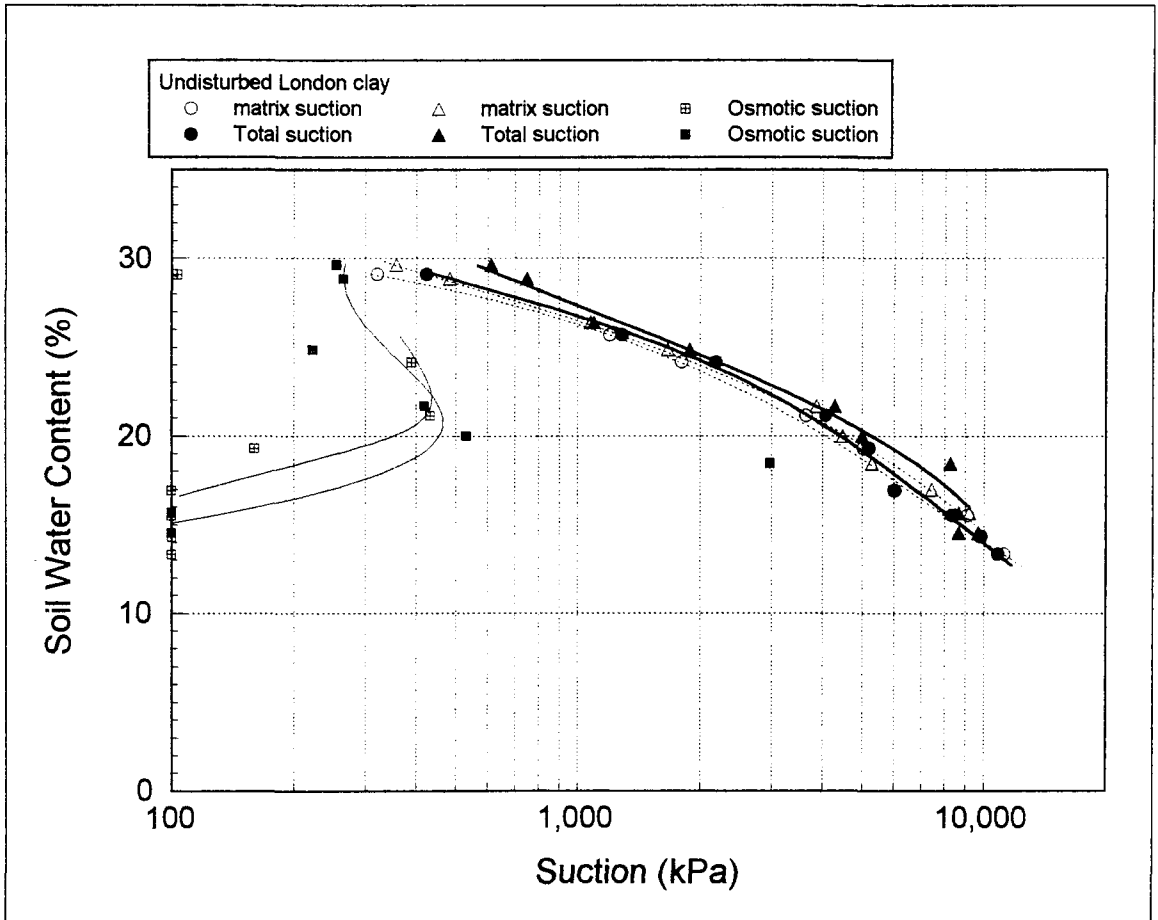


Figure 7.8c - Total, matrix and osmotic suction measurement in two undisturbed samples of London clay.

7.1.2. Osmotic Effect on the Tensiometer Probe

Suction measurement were made using the tensiometer probe described by Ridley and Burland (1993) and Ridley (1993). The measurements using the tensiometer probe were compared with suction measurements made using the filter paper method.

Figure 7.9a presents the results of suction measurements on statically compacted London Clay, prepared with the addition of pure water. It can be seen that there is good agreement between tensiometer probe and matrix suction measurements at suctions less than 500kPa, but that at higher suctions the probe apparently over-records compared with the matrix suctions measured with the filter paper. Ridley (1993) observed this, and suggested that there may have been experimental problems in obtaining good contact between the probe and the soil at high suctions and lower water contents. However, the proportion of pure water added to the compacted clay would have been less at high suctions, so that, assuming a constant salt content in the soil, the salt concentration will be higher at high suctions. This observation provides an alternative explanation for the observed differences between the matrix suction and the tensiometer probe readings at higher suctions, suggesting that the probe may be incorporating some measurement of osmotic suction, and hence is measuring total suction.

To check this possibility, both total and matrix suctions were measured using the filter paper method on a low plasticity clay and London clay. The samples were again statically compacted, one sample of the low plasticity clay being prepared with pure water and one with salt solution (0.1 molar), while a single London clay sample was prepared with salt solution. The filter paper suction measurements are plotted against tensiometer probe measurements in figure 7.9b. It can be seen that the tensiometer probe readings compare quite closely with the total suction measurements, and that with added salt the difference between matrix and total suction is increased.

The measurement of total suction using the filter paper method were performed in the way described in section 6.3.1. The equilibrium time used for the comparison with the tensiometer probe was 15 days (see table 7.1). The calibration curve used is the one presented by Chandler and Gutierrez (1986). As presented in section 7.1.1.3 the use of this calibration curve for total suction measurement is valid, provided the correct equilibrium time is used.

These observation suggest that there is an osmotic effect generated by the difference in salt concentration between the tensiometer probe system and the sample, and it appears that the porous stone has some osmotic efficiency¹. Osmotic suction is developed as an inevitable consequence of the use of a very fine porous interface and it is osmotic suction plus matrix

¹ Osmotic efficiency is described in section 2.1.4.6.

suction that is measured. Thus for soils with a high salt (NaCl) content the tensiometer probe measures total suction, and not matrix suction.

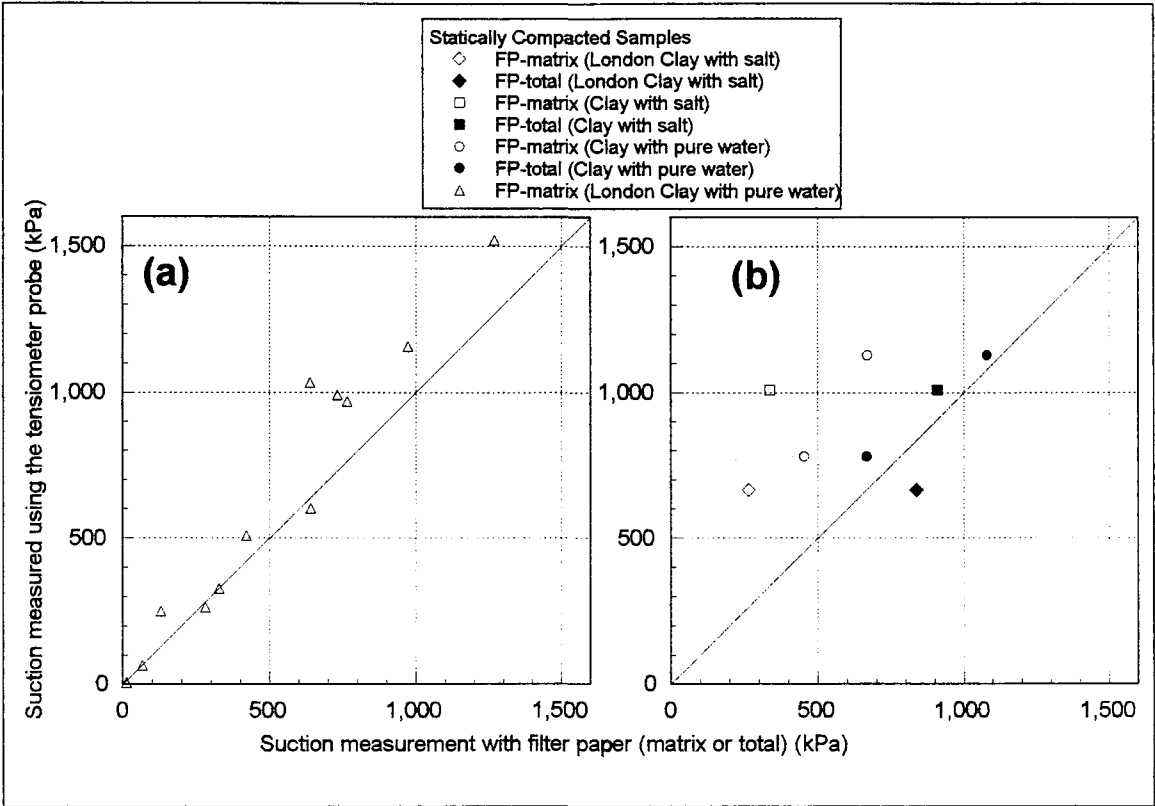


Figure 7.9 - Comparison between filter paper (FP) and tensiometer suction measurement. (a) Compacted London clay, samples having added pure water, (b) compacted low plasticity clay and London clay; open symbols indicate matrix suction and solid symbols total suction.

Contact problems can occur, as pointed out by Ridley (1993). Contact problems are likely to be related to the degree of saturation of the soil. In order check if the measurements with the tensiometer probe were affected by contact problems due to low degrees of saturation the ratio between the tensiometer measurement and the filter paper matrix suction are plotted against the degree of saturation and water content (see figure 7.10). It can be seen that the majority of the samples tested had a degree of saturation higher than 80%, with many of them above 95%, so that contact problems seem unlikely. The type of sample tested is indicated in figure 7.10.

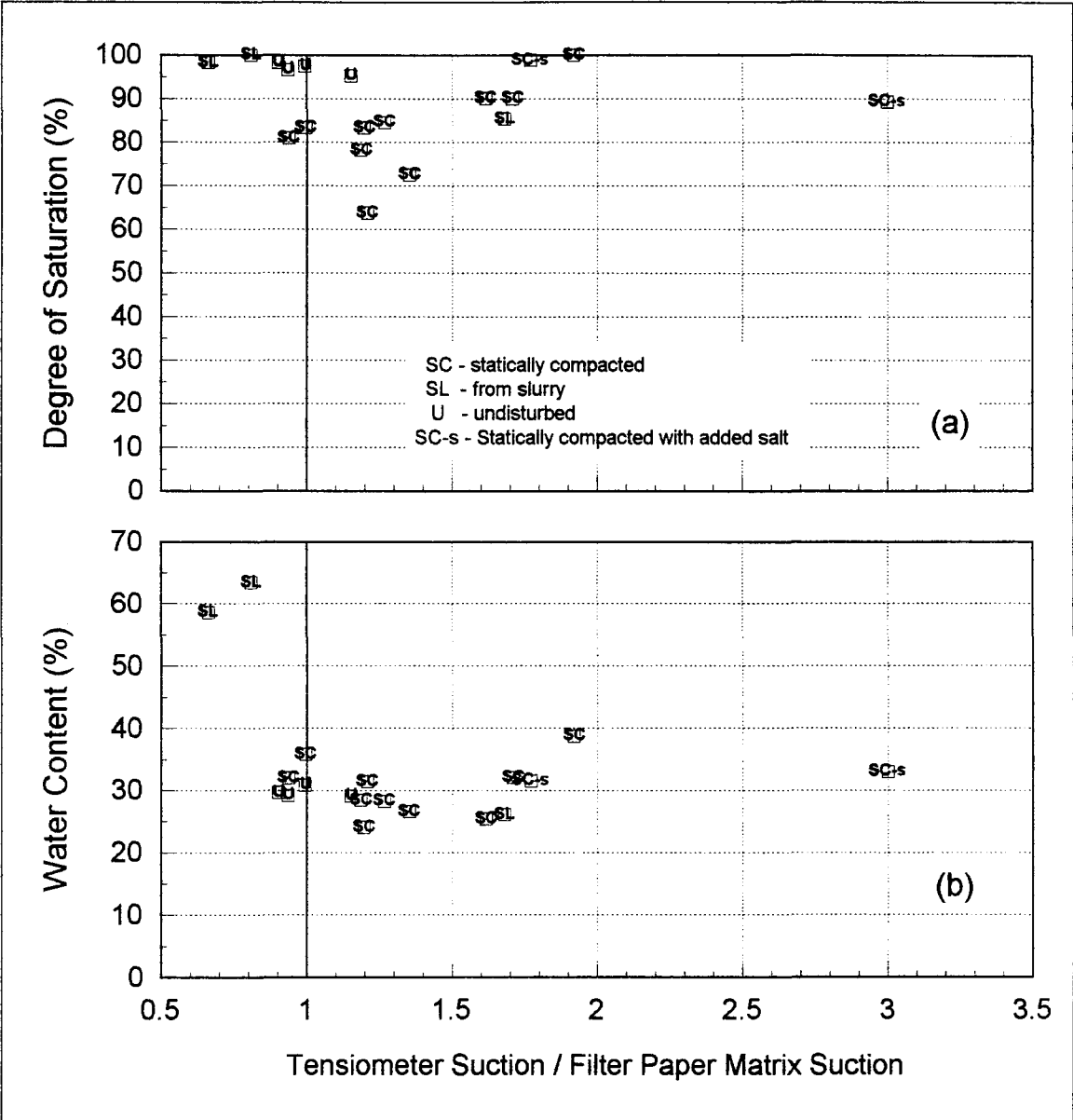


Figure 7.10 - Ratio between tensiometer suction and filter paper matrix suction versus degree of saturation and water content.

7.2. Drying Test on Compacted Soils

This section is divided in two sub-sections which present and discuss the results of drying tests on dynamically and statically compacted samples. The tests were performed as described in Section 6.4, and the characteristics of the soils are shown in Table 6.1.

7.2.1. Dynamically Compacted Samples

7.2.1.1. General Behaviour

7.2.1.1.1. Volume Change Versus Water Content

The samples were all compacted following the procedures described in section 6.2.4. A series of samples was prepared using London clay (LL= 77%), and mixtures of London clay and fine sand. In all, five different mixtures were used, ranging from 100% London clay to 30% clay and 70% sand. A total of 39 samples was prepared. The samples were compacted as presented in Figure 7.11, where the dry unit weight is plotted against the initial water content.

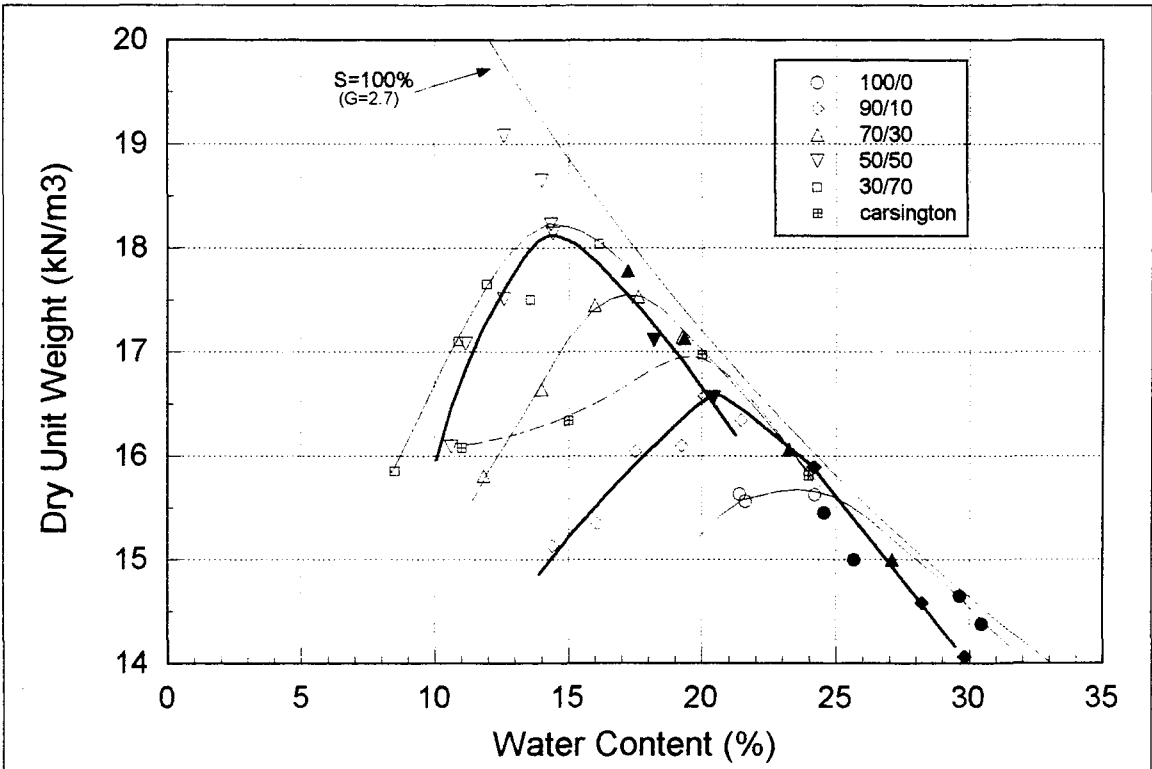


Figure 7.11 - Compaction curves for the various soil mixtures and for Carsington clay. The solid symbols are those samples that exhibit "near saturated" behaviour on drying.

Another four samples were prepared using Carsington clay. One of the samples was dried and for the others only the initial characteristics were determined. The compaction characteristics are shown in figure 7.11.

The initial characteristics of all samples tested are presented in table 7.2 for the London clay and mixtures, and in table 7.3 for the Carsington clay.

Soil	w_i (%)	e_i	S_i (%)	Suction (kPa)
Clay/sand 100/0 (London clay)	25.7	0.764	91	1,638
	21.4	0.716	81	1,905
	21.6	0.73	80	1,688
	24.6	0.735	90	1,176
	24.2	0.71	91	1,537
	29.6	0.809	98	327
	30.5	0.867	95	369
Clay/sand 90/10	20.1	0.621	87	2,901
	24.2	0.684	95	1,332
	28.2	0.826	92	583
	29.8	0.894	90	294
	14.4	0.775	49	7,527
	16.1	0.749	58	4,194
	17.5	0.673	70	3,122
	19.2	0.669	77	2,240
	21.5	0.639	90	1,222
Clay/sand 70/30	17.2	0.497	92	1,151
	19.3	0.544	95	958
	23.3	0.643	96	269
	27.1	0.749	97	77
	11.8	0.677	46	5,945
	14	0.592	63	3,079
	16	0.521	82	1,753
	17.6	0.515	91	1,437
	19.3	0.534	96	818
Clay/sand 50/50	12.6	0.377	88	1,398
	14	0.413	89	958
	18.2	0.527	91	304
	20.4	0.577	93	189
	10.6	0.637	44	3,741
	11.1	0.541	54	2,640
	12.6	0.503	66	1,815
	14.3	0.439	86	847
	14.4	0.447	85	937
Clay/sand 30/70	8.5	0.654	33	1,910
	10.9	0.53	53	656
	11.9	0.485	64	452
	13.6	0.475	74	341
	16.1	0.454	93	64

Table 7.2 - Initial characteristics of the samples (clay and mixtures).

Soil	w_i (%)	e_i	S_i (%)	Suction (kPa)
Carsington	11	0.647	46	8,028
	15	0.621	65	2,836
	20	0.561	96	801
	24	0.676	96	213

Table 7.3 - Initial characteristics of the Carsington samples.

Experimental drying curves are plotted in figures 7.12 to 7.17, following the representation suggested by Haines (1923). The physical meaning of this plot and its description is given in section 5.3.1. The theoretical saturation line, assuming $G=2.70$, is shown.

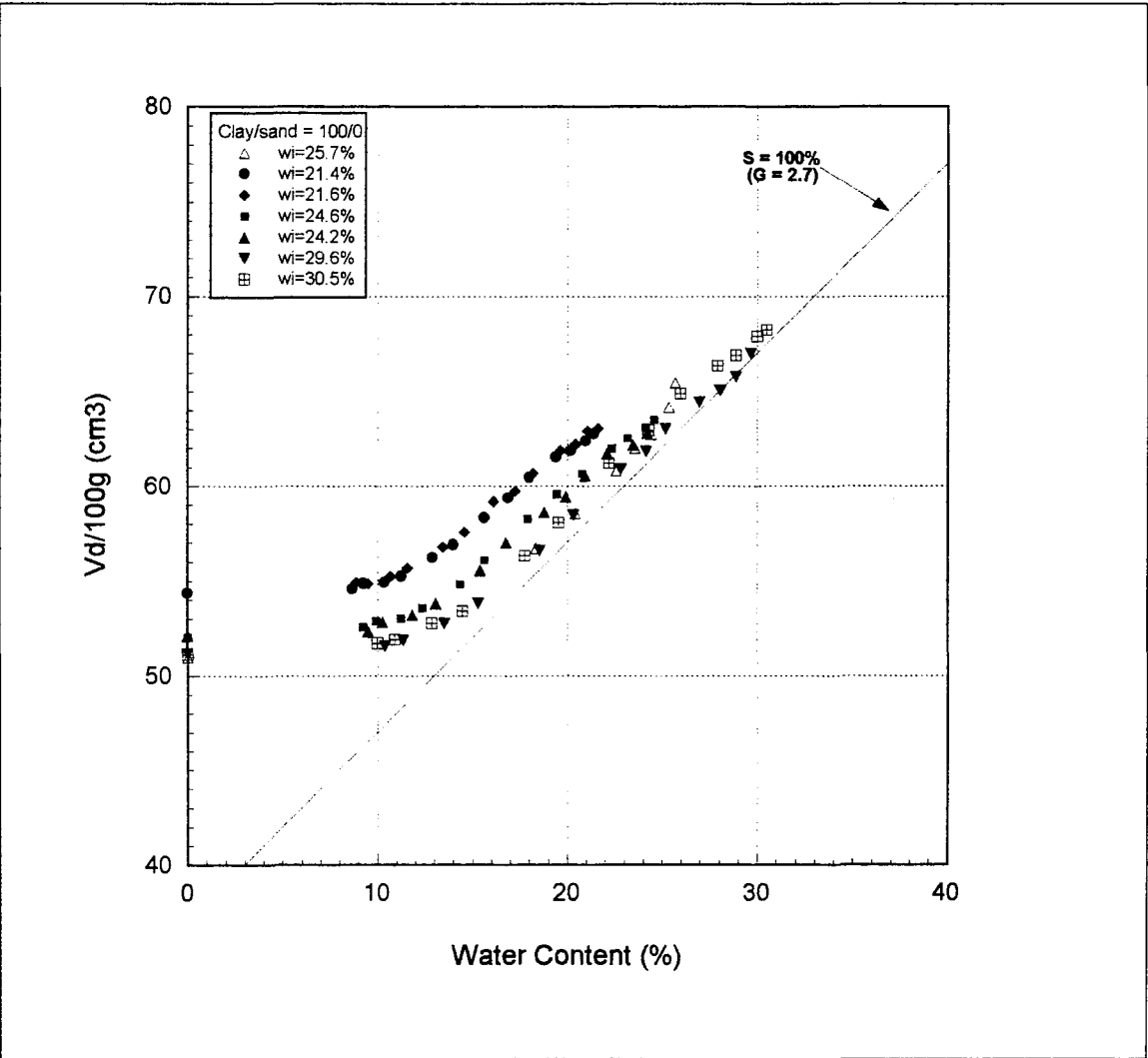


Figure 7.12 - Drying behaviour of London clay (100/0%); V_d is the volume per 100g of soil solids.

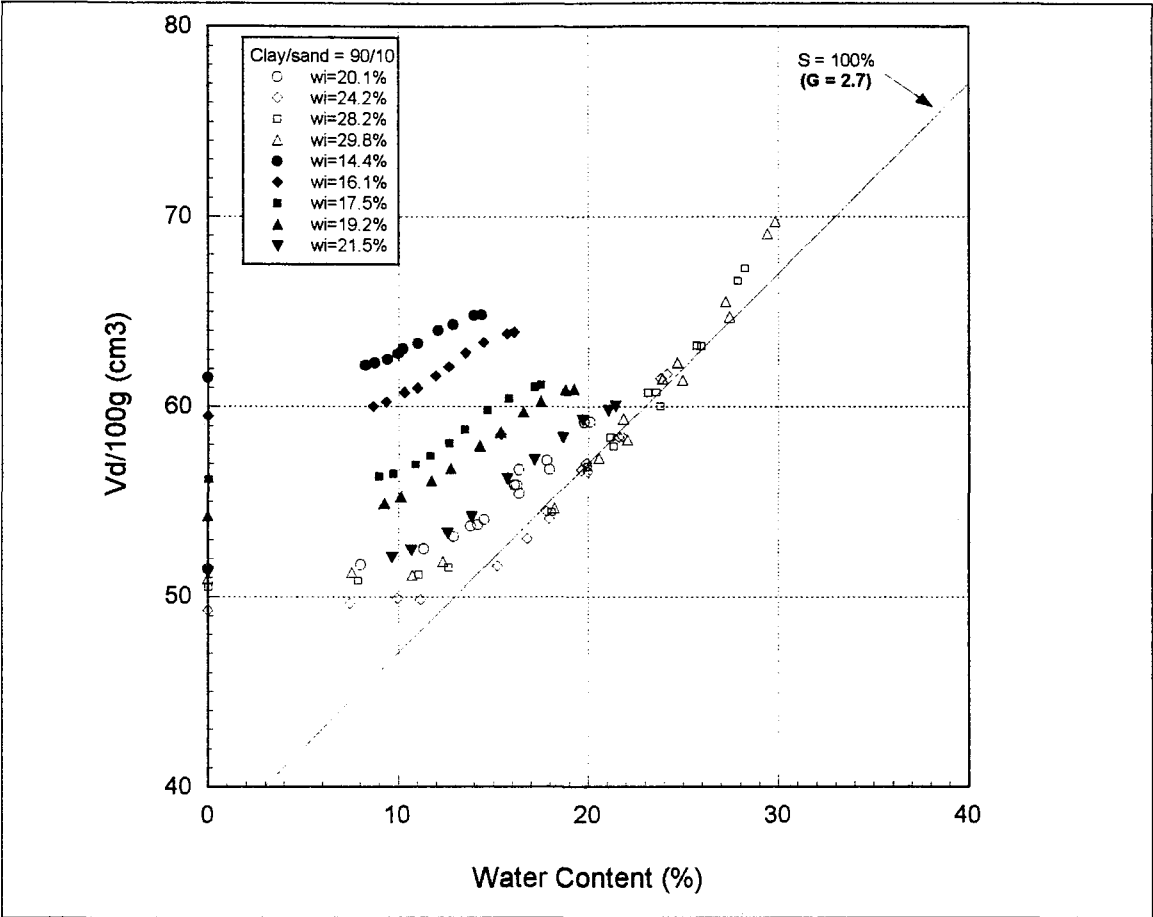


Figure 7.13 - Drying behaviour of 90/10% clay/sand mixture; V_d is the volume per 100g of soil solids.

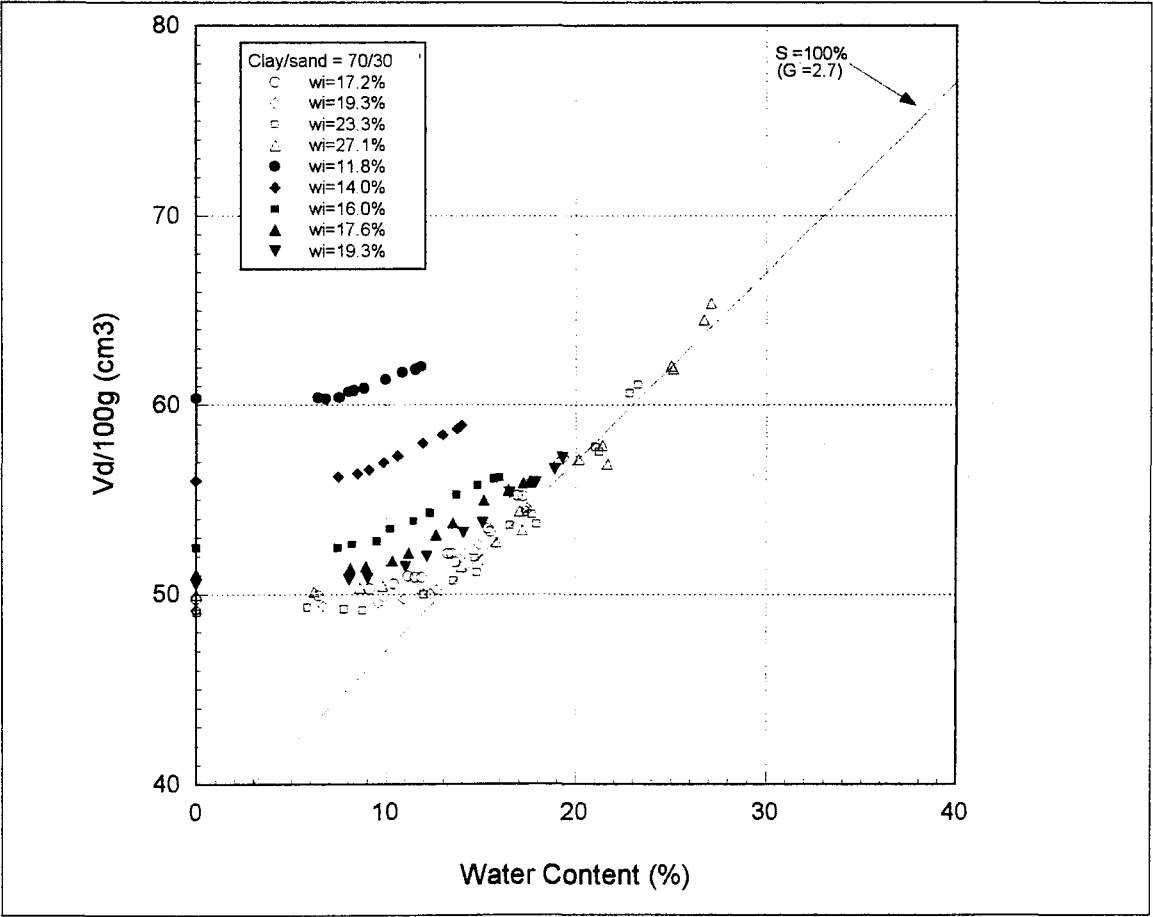


Figure 7.14 - Drying behaviour of 70/30% clay/sand mixture; V_d is the volume per 100g of soil solids.

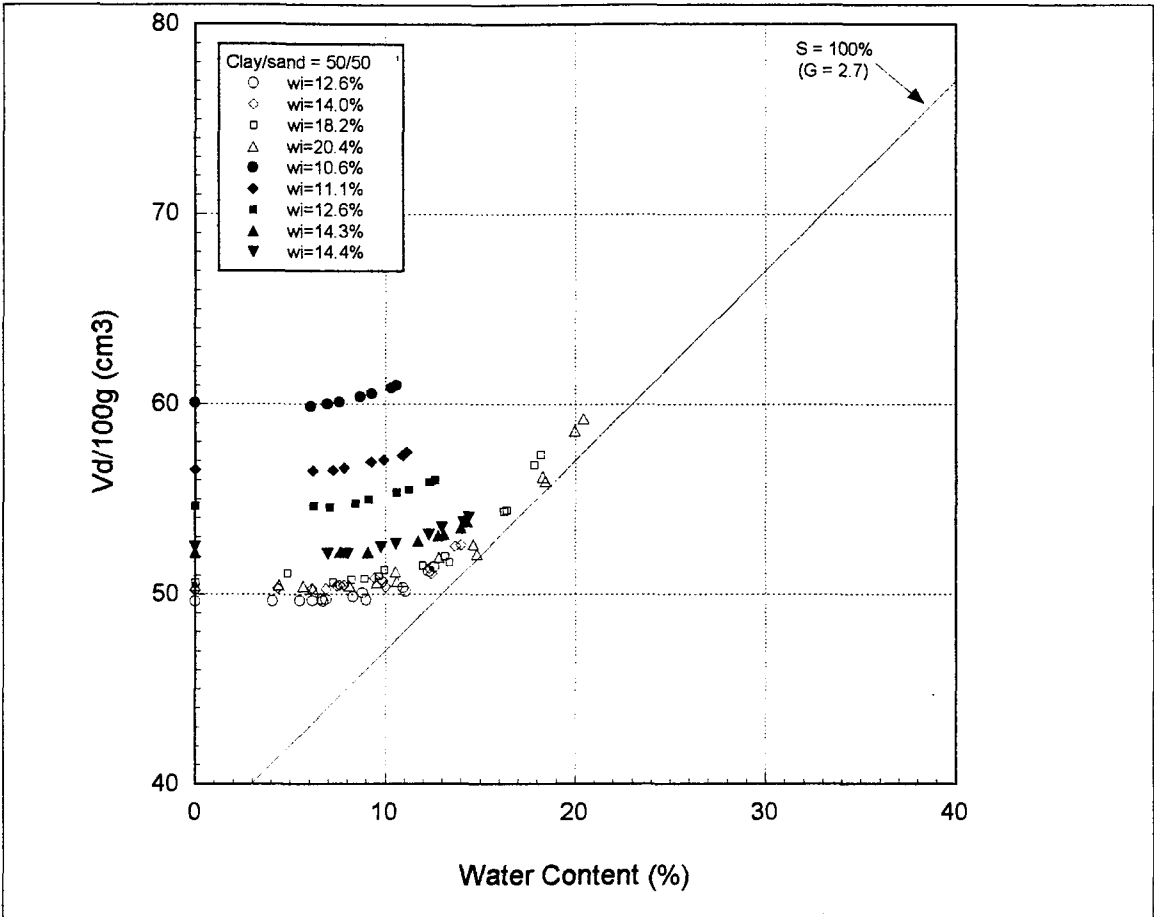


Figure 7.15 - Drying behaviour of 50/50% clay/sand mixture; V_d is the volume per 100g of soil solids.

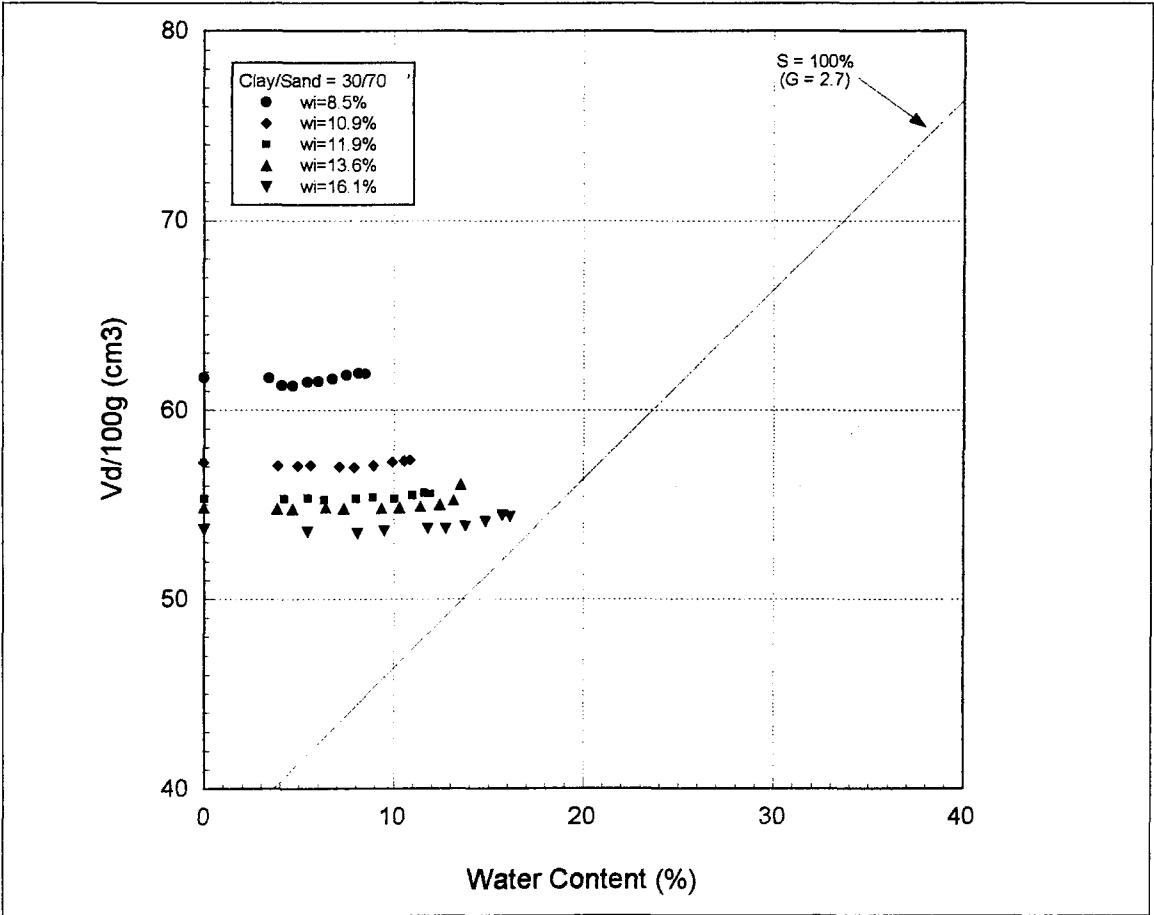


Figure 7.16 - Drying behaviour of 30/70% clay/sand mixture; V_d is the volume per 100g of soil solids.

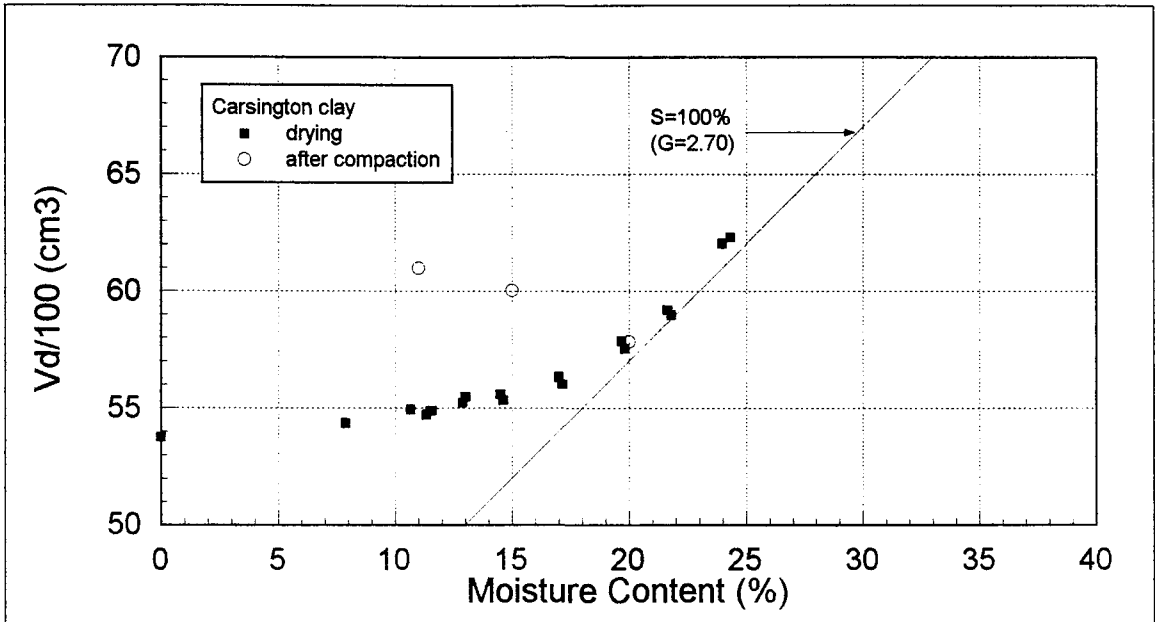


Figure 7.17 - Drying behaviour of Carsington clay; V_d is the volume per 100g of soil solids.

It can be seen that the drying curves fall in two types, depending on the initial water content and initial degree of saturation of the sample. Where the preparation water content lies on the wet side of optimum, the drying relationship initially lies on, or parallel and close to, the $S = 100\%$ line. At lower preparation water contents the drying curve may show an initial linear portion, though this diverges from the $S = 100\%$ line. This behaviour is particularly obvious at the lowest preparation water contents, e.g. Figure 7.14. Drying parallel to the $S = 100\%$ line implies that the volume of air remains constant, while a diverging drying line is consistent with an increasing volume of air. The line for $S = 100\%$ makes an angle of 45° with the water content axis.

7.2.1.1.2. Water Content, Volume Change and Suction

The experimental results are also plotted against the interrelated parameters of void ratio, degree of saturation (S), water content and suction, as shown in figures 7.18 to 7.23. The void ratio versus water content relationships shown in part *a* of these figures are effectively the same as those in Figure 7.12 to 7.17. The plot of degree of saturation versus water content, shown in part *b* of the figures, demonstrates the point at which desaturation occurs for the initially saturated or "near saturated" samples, and also indicates the point where air starts to enter the sample changing the gradient of S in relation to the water content. This is the general air entry point, described in section 5.3.1. The relationship between water content and suction presented in figure *e* of these figures, shows linear behaviour. The importance of these interrelated plot is that it gives a general view of the behaviour of the samples, enabling particular points to be easily identified and correlated with any of the parameters shown.

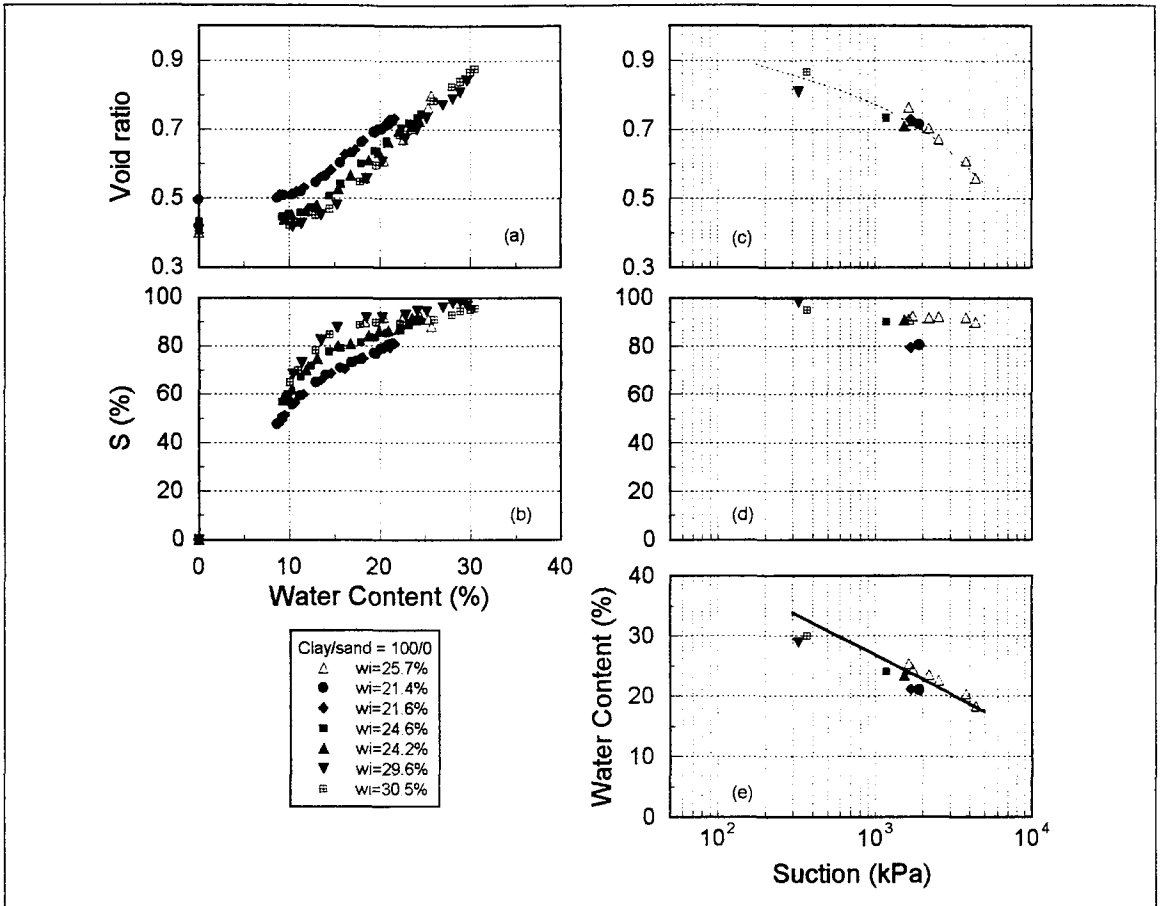


Figure 7.18 - Drying behaviour of London clay (100/0%) plotted against common axes of water content and suction.

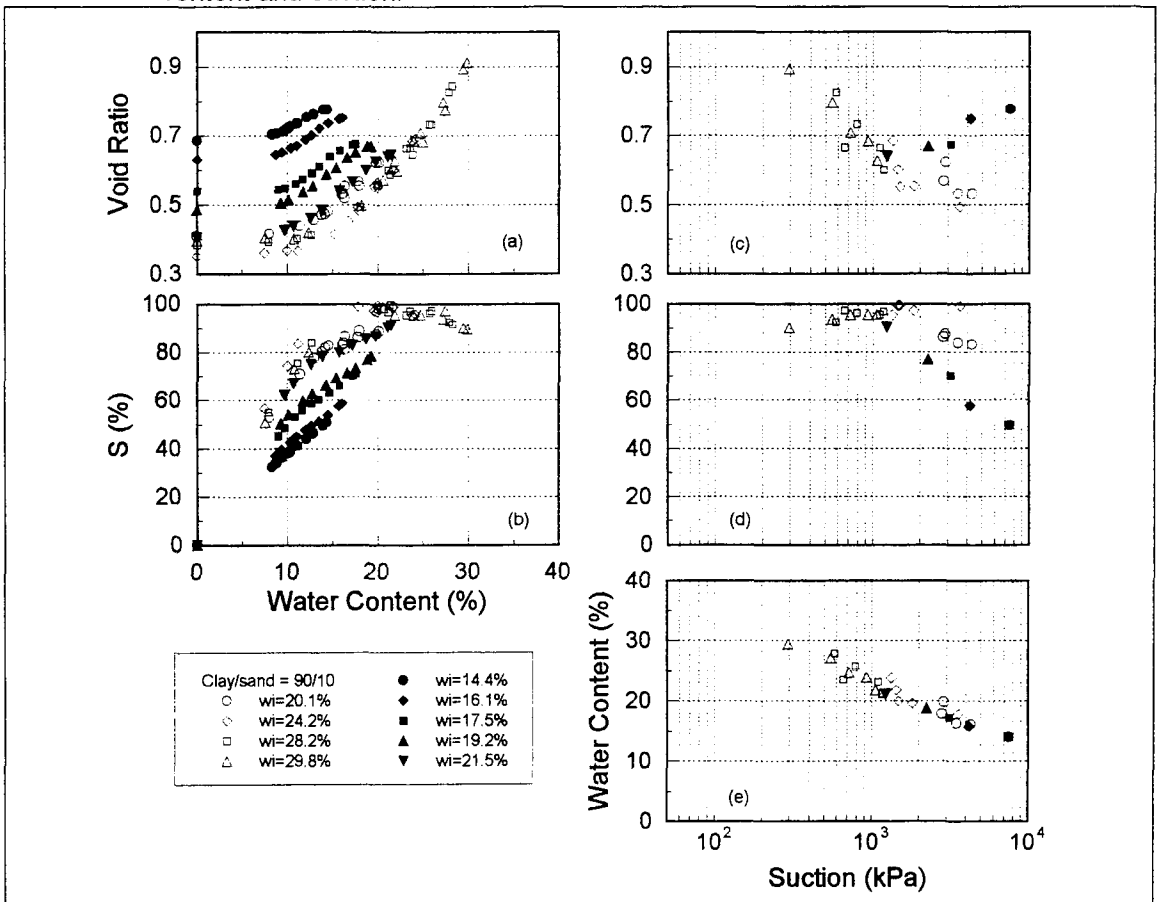


Figure 7.19 - Drying behaviour of 90/10% clay/sand mixture plotted against common axes of water content and suction.

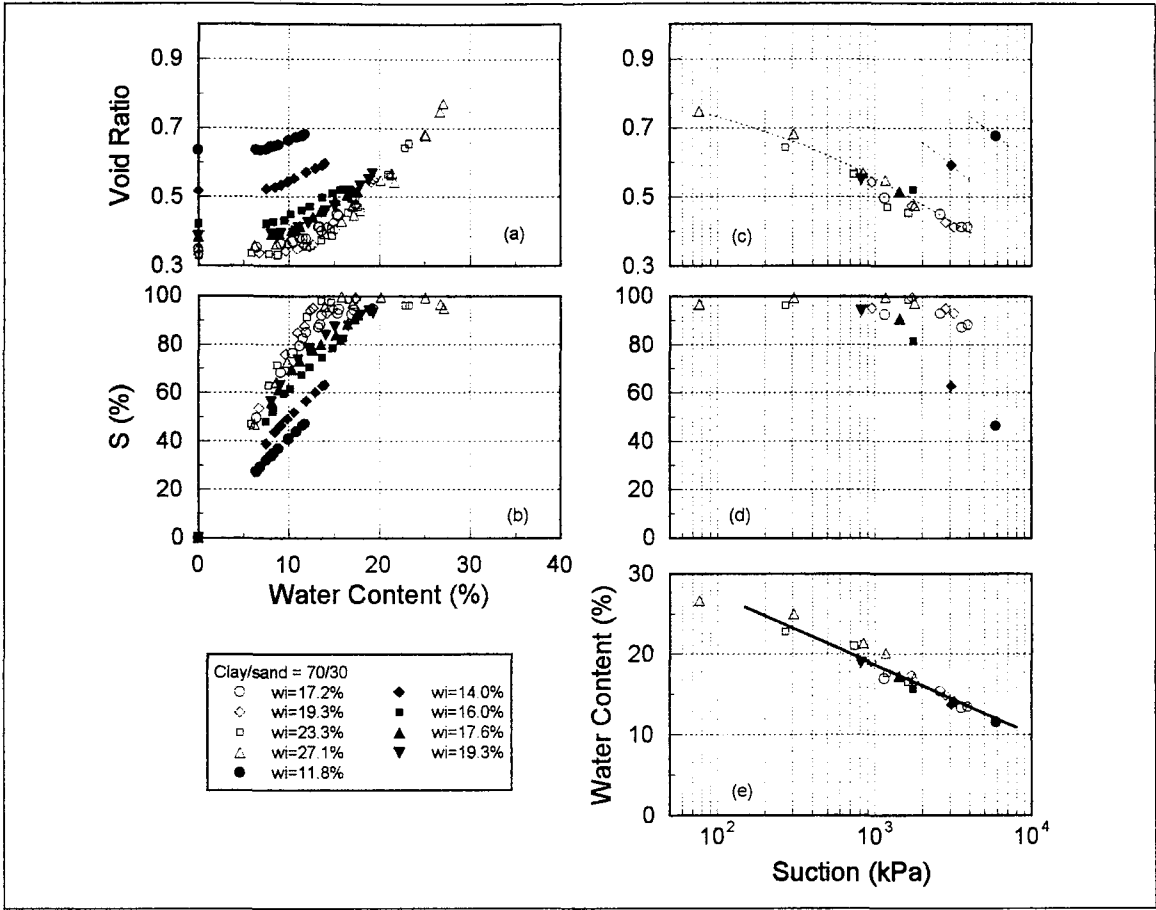


Figure 7.20 - Drying behaviour of 70/30% clay/sand mixture plotted against common axes of water content and suction.

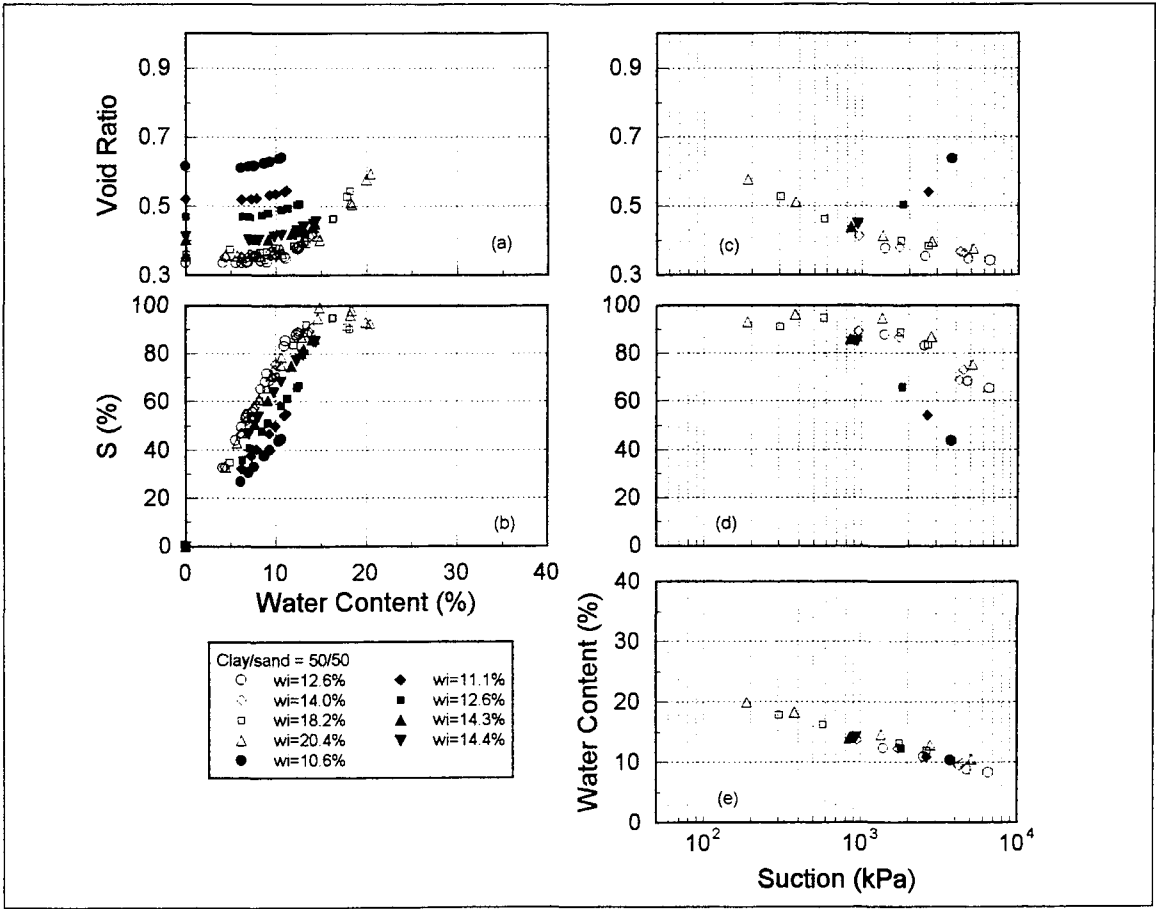


Figure 7.21 - Drying behaviour of 50/50% clay/sand mixture plotted against common axes of water content and suction.

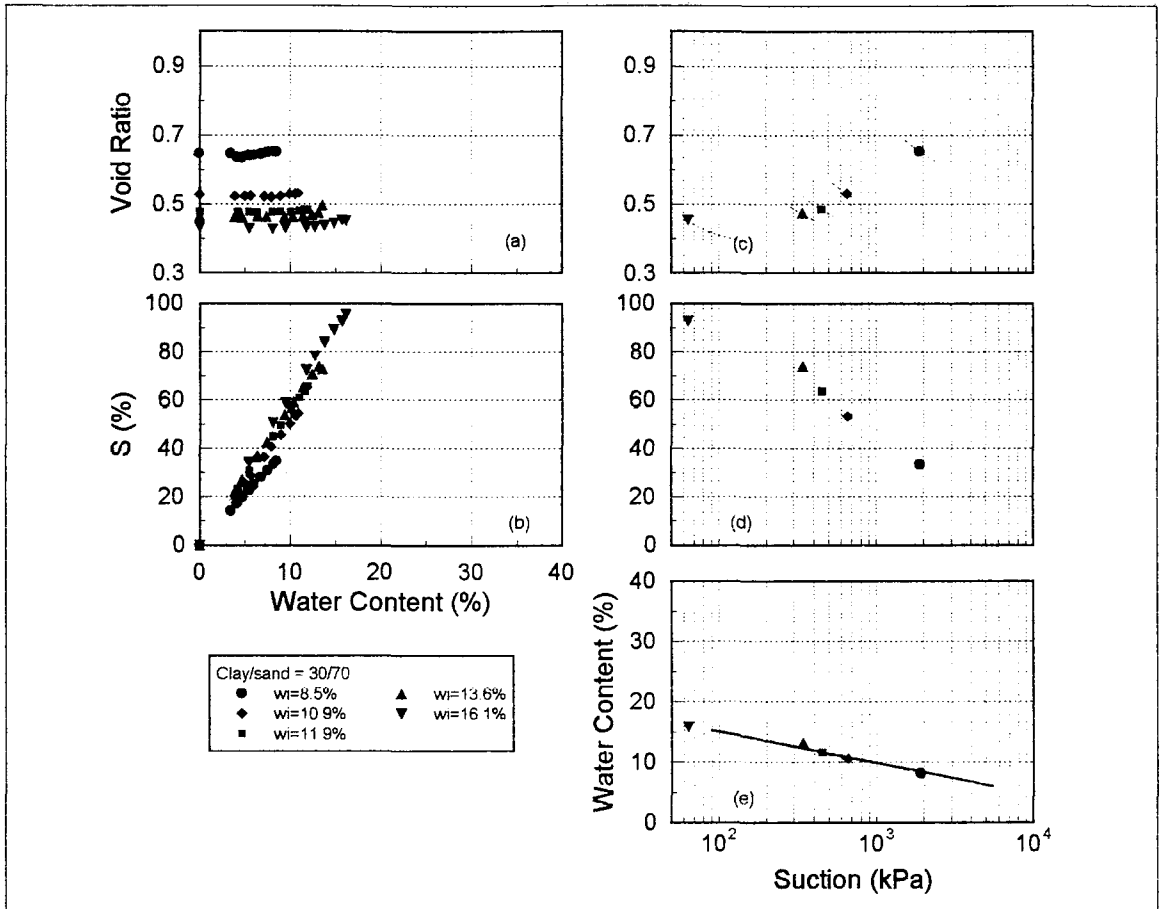


Figure 7.22 - Drying behaviour of 30/70% clay/sand mixture plotted against common axes of water content and suction.

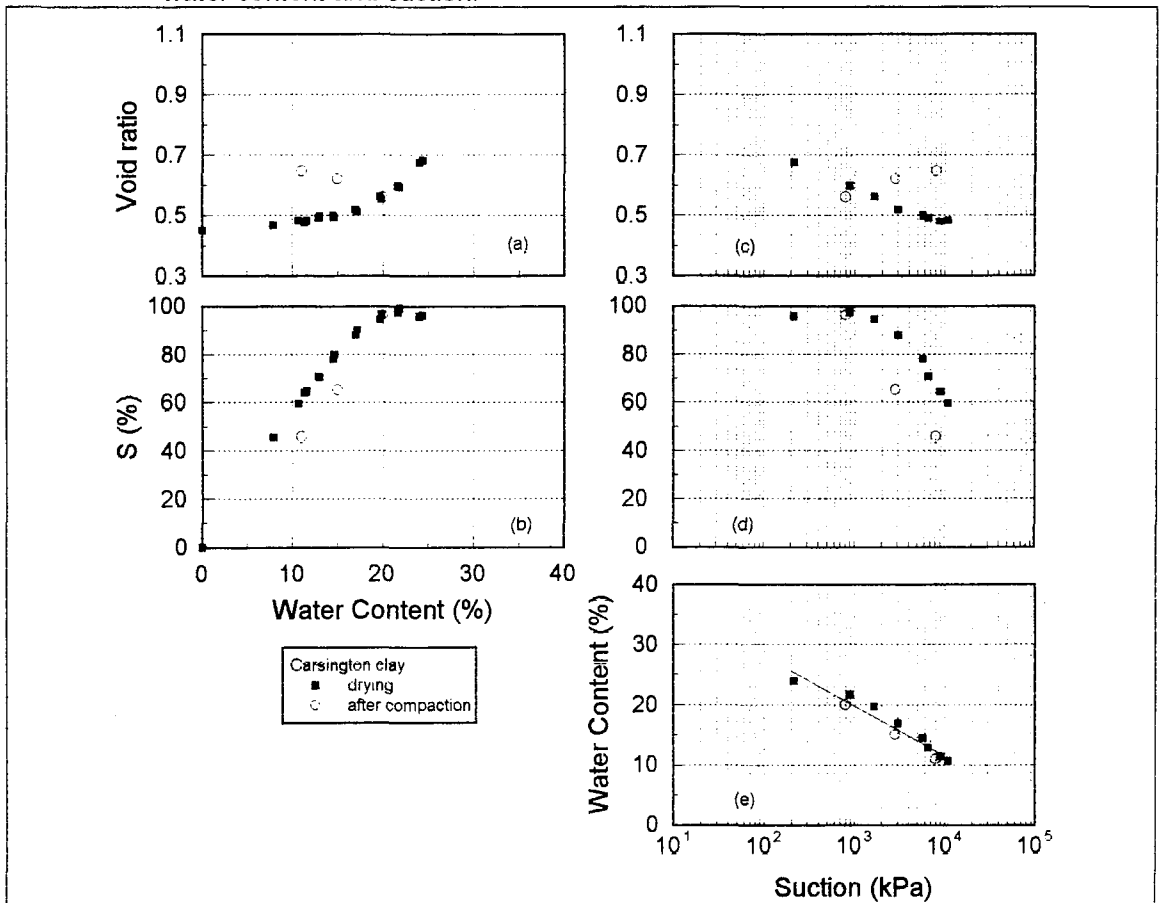


Figure 7.23 - Drying behaviour of Carsington clay plotted against common axes of water content and suction.

7.2.1.2. Water Content Versus Suction Relationship

If the relationship between water content and suction for all soils and samples tested is plotted, it can be observed that a systematic relationship exists between the data (see figure 7.24). The more plastic the soil, the higher is the water content for a given suction. The plotted lines are the regression lines obtained for all data points for each soil tested, apart from the 100/0% clay/sand mixture for which the relationship shown has been plotted noting the trend of the relationships found for the other soil mixtures. The greater scatter of the data for the 100/0% mixture is probably related to the practical difficulties encountered in compacting this soil, mainly at high water content. The results obtained with Carsington clay are also plotted in Figure 7.24, and they show reasonable agreement with the other data. The equations of the lines are as follows.

Clay/sand = 100/0% :	$w = 67.3 - 13.5 \log(\text{suction})$	{7.1}
Clay/sand = 90/10% :	$w = 57.7 - 11.5 \log(\text{suction})$	{7.2}
Clay/sand = 70/30% :	$w = 44.8 - 8.7 \log(\text{suction})$	{7.3}
Clay/sand = 50/50% :	$w = 35.8 - 7.1 \log(\text{suction})$	{7.4}
Clay/sand = 30/70% :	$w = 25.5 - 5.2 \log(\text{suction})$	{7.5}
Carsington clay :	$w = 44.7 - 8.3 \log(\text{suction})$	{7.6}

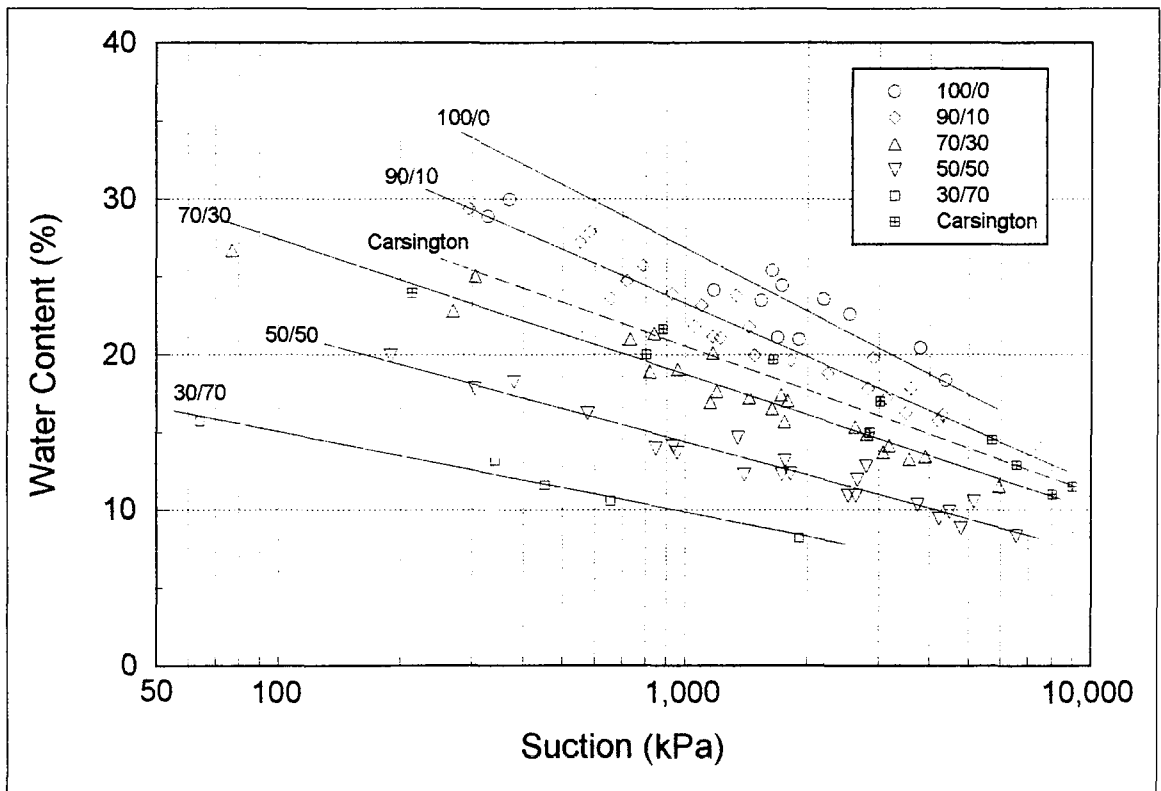


Figure 7.24 - Relationship between water content and suction for all six soils tested.

The slope of the lines is seen to vary with the plasticity of the soils. This slope can be described as the reduction in water content (expressed in percentage) over one logarithmic cycle (see Section 5.3.1). This will be termed the "Suction Capacity" (C). Table 7.4 presents the suction capacity for the dynamically compacted samples.

Soils	Suction Capacity (C)
Clay/sand = 100/0%	13.5
Clay/sand = 90/10%	11.5
Clay/sand = 70/30%	8.7
Clay/sand = 50/50%	7.2
Clay/sand = 30/70%	5.2
Carsington clay	8.3

Table 7.4 - Suction capacity for the soils tested using dynamically compacted samples.

Plotting the suction capacity against liquid limit yields a direct relationship, figure 7.25, to which may be added data from Ho *et al.*(1992), also for dynamically compacted samples, which support the results of the present study. The suction capacity is a function of the soil type for soils with liquid limit higher than 25%. At lower liquid limit the determination of C may be difficult, since a linear relation between water content and suction is often not obtained.

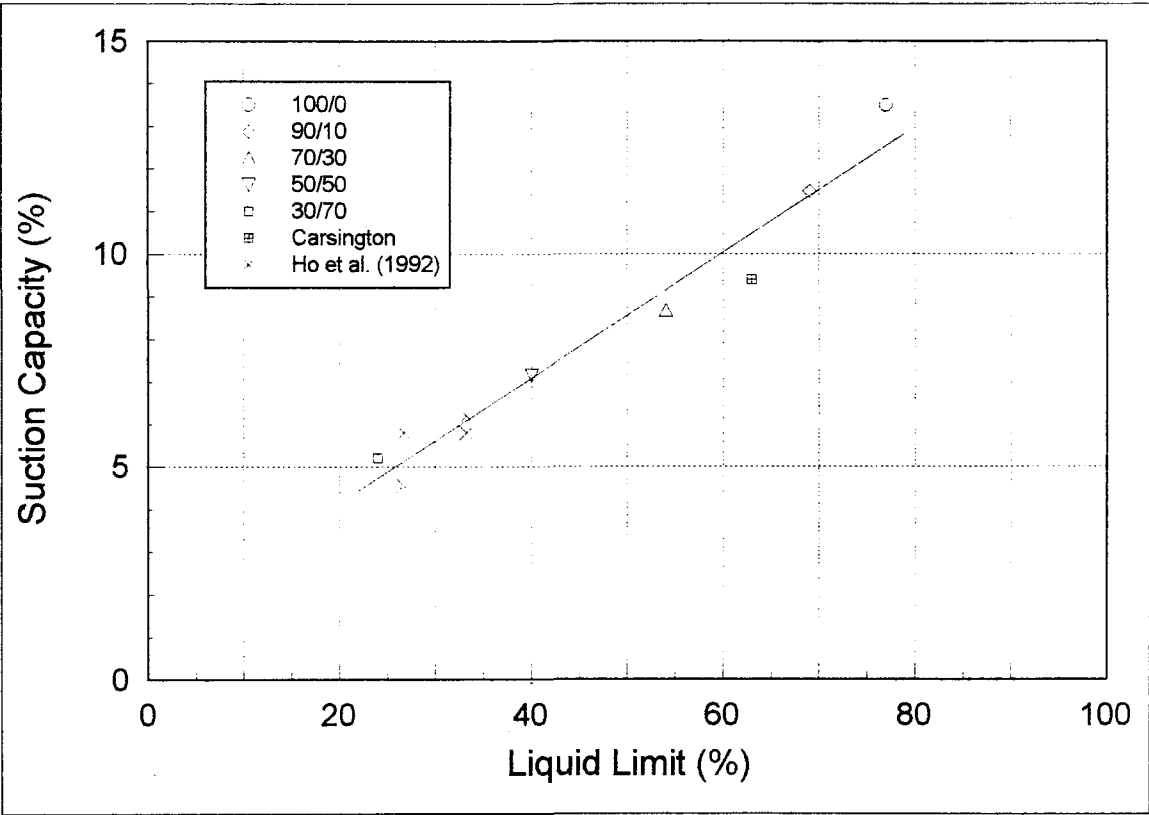


Figure 7.25 - Suction capacity versus liquid limit for various compacted soils.

It has been noted that the various drying curves either initially follow the saturation line ("near saturated behaviour") or that they immediately diverge from it, depending on the initial water content and degree of saturation. Typically the near-saturated samples were compacted wet of optimum, with an initial degree of saturation of 95-100%. Samples compacted at or dry of optimum have an initial degree of saturation less than 95%. The drying behaviour in terms of the relation between degree of saturation and water content can be considered bilinear, the point where the change in gradient occurs being defined as the general air entry point (GAE point. See section 5.3.1). The importance of the GAE point is that it provides a useful means of

assessing the range of saturated behaviour of initially near-saturated samples. Such samples are found to reach the point of general air entry at degrees of saturation in excess of 90%, whereas those samples which initially had lower degrees of saturation show a more rapid reduction in the degree of saturation in relation to changing water content. The GAE point is intended to provide a reference point in helping to analyse the results of drying tests.

The suctions developed for near-saturated samples at the GAE point (GAE value) can be obtained from the data in figures 7.18 to 7.23 or by using the equations 7.1 to 7.6, and are shown in figure 7.26 plotted on the relations between water content and suction. The 100/0% samples appear to be capable of sustaining suctions as high as 7MPa before "desaturation", but the less plastic samples show progressively lower suctions at the GAE point. An interesting behaviour was observed by plotting the GAE point for the Carsington clay. Although the Carsington clay is located between the 90/10% and 70/30% soil, in terms of plasticity and suction capacity, the GAE point determined was much lower than the two similar ones. This is probably a reflection of the pore size. The pore size distribution index (λ) and the suction at the air entry value, described by Brooks and Corey (1966) and presented in section 5.3.3.3, are 3675kPa and 1.23, respectively. It was not possible to determine these parameters for the other soils since the number of data points after the general air entry point was not sufficient.

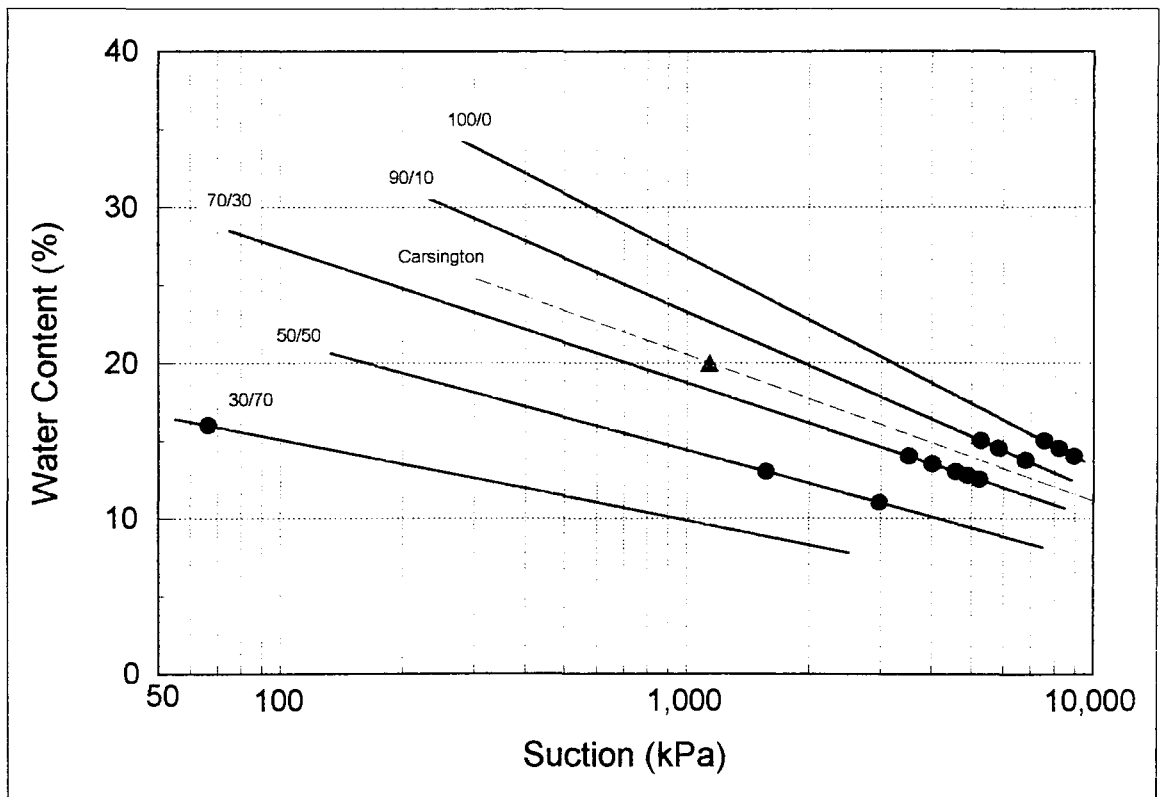


Figure 7.26 - Suction at general air entry for saturated or near-saturated samples.

The data presented in figure 7.24 can be further normalised with respect to suction capacity (C), as shown in figure 7.27, where a near unique linear relation is shown to exist between water content normalised by C , and the logarithm of suction. The results obtained with

Carsington clay lies slightly above the data from the London clay and mixtures. One explanation for that may be the grain size distribution of the soils tested. While the London clay mixtures have grain-size distribution curves that are parallel, and probably have similar pore-size distributions, the Carsington clay has some what different grain-size distribution (see Figures 6.2 and 6.4). Although it is believed that the plasticity is the main factor controlling the behaviour, the similarities of the mixtures may have reduced the scatter of the results. The regression line obtained, using only the data from the London clay and mixtures, are presented in figure 7.27 and is represented by the following equation,

$$\frac{w}{C} = 4.9 - 0.96 \log(\text{suction})$$

{7.7}.

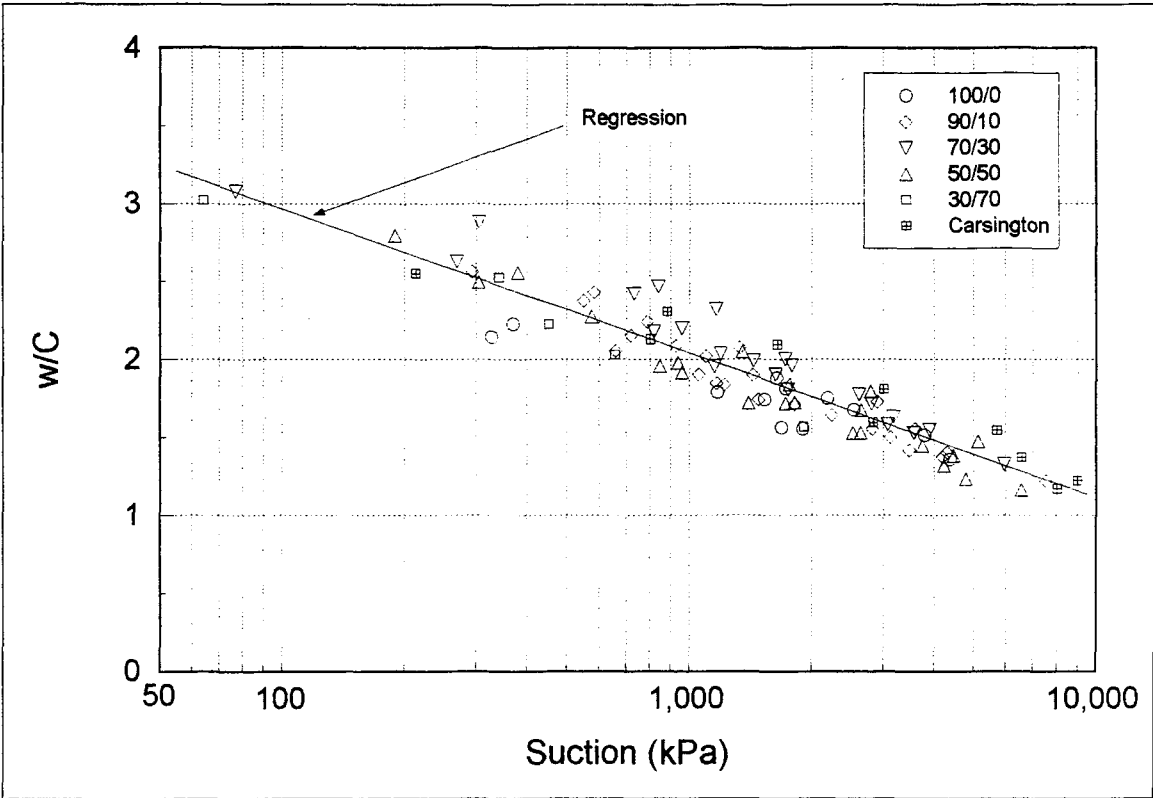


Figure 7.27 - Relationships from figure 7.24, with water content normalized by suction capacity(C).

7.2.1.3. Initial Degree of Saturation, Final Void Ratio and Suction

Figure 7.28 shows the relationship between final void ratio, initial degree of saturation and suction for all the samples tested. The final void ratio refers to the oven-dry state. The relationship between final void ratio and initial suction shows a reasonable trend for each soil (Figure 7.28a). The higher the initial degree of saturation, the lower is the final void ratio reached by the samples in the oven-dry state. The relationship between final void ratio and initial suction (Figure 7.28b) shows that higher the initial suction the higher is the final void ratio, though this behaviour depends on the initial void ratio. Both relationships presented in Figure

7.28, tend to an horizontal line when the initial void ratio is the same as the final void ratio, i.e. the suction is infinite and the degree of saturation is zero.

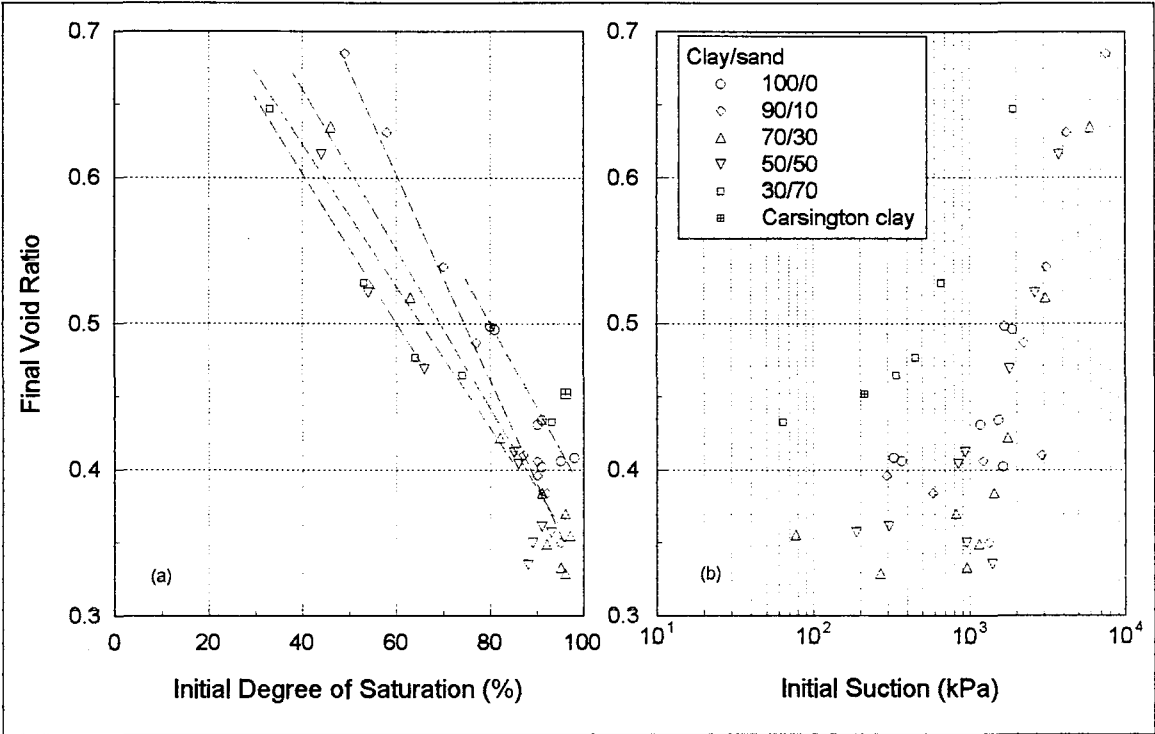


Figure 7.28 - Final void ratio versus Initial degree of saturation and logarithm of Initial suction.

7.2.2. Statically Compacted Samples

7.2.2.1. General Behaviour

7.2.2.1.1. Volume Change Versus Water Content

These samples were prepared following the procedures described in section 6.2.3. The soils used were London clay from Chattenden, Boom clay, Janga clay, a mixture of London clay and 40% silt (L40S), and a soil "produced" by placing London clay under 500°C for 24 hours (LC500). Some samples were prepared using London clay or LC500 soil, with salt solution as pore fluid instead of pure water.

The initial characteristics of the London clay samples in terms of dry unit weight and water content is shown in Figure 7.29. The samples prepared using London clay covered a wide range of water contents and dry unit weights. Table 7.5 presents the initial characteristics of all statically compacted samples tested.

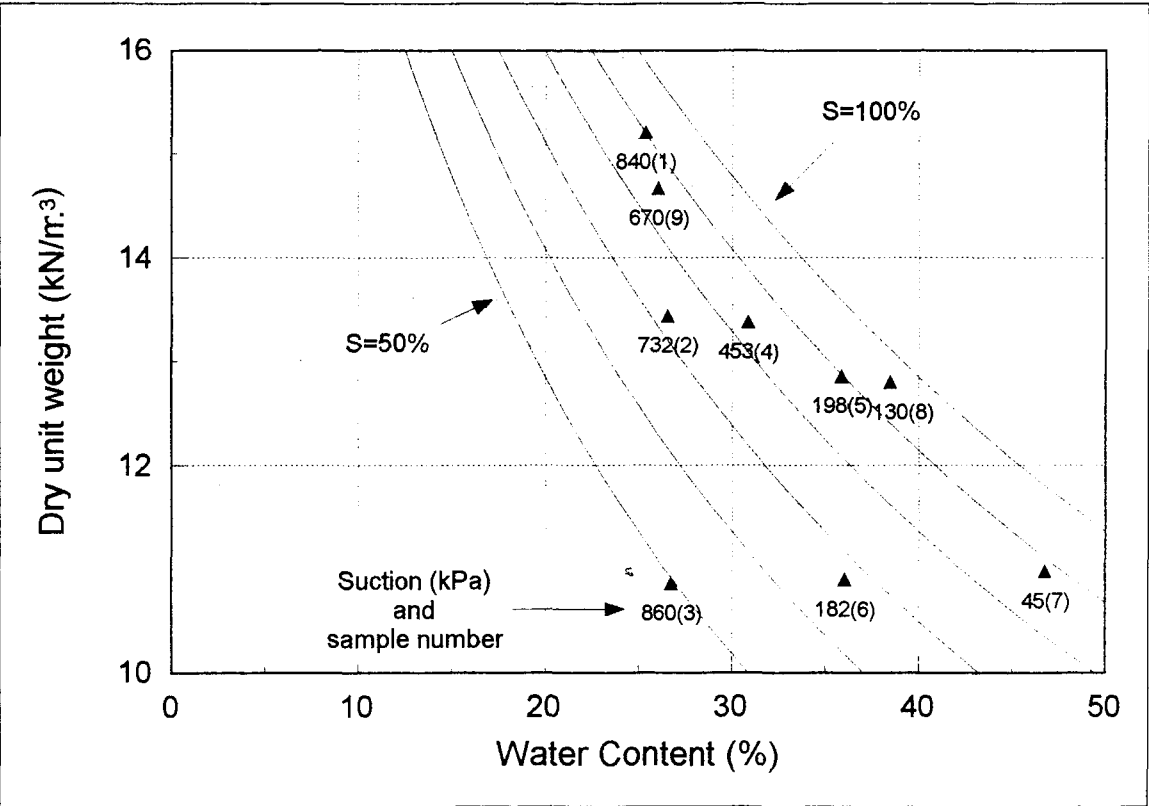


Figure 7.29 - Initial conditions of the samples of London clay in terms of dry unit weight and water content.

The experimental results of the drying tests obtained with London clay are presented in figure 7.30. It can be observed that during drying the samples followed a line parallel to the saturation line. This behaviour indicates that the samples have a reducing degree of saturation but a constant volume of air. As seen in section 7.2.1, samples dynamically compacted at water contents above the optimum showed similar behaviour. All these London clay samples were

prepared with a water content near or higher than optimum water content (BS heavy compaction test).

Soil	Sample	W_i (%)	S_i (%)	e_i	suction _i (kPa)
London clay from Chattenden	LCST 1	25.4	90	0.774	640
	LCST 2	26.6	73	1.007	732
	LCST 3	26.8	50	1.484	860
	LCST 4	30.9	83	1.016	453
	LCST 5	35.9	90	1.098	198
	LCST 6	36	67	1.475	182
	LCST 7	46.8	88	1.458	45
	LCST 8	38.5	96	1.108	130
	LCST 9	26.1	85	0.839	670
London clay with 0.1 molar of NaCl	S - 1	31.5	99	0.878	266
	S - 2	31.8	96	0.905	341
LC500 (pure water)	LC500-SP	35.5	93	1.057	105
LC500 (0.1 molar)	LC500-SS	36.1	92	1.077	74
L40S	S - 1	27.9	97	0.774	211
	S - 2	28	94	0.82	177
Janga clay	S - 1	26	61	1.131	942
	S - 2	26.5	62	1.139	838
	S - 3	40.8	100	1.081	75
Boom clay	S - 1	28	92	0.839	464
	S - 2	39.2	96	1.121	46
Carsington clay	S - 1	29.1	-	-	214

Table 7.5 - Initial characteristics of statically compacted samples.

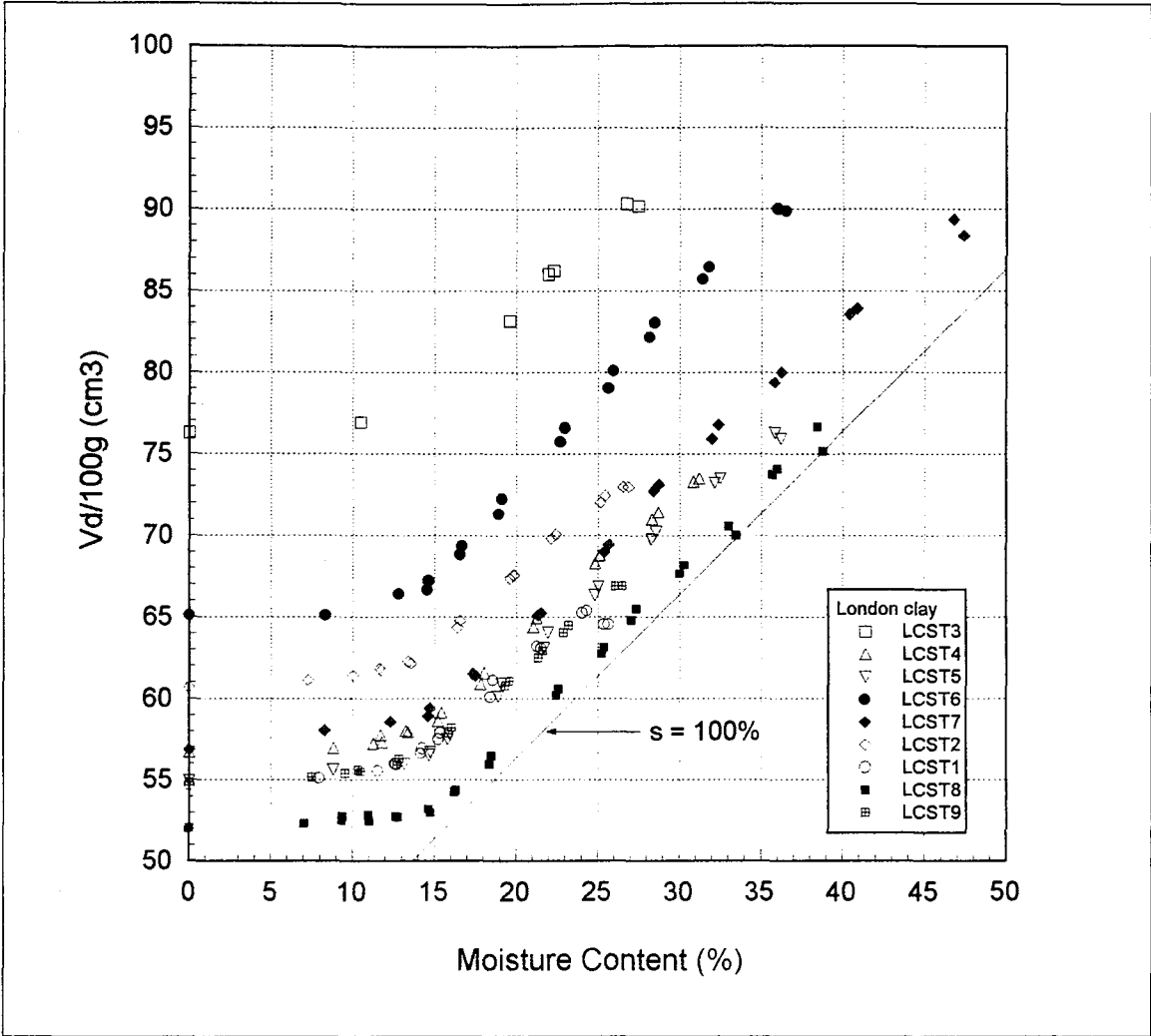


Figure 7.30 - Drying behaviour of statically compacted London clay; $V_d/100$ is the volume per 100g of soil solids.

Figure 7.31 shows the results obtained with a mixture of 60% London clay and 40% silt (L40S), which are similar to those from the London clay samples given in Figure 7.30.

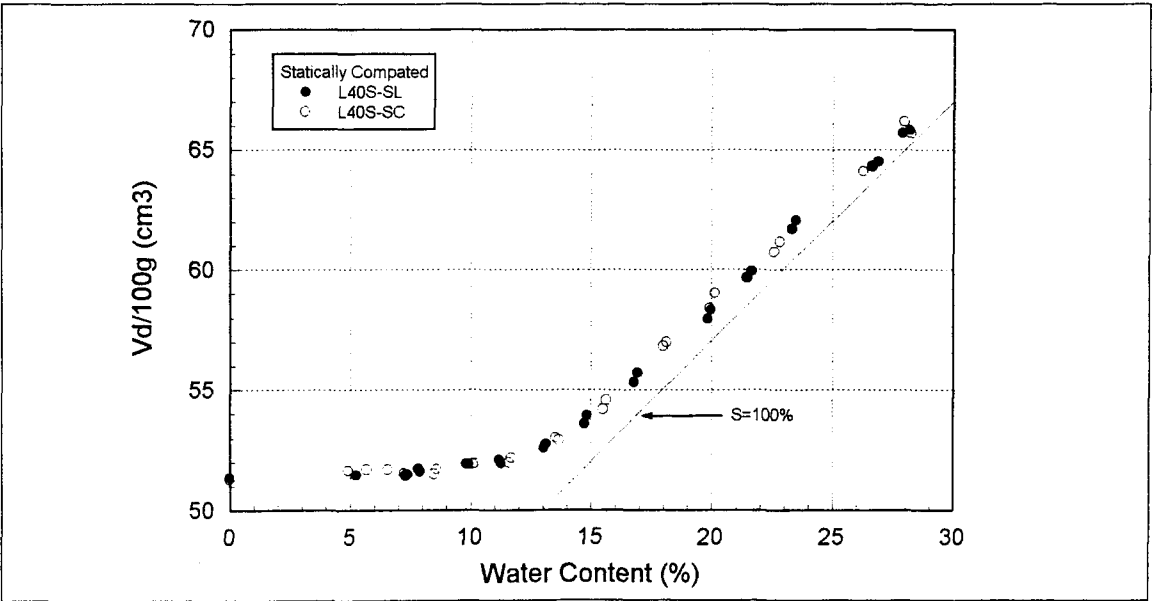


Figure 7.31- Drying behaviour of statically compacted L40S soil mixture; $V_d/100$ is the volume per 100g of soil solids.

The drying curves of the Janga clay, a tropical soil from Brazil, are presented in figure 7.32. Three samples were tested, each having different characteristics in terms of macro structure. Sample 1 was compacted using "undisturbed" soil lumps of equal nominal size (approx. 0.5 cm diameter). Sample 2 was compacted using soil lumps of approximately 2.5mm diameter and sample 3 was obtained using the same soil passed through n° 40 sieve (0.425mm). Samples 1 and 2 were compacted with the same water content (the *in situ* water content) and the same initial void ratio. Although the macro structure of these two samples was completely different, the drying curves showed identical behaviour. This suggests that the micro structure is controlling the behaviour. Sample 3 started from a saturated condition and followed the saturation line down to a water content of 18%. Sample 3 has a initial void ratio only 5% lower than the other samples, but it had a final volume 26% lower than sample 1 and 2. This behaviour is a result of differences in the initial degree of saturation of the samples.

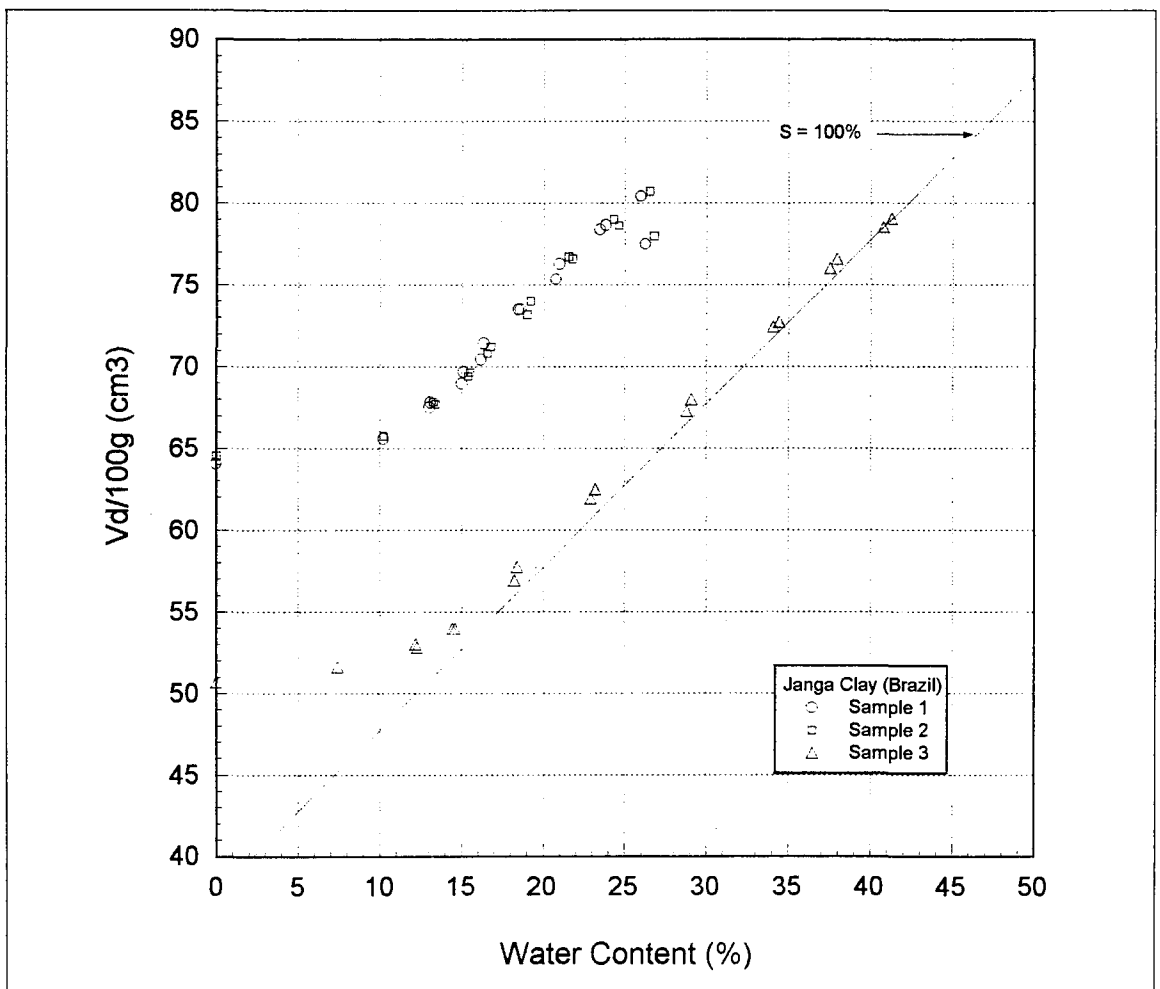


Figure 7.32 - Drying behaviour of statically compacted Janga clay; $V_d/100$ is the volume per 100g of soil solids.

The Boom clay samples were obtained using soil passed through a n° 40 sieve. The drying curves are presented in figure 7.33. The samples were compacted with different initial conditions. During drying, sample 2 approximately coincided with the initial condition of sample 1. However the two sample diverges at that point, and sample 2 has a final volume 5% lower

than sample 1. The difference in the initial degree of saturation is 4%, which may explain the results.

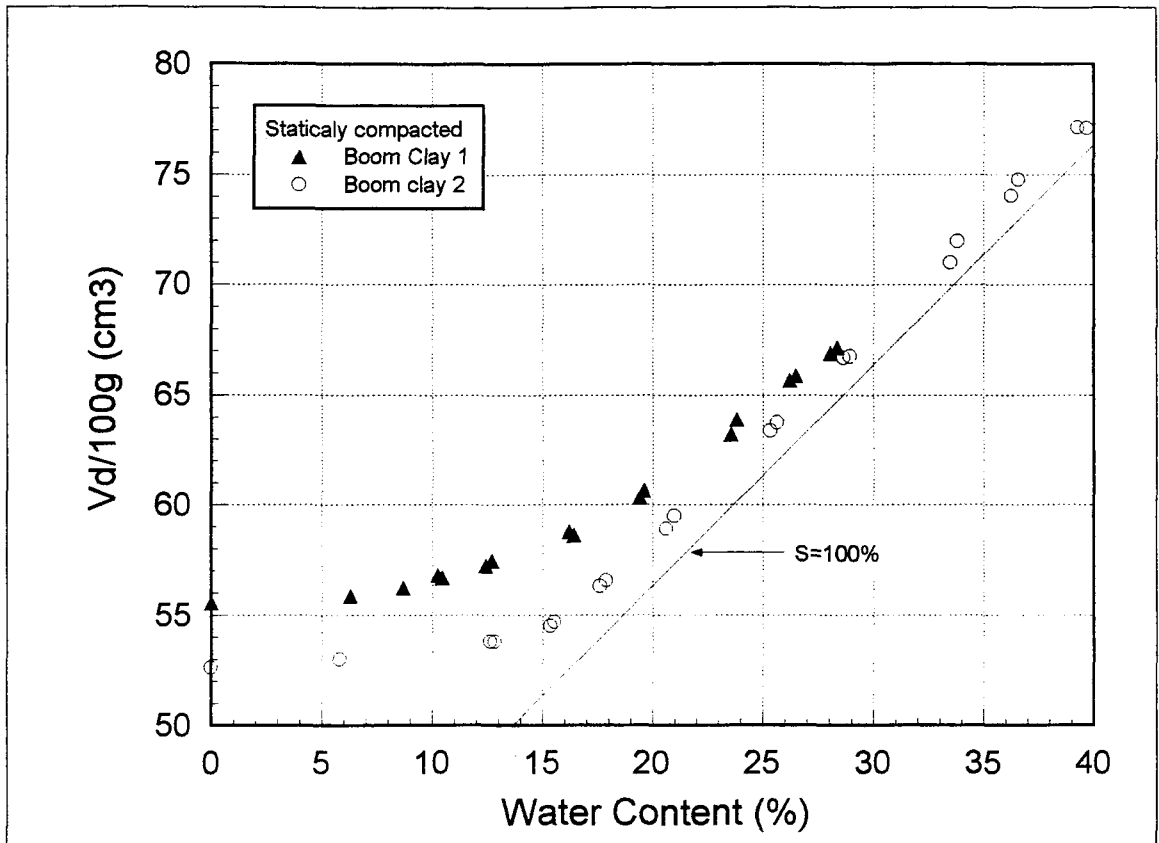


Figure 7.33 - Drying behaviour of statically compacted Boom clay; $V_d/100$ is the volume per 100g of soil solids.

7.2.2.1.1.1. Samples With Added Salts

In figure 7.34 the results of a drying test performed in London clay with salt solution as pore fluid is presented. For reference two samples compacted using pure water as the pore fluid are also plotted (LCST 4 and LCST 8). By adding salt to a soil the plasticity is expected to reduce, the reduction being function of the soil type. For Regina clay (LL = 75%) the plasticity index reduced by approximately 3% when 0.1 molar of NaCl is added. If 1 molar is added the liquid limit reduces by 15%. The plastic limit remains approximately constant (Barbour and Yang, 1993). The two samples with added salt had an initial degree of saturation higher than 95%. During drying they followed the line of 100% degree of saturation. Sample 2 was slightly less saturated than sample 1 and presented a final volume ($V_{d/100}$) 2% higher. These differences are considered small and the samples are assumed to be identical. Using sample LCST 8 for comparison with the two samples with added salt, it can be observed that there is no significant difference between the three samples. Although a reduction in plasticity may have occurred, it was not evident in the drying tests. The results with the sample LCST 4 showed that the initial degree of saturation has a great effect on the final volume of the sample, which is more detectable than the increase in osmotic suction.

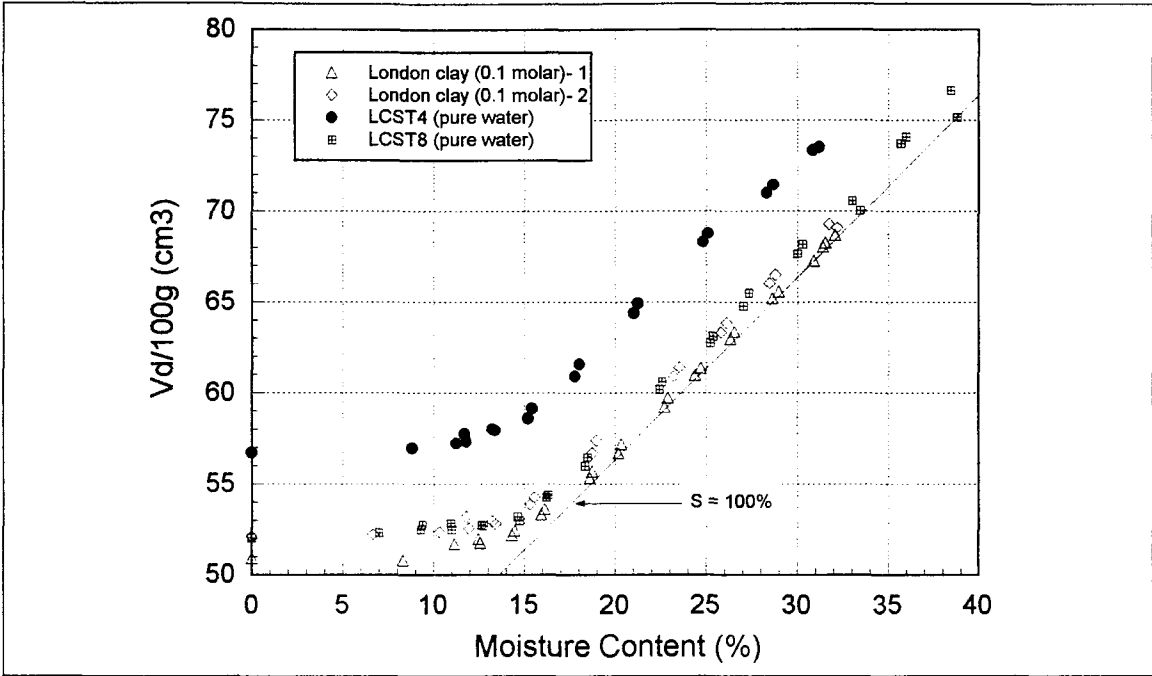


Figure 7.34 - Drying behaviour of statically compacted London clay with added salt; $V_d/100$ is the volume per 100g of soil solids.

The addition of salt to soil with low plasticity do not affect significantly the plasticity of the soil (e.g. (Barbour and Yang, 1993)). Figure 7.35 presents the results of two drying tests performed in a LC500 clay ($LL=50\%$), using pure water and a solution of 0.1 molar of NaCl. Again no apparent difference was observed between the samples. It can be concluded that the osmotic suction induced (approx. 460kPa) by the addition of this salt solution does not generate any kind of "effective stress" sufficient to alter the volume change of the soils tested. If a higher amount of salt is added the soil characteristics will be dramatically altered and the comparison with the original soil is no longer valid.

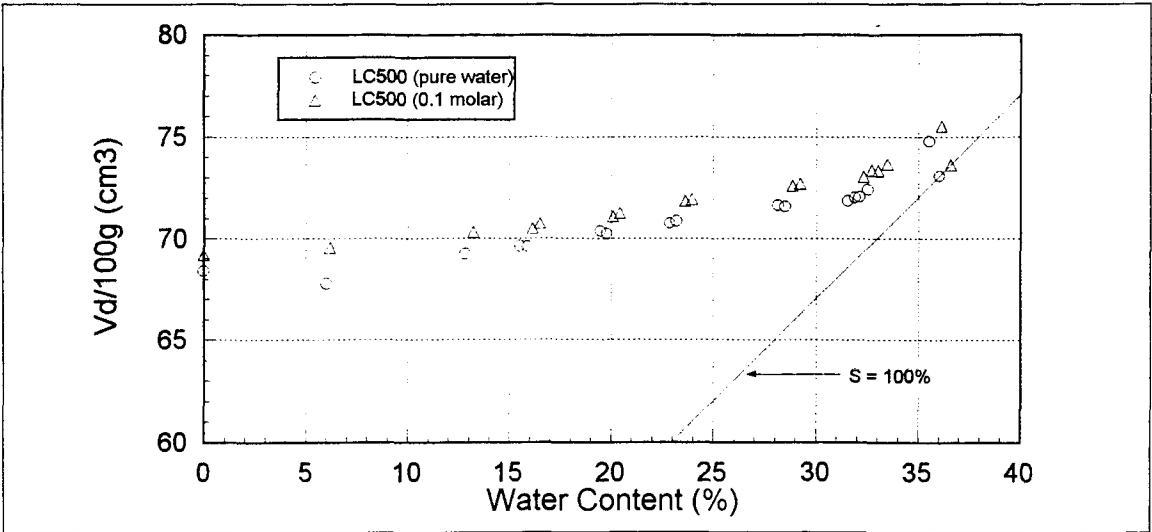


Figure 7.35 - Drying behaviour of statically compacted LC500 clay with added salt; $V_d/100$ is the volume per 100g of soil solids.

7.2.2.1.2. Water Content, Volume Change and Suction

The results of the drying tests are also plotted against void ratio, degree of saturation, water content and suction in figures 7.36 to 7.45. Wetting behaviour was also studied and the test procedures are presented in Section 6.5.

Figure 7.36 presents the results obtained with ^{compacted}statically London clay. The GAE point can be identified on the samples with an initially high degree of saturation. A yield point is clearly observed on the relationship between degree of saturation and suction (figure 7.36d). This point of inflection seems to coincide with the GAE point. The relationship between water content and suction showed a unique relationship (see figure 7.36e), and can be expressed by the equation,

$$w = 66.73 - 13.11 \log(\text{suction}).$$

{7.8}

The wetting paths of some of the samples are shown in figure 7.37. Wetting was obtained by vapour absorption. This procedure avoided sample cracking, and made it possible to characterize the wetting path. Hysterisis is clearly observed.

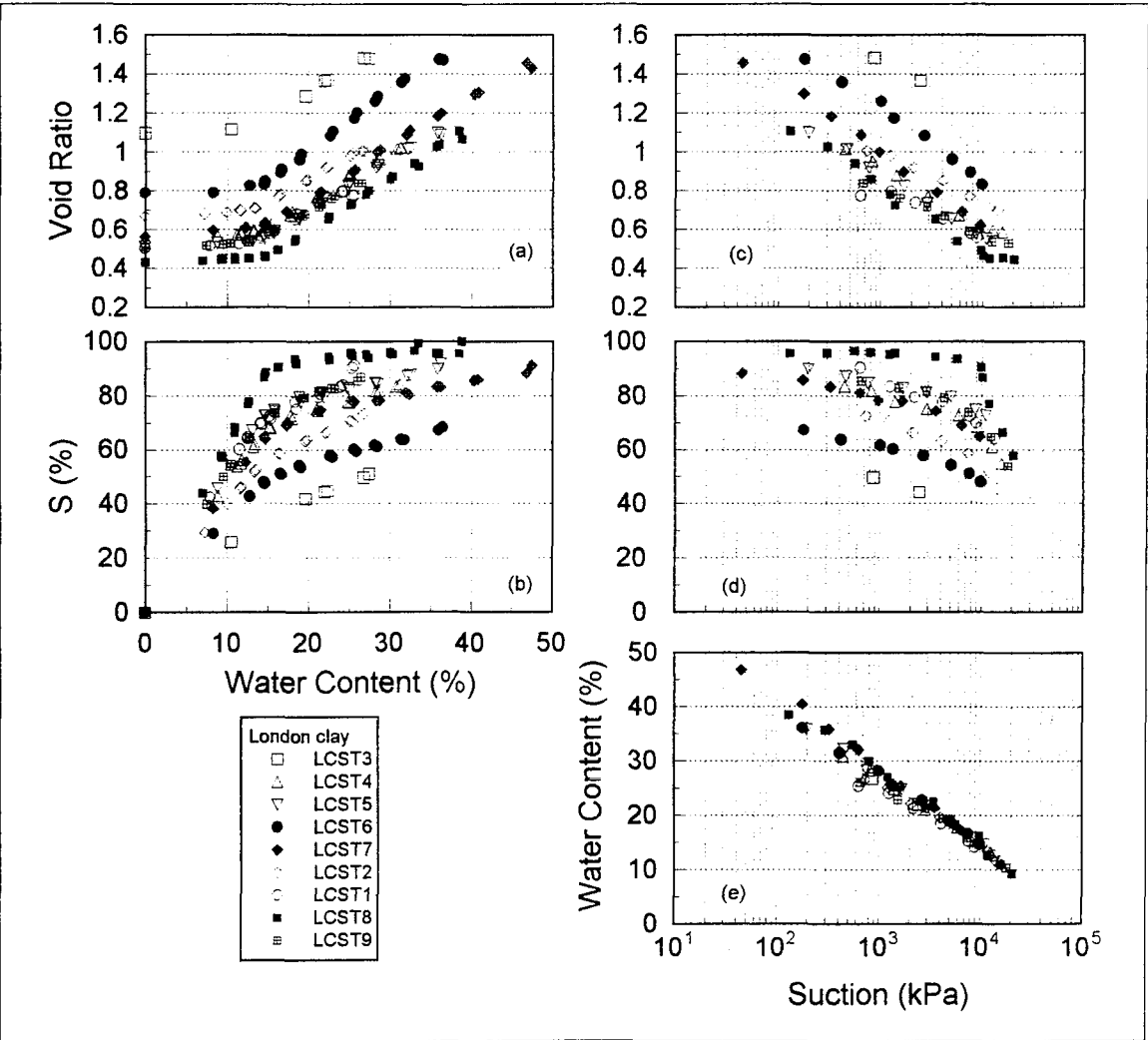


Figure 7.36 - Drying behaviour of London clay plotted against common axes of water content and suction.

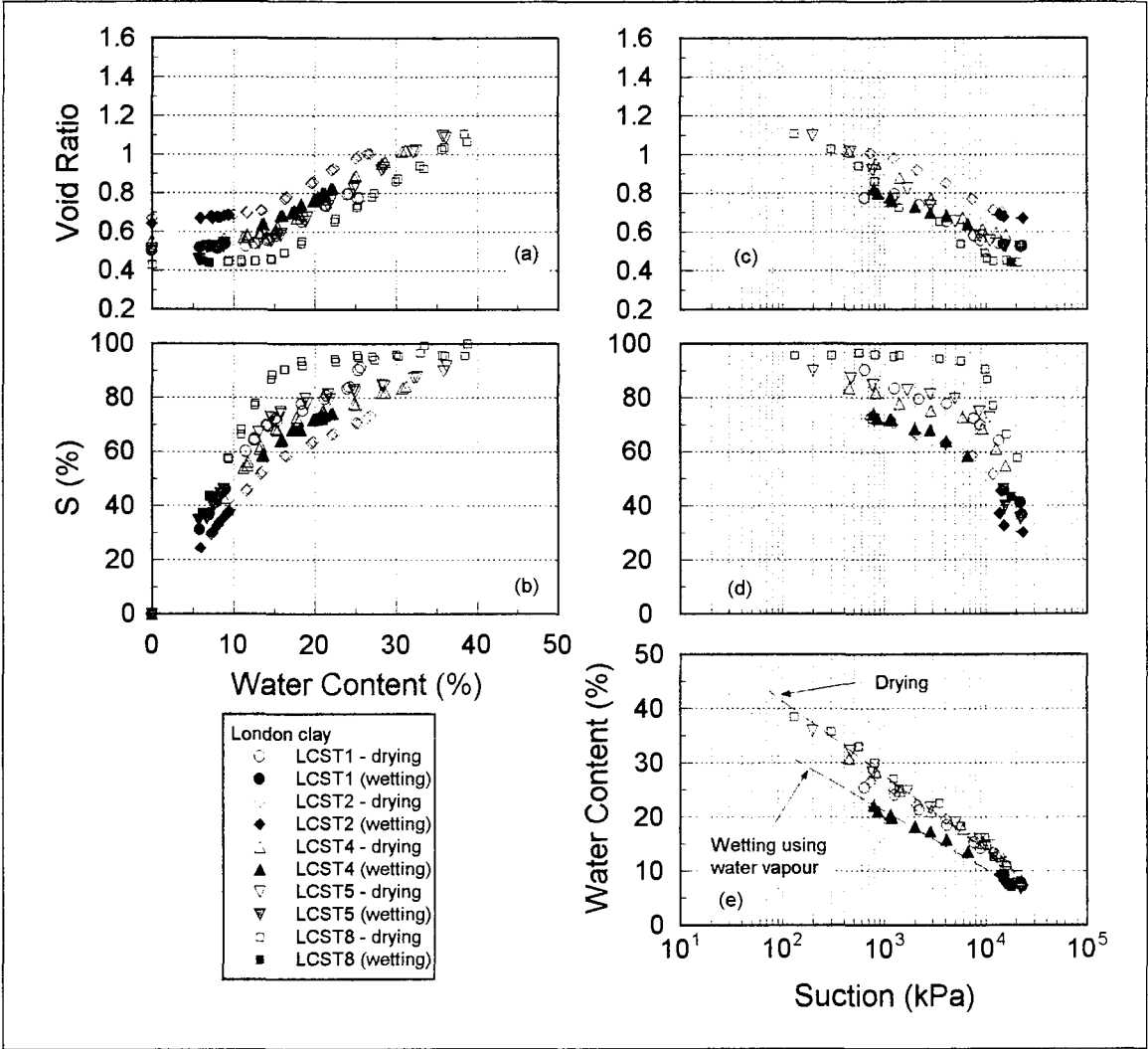


Figure 7.37 - Drying and wetting behaviour of London clay plotted against common axes of water content and suction.

Figure 7.38 presents the results obtained with the mixture 60% London clay and 40% silt (L40S). The two samples tested presented identical behaviour and shows very clearly the GAE point on figure 7.38b and the yield point on the relationship between degree of saturation and suction (figure 7.38d) seems to coincide with the GAE point. The relationship between water content and suction for the L40S clay, can be expressed by the equation,

$$w = 52.3 - 10.36 \log(\text{suction}) \quad \{7.9\}.$$

Results obtained with Janga clay is presented in figure 7.39. The description of the samples tested were presented previously in this section. The results of sample 3 characterize very well the GAE point (figure 7.39b), while in the other two sample it is not so clear. Again the yield point on figure 7.39d is only observed in sample 3. Although the soil lumps in the sample 1 and 2 are probably saturated, the air surrounding them is likely to be connected. The general air entry point to be observed in samples 1 and 2 would be the lumps one. This point can be identified in figure 7.39b, and approximately coincide with the GAE of sample 3.

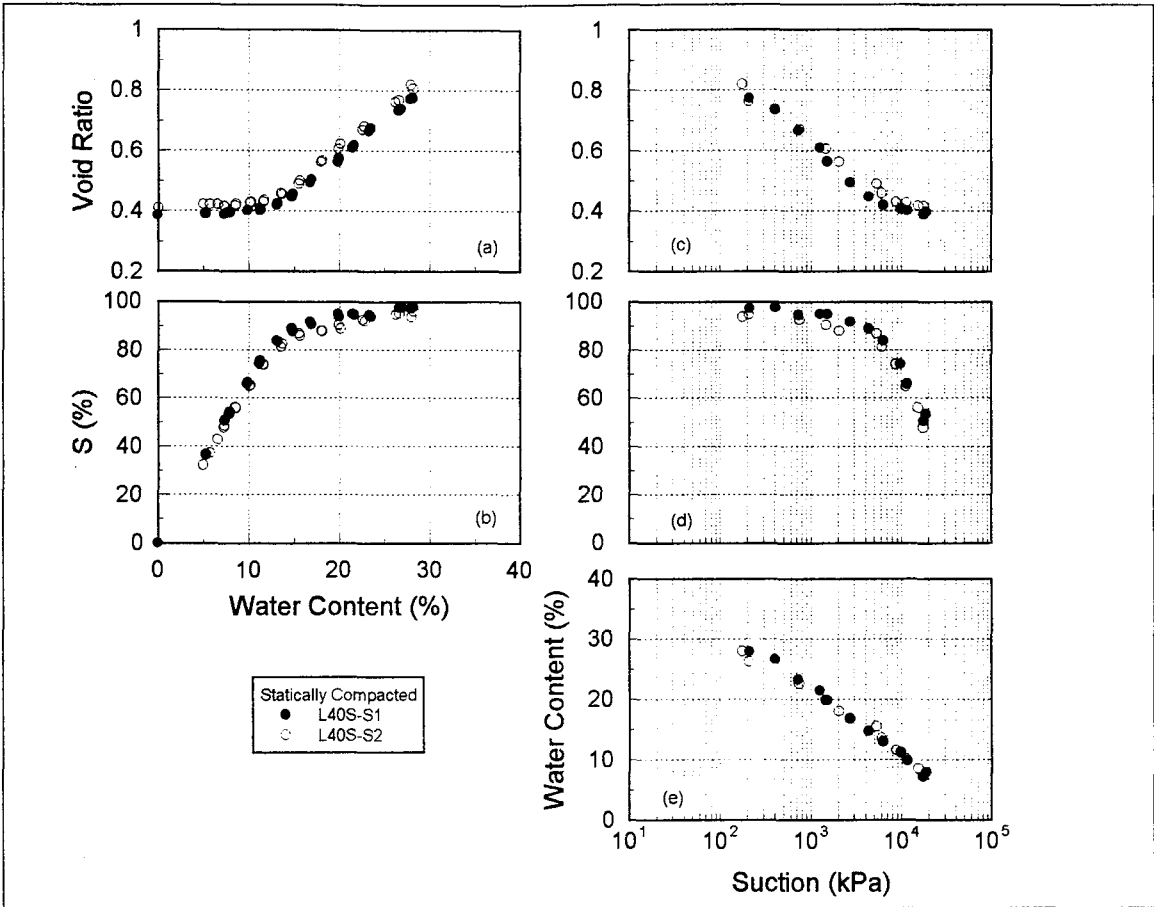


Figure 7.38 - Drying behaviour of L40S mixture plotted against common axes of water content and suction.

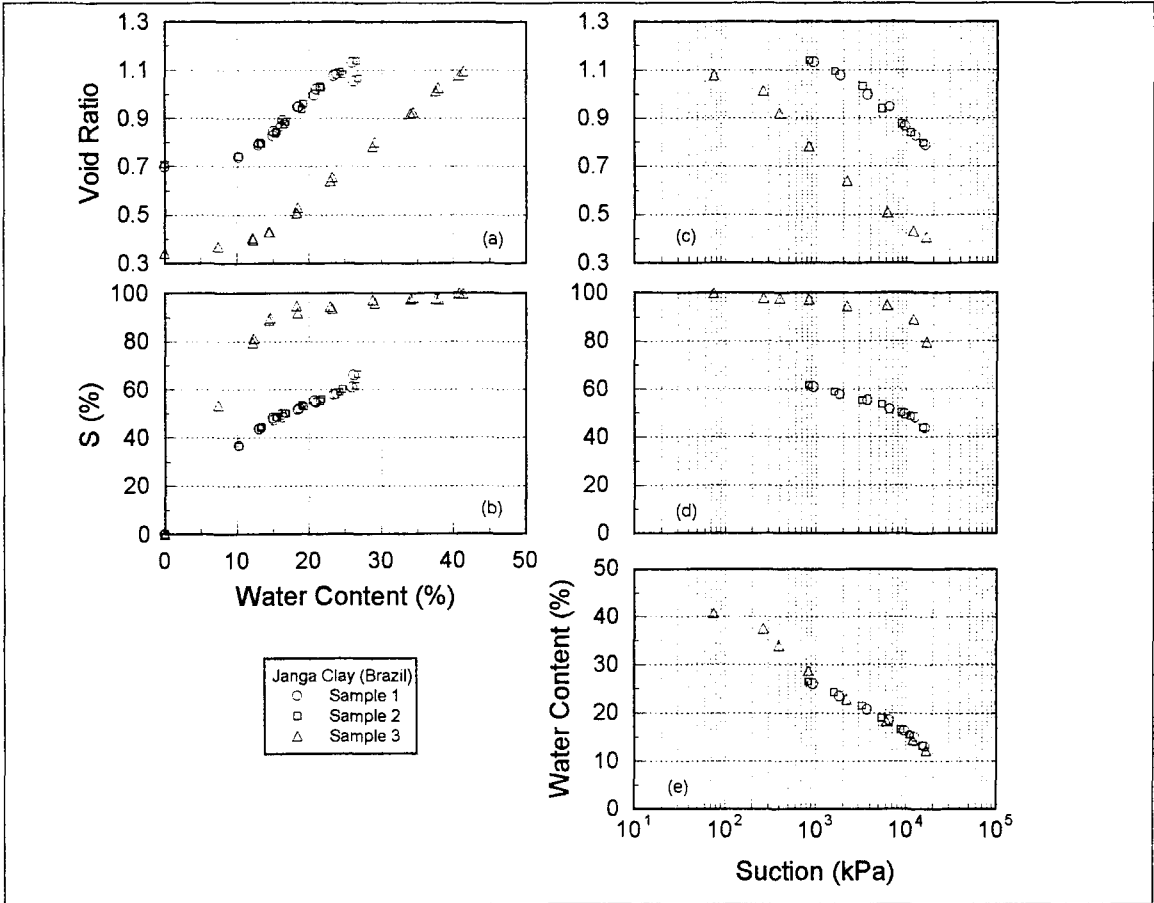


Figure 7.39 - Drying behaviour of Janga clay plotted against common axes of water content and suction.

The relationship between water content and suction, for Janga clay, is represented by the equation,

$$w = 64.02 - 12.13 \log(\text{suction}) \quad \{7.10\}.$$

The results of the two samples of Boom clay tested are shown in figure 7.40. The GAE point of the samples are approximately the same (18%), being easier to identify it on sample 2 than in sample 1. It is very clear the importance of the degree of saturation in controlling the volume change. For instance, if the degree of saturation of both samples are taken for the same suction (i.e. 3MPa), sample 1 has $S=80\%$ and sample 2 has $S=90\%$, in terms of further reduction in volume the sample with higher degree of saturation reach^s a lower void ratio. This behaviour is a reflection of the structure of the soil at that particular degrees of saturation. An increase in suction in sample 1 ($S=80\%$) is not so effective as the same increase in sample 2 ($S=90\%$).

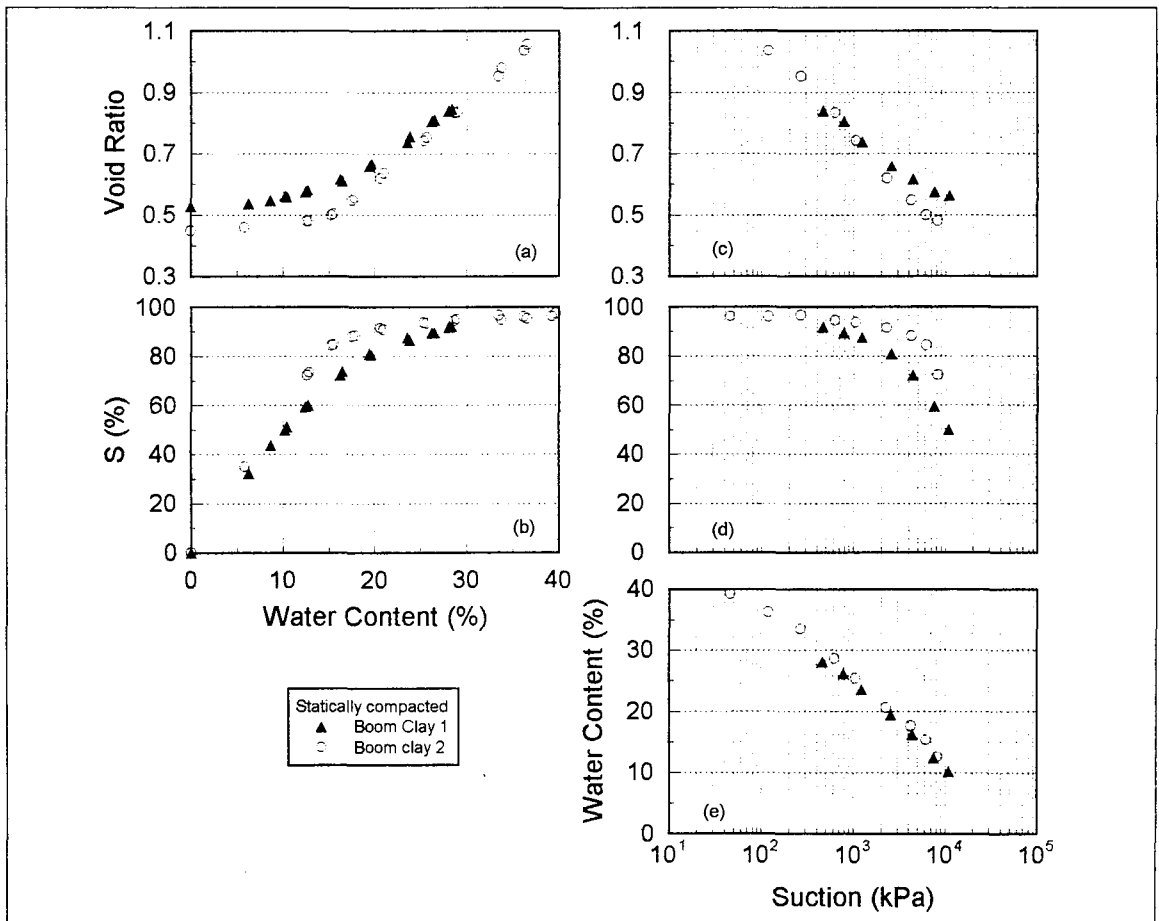


Figure 7.40 - Drying behaviour of Boom clay plotted against common axes of water content and suction

The relationship between water content and suction for Boom clay, has the same characteristics of the others clay soils tested. This relationship can be represented by the equation,

$$w = 62.27 - 12.55 \log(\text{suction}) \quad \{7.11\}.$$

Figure 7.41 presents the result obtained with Carsington clay. In this case only the water content and suction were determined. The curve characteristic in this case can be represented by the equation,

$$w = 57.26 - 11.61 \log(\text{suction}) \quad \{7.12\}.$$

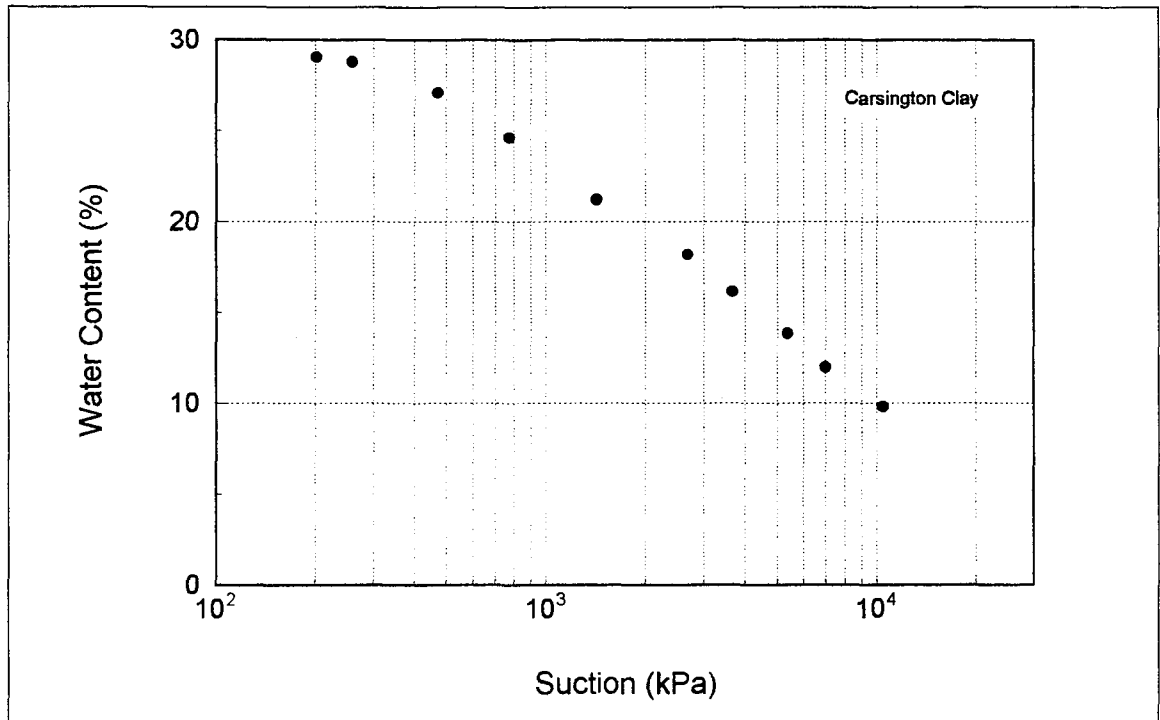


Figure 7.41 - Relationship between water content and suction for Carsington clay during drying.

7.2.2.1.2.1. Matrix and Total Suction

The drying behaviour of the samples on which matrix and total suction measurements were made are presented in figures 7.42 to 7.46.

The drying test on London clay (sample LCST 9) is presented in figure 7.42 with matrix and total suction measurement. The initial osmotic suction determined was 410kPa. Matrix and total suction measurements converge to the same value at suction of 3MPa. This behaviour can be due to a combination factors; the reduction in contact between the filter paper and the soil water or/and the time left for equilibration which may not be enough (see also chapter 4 and section 7.1.1.2).

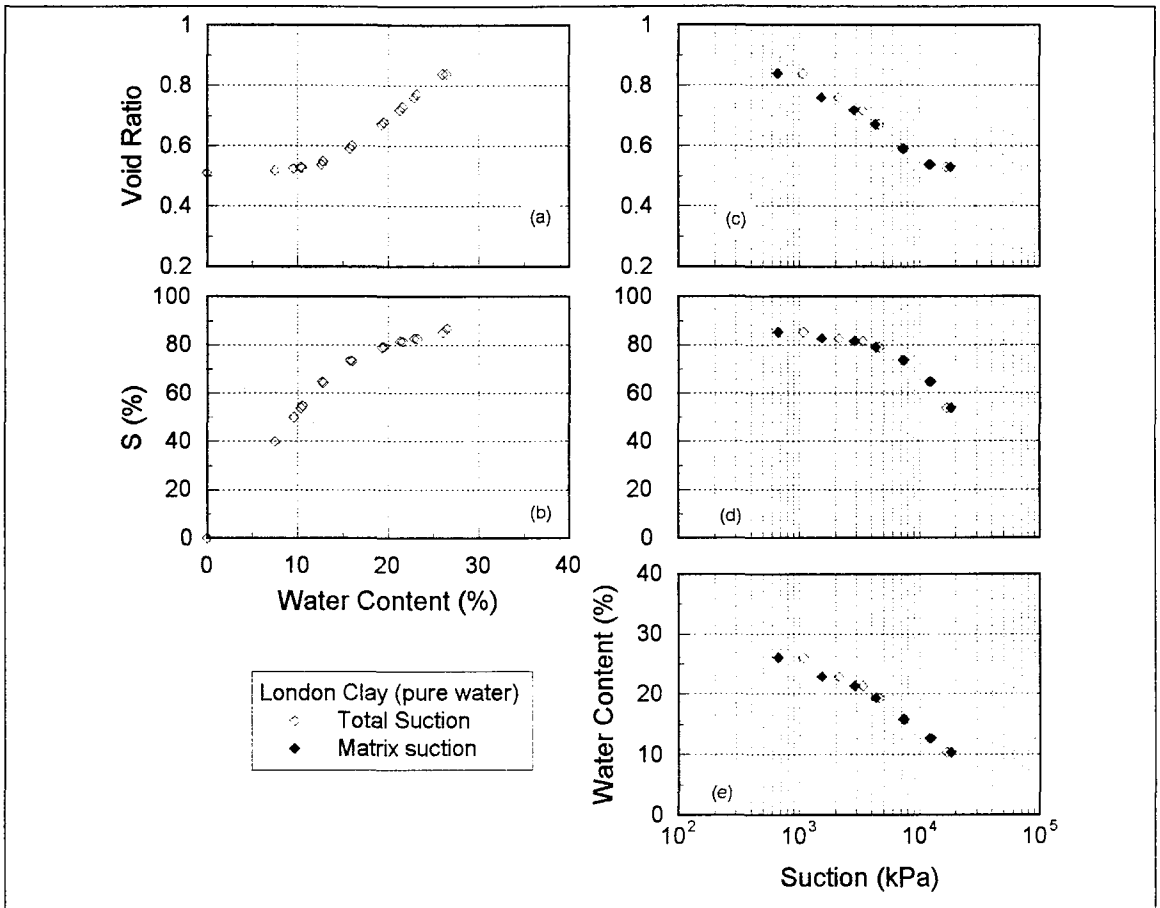


Figure 7.42 - Drying behaviour of London clay plotted against common axes of water content and matrix or total suction.

Figures 7.43 and 7.44 presents the results obtained with London clay mixed with a 0.1 molar NaCl solution. The general behaviour of the two samples tested in terms of matrix or total suction is similar and the only apparent difference is slope of the relationship between void ratio and suction, and water content and suction, both increase when total suction is used. The osmotic suction determined at the beginning of the tests for the two samples were approximately 700kPa. The salt solution used had a osmotic suction of 460kPa.

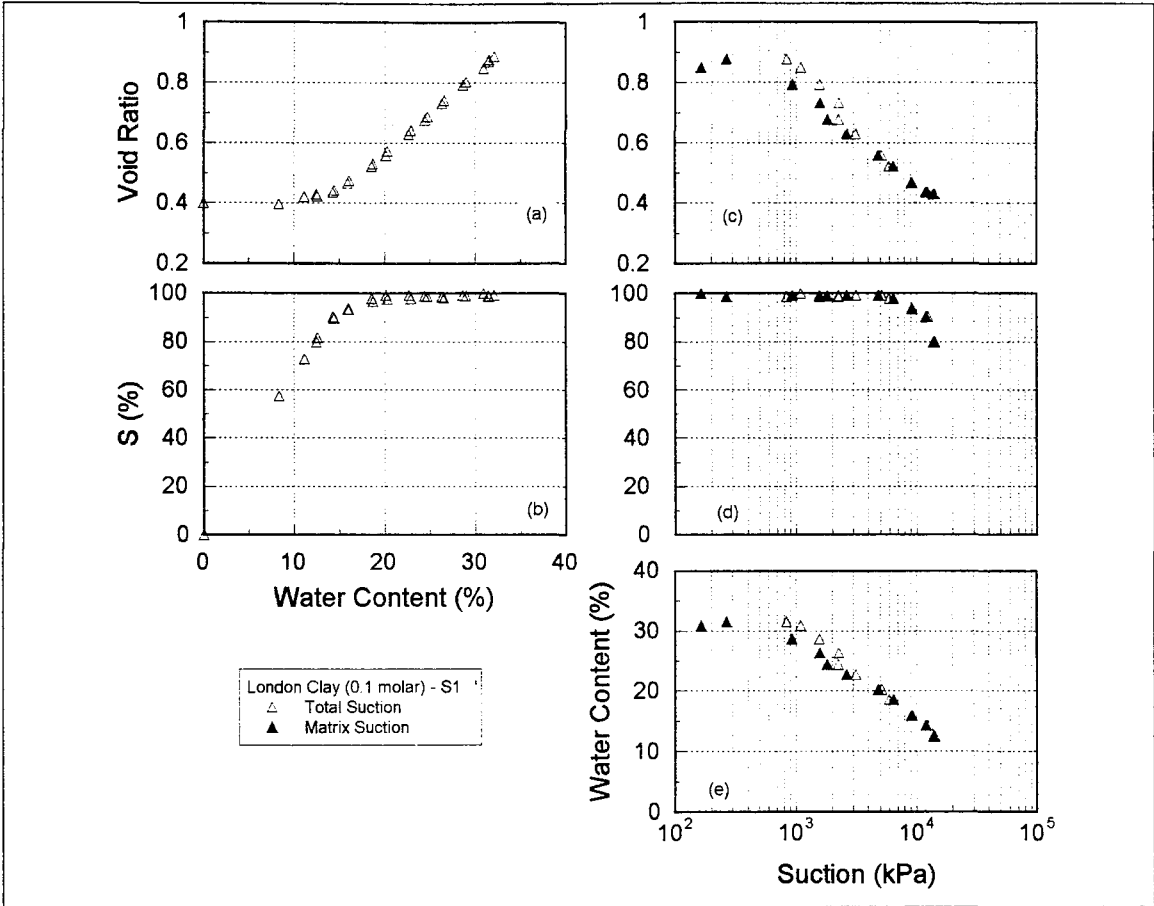


Figure 7.43 - Drying behaviour of London clay with added salt plotted against common axes of water content and matrix or total suction.

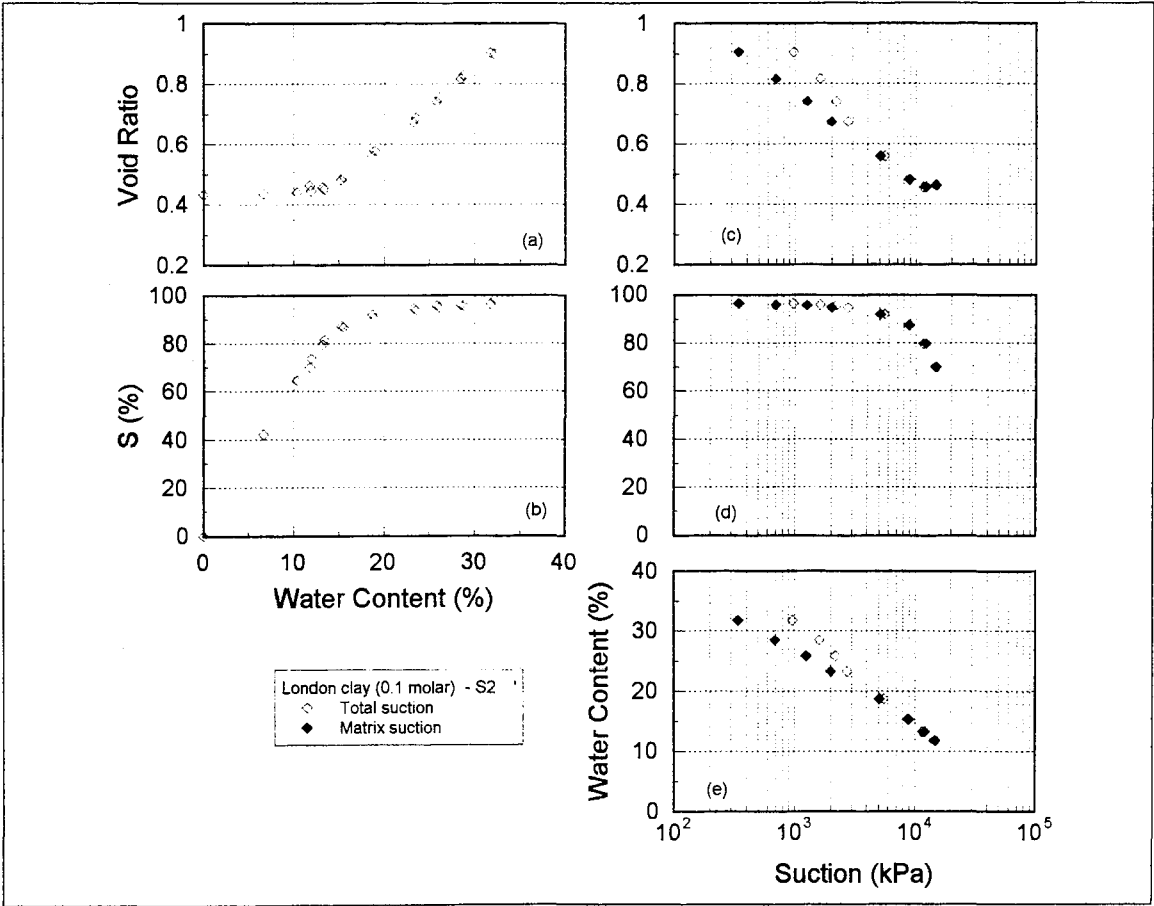


Figure 7.44 - Drying behaviour of London clay with added salt plotted against common axes of water content and matrix or total suction

In figure 7.45 the results of the drying test in the LC500 clay is presented. Measurements of matrix and total suction are shown. The initial osmotic suction is 350kPa and the matrix and total suction coincide at about 2MPa of suction. In figure 7.46 are presented the results obtained with the same soil, but with added salt (0.1 molar of NaCl). The initial osmotic suction for the sample with added salt is 600kPa which is 210kPa lower than the expected. The complexity involved in the osmotic process in soils is reflected by the difficulties in evaluate the soil osmotic suction by using the osmotic suction of the solution added (see section 2.1.4 and 7.1.1.4 for more discussion on osmotic suction). The relationship between water content and matrix suction for the LC500 clay (mixed with pure water) is described by the equation,

$$w = 65.75 - 13.58 \log(\text{suction})$$

{7.13}.

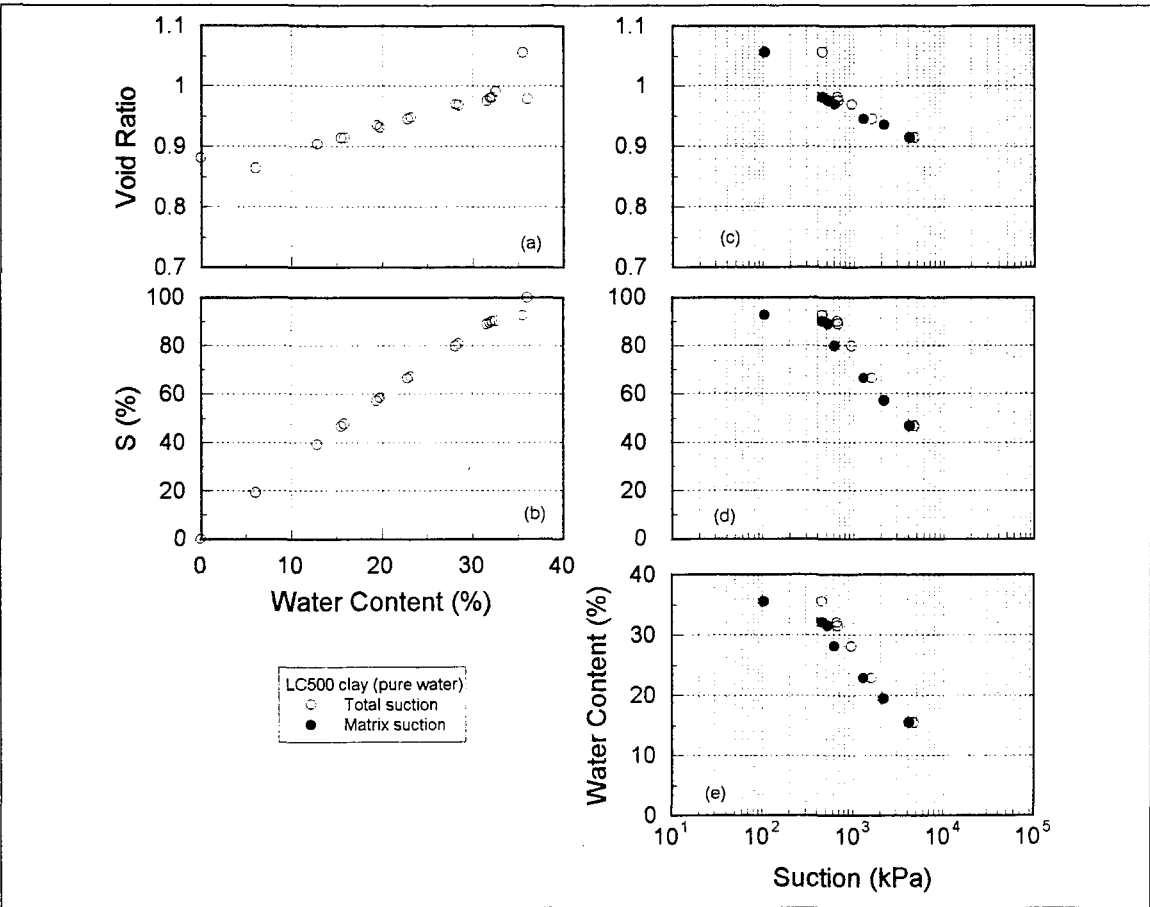


Figure 7.45 - Drying behaviour of LC500 clay plotted against common axes of water content and matrix or total suction.

The results suggest that is the matrix suction which controls the behaviour of soils with constant salt content. The relationships involving matrix suction show more clearly the yield points at the general air entry. The yield point observed in figure 7.45d and 7.46d can be detected in the relationship between water content and suction for the LC500 clay.

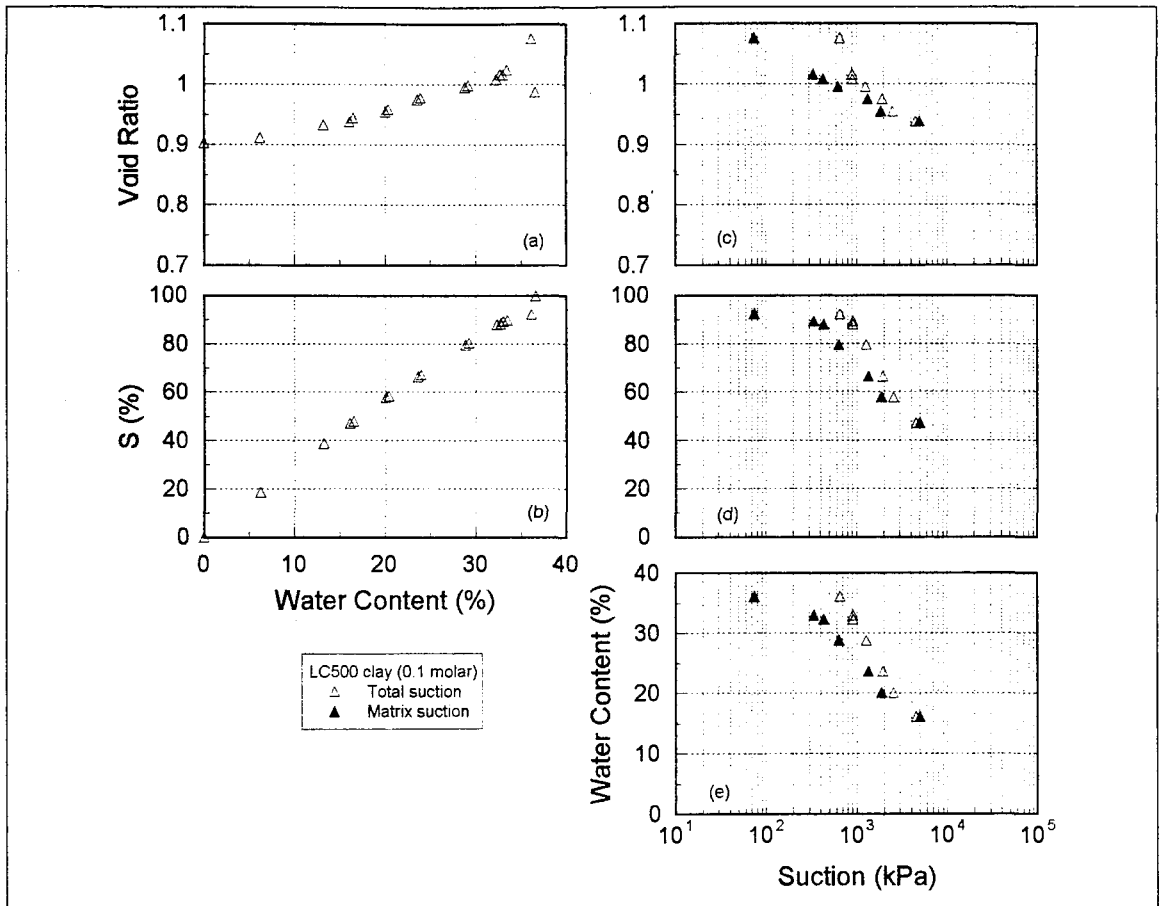


Figure 7.46 - Drying behaviour of LC500 clay with added salt plotted against common axes of water content and matrix or total suction.

7.2.2.2. Degree of Saturation Versus Suction

Using the results obtained with the set of samples of London clay, the relationship between degree of saturation and suction can be considered in more detail. Figure 7.47 presents curves of iso-void ratio (dotted lines) on the relationship of degree of saturation versus suction, based on the test results. Assuming the relative humidity of the laboratory was 60%, it is possible to calculate the equivalent suction at the air-dry state. The suction at 60% relative humidity, approximately that in the laboratory, is about 69MPa. The solid lines indicate the path followed by the tested sample during the drying process. Intermediate sample should follow the same trend.

The point A in figure 7.47 represents the initial condition for sample 8. Following the solid line, the degree of saturation is fairly constant until the point B is reached. After point B the volume change is dramatically reduced and the sample follows an approximately constant void ratio curve. The point C is the air-dry condition of the sample. Comparing the air-dry states of each sample it can be seen that the degree of saturation at this state reduces as the initial degree of saturation reduces.

The line SS presented in figure 7.47 indicates the GAE value boundary. It can be observed that the line SS is almost vertical, suggesting that all nine samples tested had very similar GAE values (*i.e.* suctions at the GAE point).

The suction at a particular degree of saturation varies with the void ratio. However, if the soil is saturated the suction can assume any value providing it is below the desaturation suction; this will be independent of the void ratio.

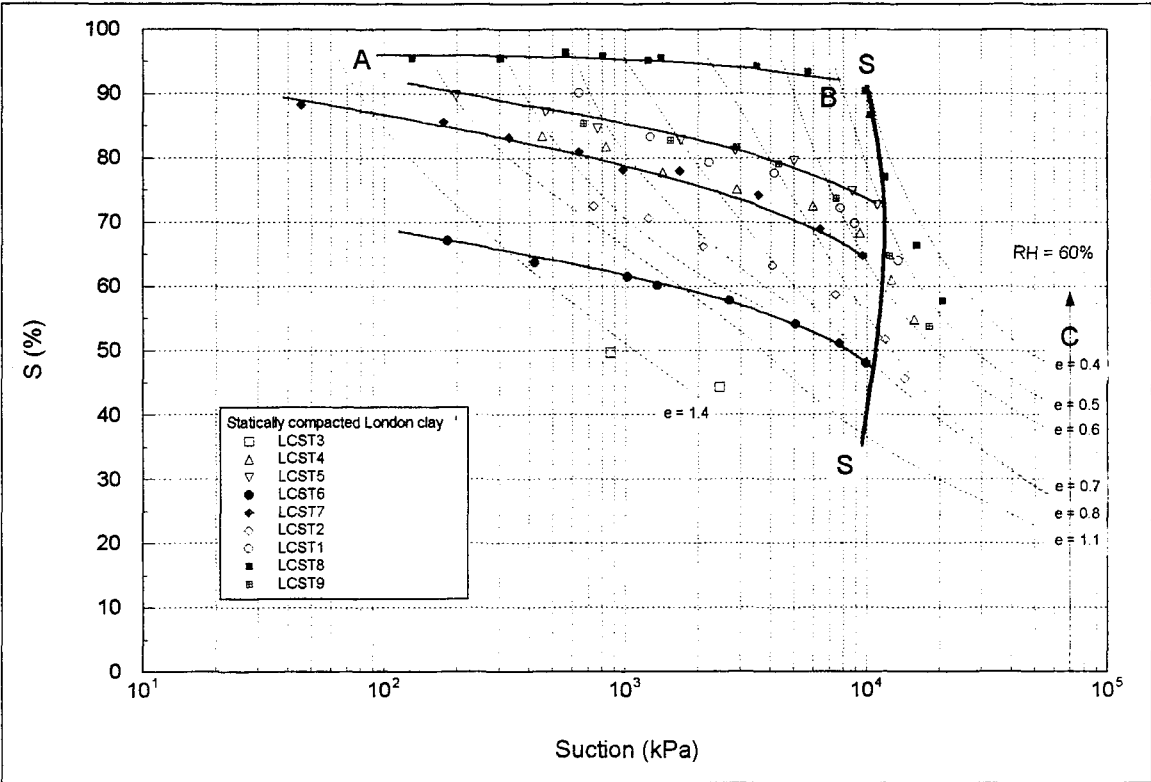


Figure 7.47 - Curves of iso-void ratio for London clay on the relationship between degree of saturation and suction.

7.2.2.3. Using a Model for Inferring the Pore-size Distribution

It was not possible to define the residual degree of saturation (S_r) defined by Brooks and Corey (1966). However, in order to analyse the data, the degree of saturation at the air-dry condition is assumed to be the residual degree of saturation (see Section 5.3.3.3).

Figure 7.48 presents the relationship between the effective degree of saturation (S_e) versus suction, for two samples of statically compacted London clay (LCST 2 and LCST 8). These samples were chosen because of their very different residual degree of saturation (25% and 42%). The air entry value of the soil ($(u_a - u_w)_b$) and the pore size distribution index (λ), as defined by Brooks and Corey (1966) is indicated. Soils with an uniform pore size distribution present a value of λ larger than soils with a wide range of pore sizes.

Although the value of the residual degree of saturation of the two samples is quite different, the value of the pore size distribution index is similar (1.41 and 1.48), suggesting that the pore size distributions of both samples are similar. The air entry value for samples 1 and 2 are 5720kPa and 8650kPa, respectively.

The concepts introduced by Brooks and Corey (1966) are more applicable for soils starting from the saturated condition. However, a good indication of the pore size distribution seems to be possible even with samples starting from a degree of saturation below 80%.

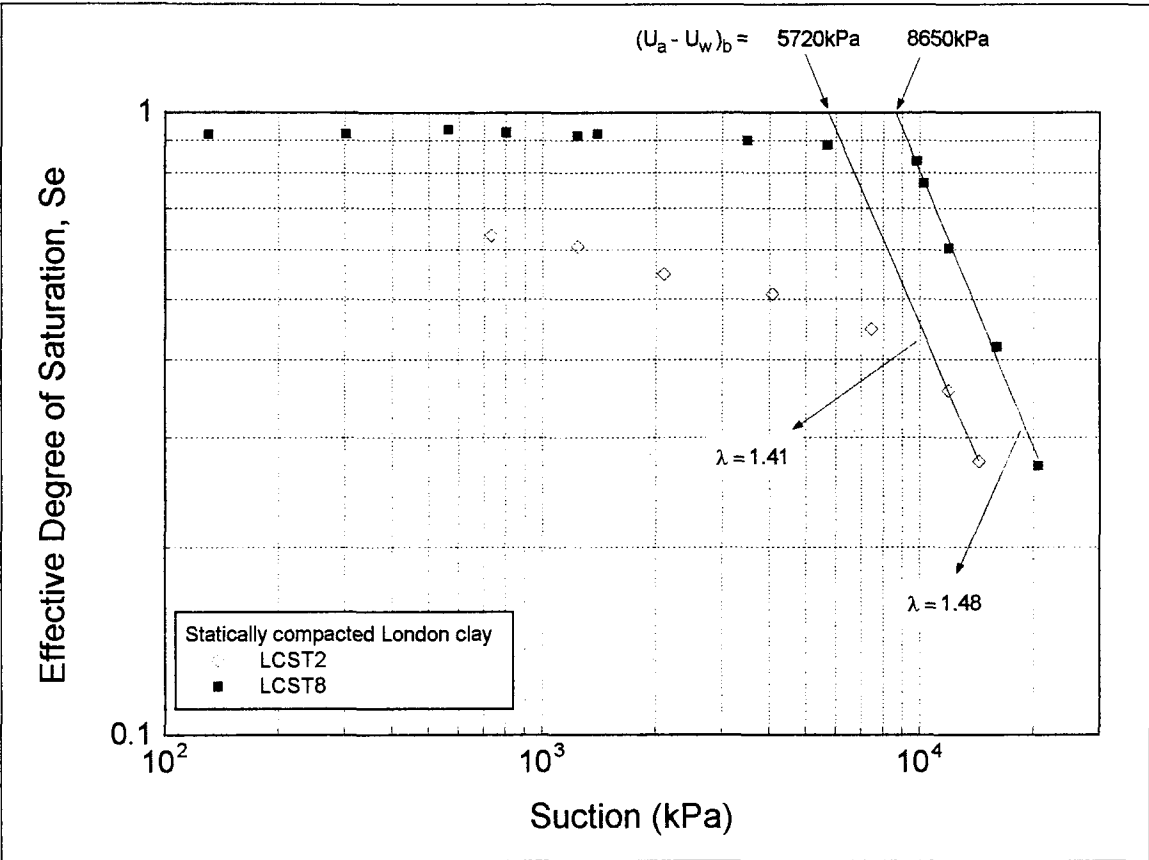


Figure 7.48 - Relationship between the effective degree of saturation (S_e) and suction, showing the air entry value and the pore size distribution index (λ) for London clay.

Figure 7.49a shows the relationship between S_e and suction for the three samples of Janga clay. The value of λ obtained varied from 0.6 to 0.7. Since the macro structures of these samples are very different, it seems that for samples 1 and 2 the value of λ obtained referred to the micro structure of the lumps. Because the level of suction at which the pore size distribution index is determined is very high, any deviation from the exact value of suction can cause a large change in the value of λ .

In figure 7.49b a comparison in terms of effective degree of saturation versus suction, is presented for the mixture L40S and the clay LC500. The results suggest that the LC500 clay has a wider pore-size distribution than the mixture L40S. London clay presented a pore size distribution more uniform than the other soils analysed. The L40S mixture is similar to the Janga clay in terms of pore-size distribution index. Although the LC500 clay has a wider pore-size

distribution, the air entry suction is the lowest (348kPa). This is due to the large pore sizes, which is associated with the lower plasticity.

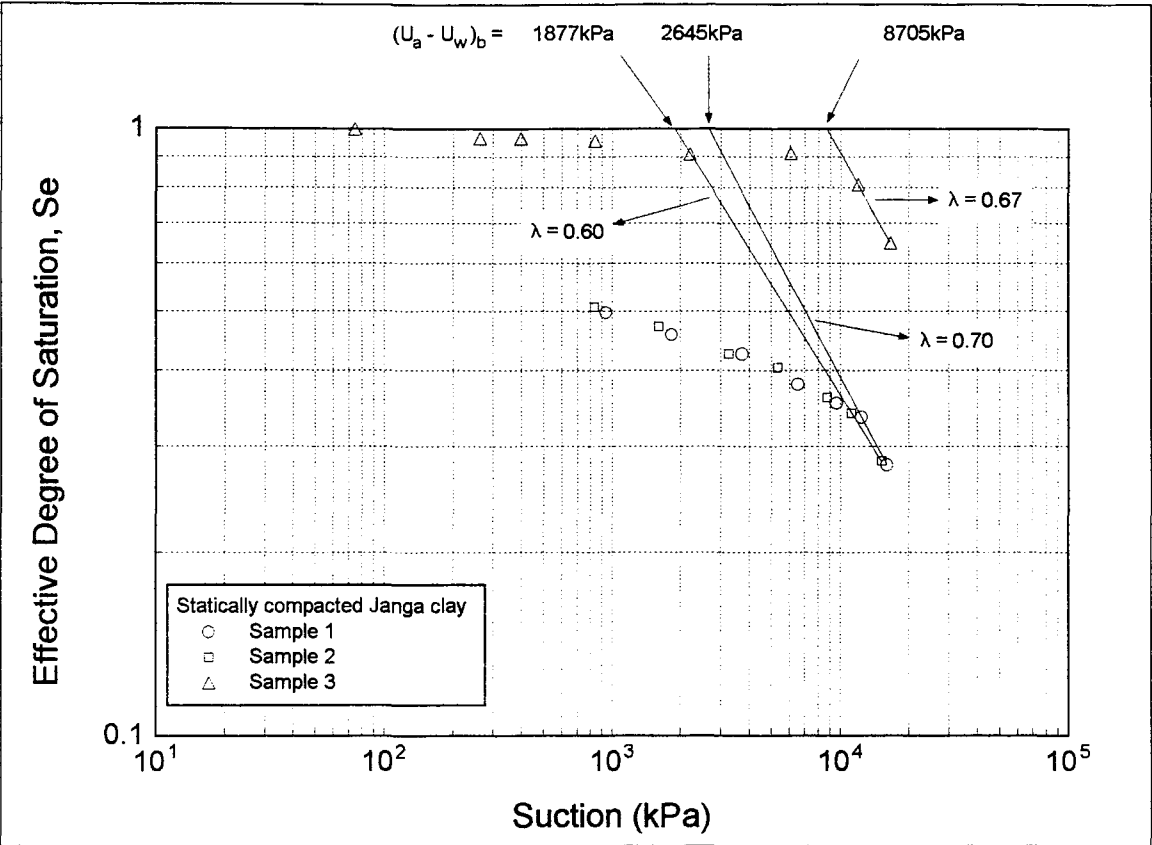


Figure 7.49a - Relationship between the effective degree of saturation (S_e) and suction, showing the air entry value and the pore size distribution index (λ) for Janga clay.

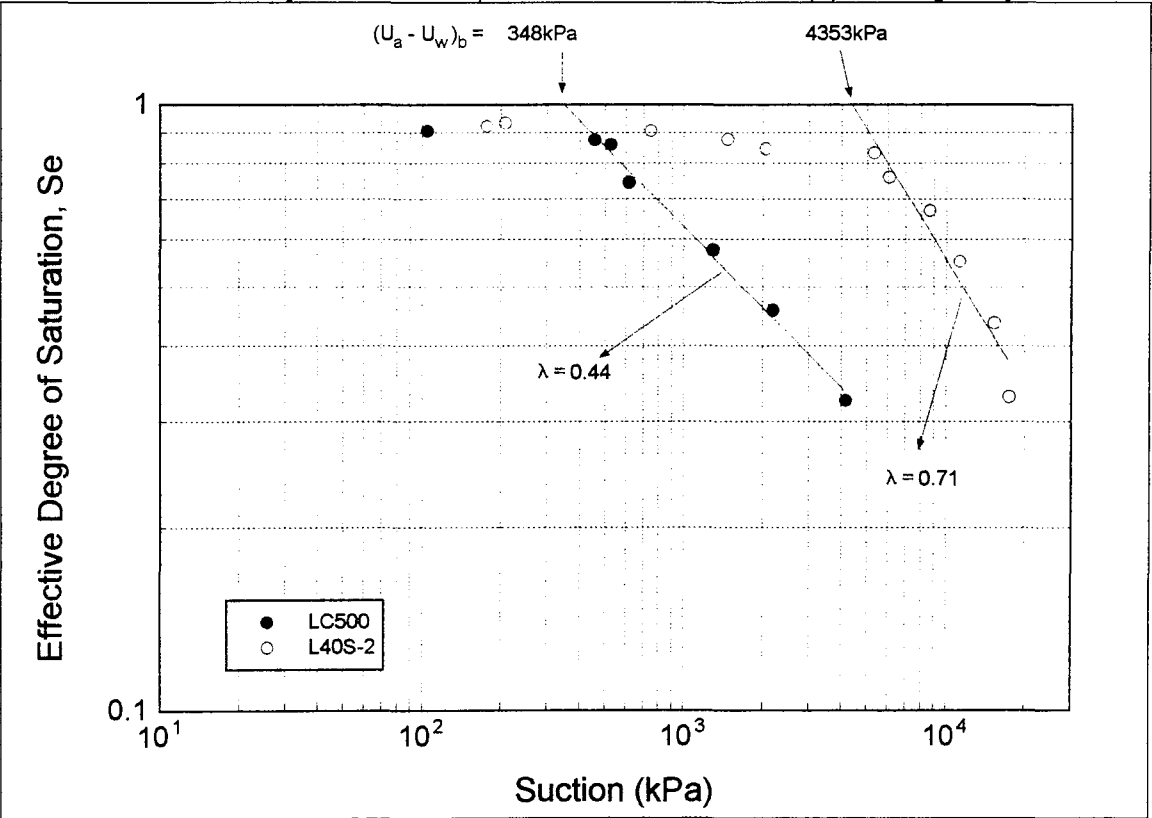


Figure 7.49b - Relationship between the effective degree of saturation (S_e) and suction, showing the air entry value and the pore size distribution index (λ) for LC500 clay and L40S mixture.

7.2.2.4. Initial Degree of Saturation, Final Void Ratio and Suction

Figure 7.50 presents an interrelated plots showing the relationships between the final void ratio, degree of saturation, and initial suction for each sample of London clay. The final void ratio was obtained by oven drying the samples. In Figure 7.50a it can be seen that the higher the initial degree of saturation the lower is the final void ratio, this relationship being apparently unique for the present test data.

Four groups of samples can be identified in Figure 7.50b by the dotted lines connecting the samples with approximately the same initial void ratio. The result shows a relationship between suction and final void ratio, for samples with the same initial void ratio. Sample 3 was compacted at a very low degree of saturation and high suction; when dried this sample reduced its initial void ratio from 1.48 to 1.1, a reduction of 25.7%. Sample 6 was compacted to the same initial void ratio as sample 3, but with lower suction; the change in void ratio of sample 6 was 45.9%, an increase of 20.2% in relation to sample 3. By statically compacting London clay to the same void ratio (1.5), a reduction on the initial suction from 860kPa to 182kPa implies in 20% further increase in the void ratio change due drying, for the sample with initially lower suction.

The lines of iso-void ratio in Figure 7.50b are approximately parallel in the range of suction up to 1MPa. As the suction increases to infinity the final void ratio must coincide with the initial void ratio. Samples compacted with approximately the same degree of saturation (*i.e.* samples 5 and 1) had very different initial suctions due to their different initial void ratios, though when oven dried these two samples exhibited the same final void ratio.

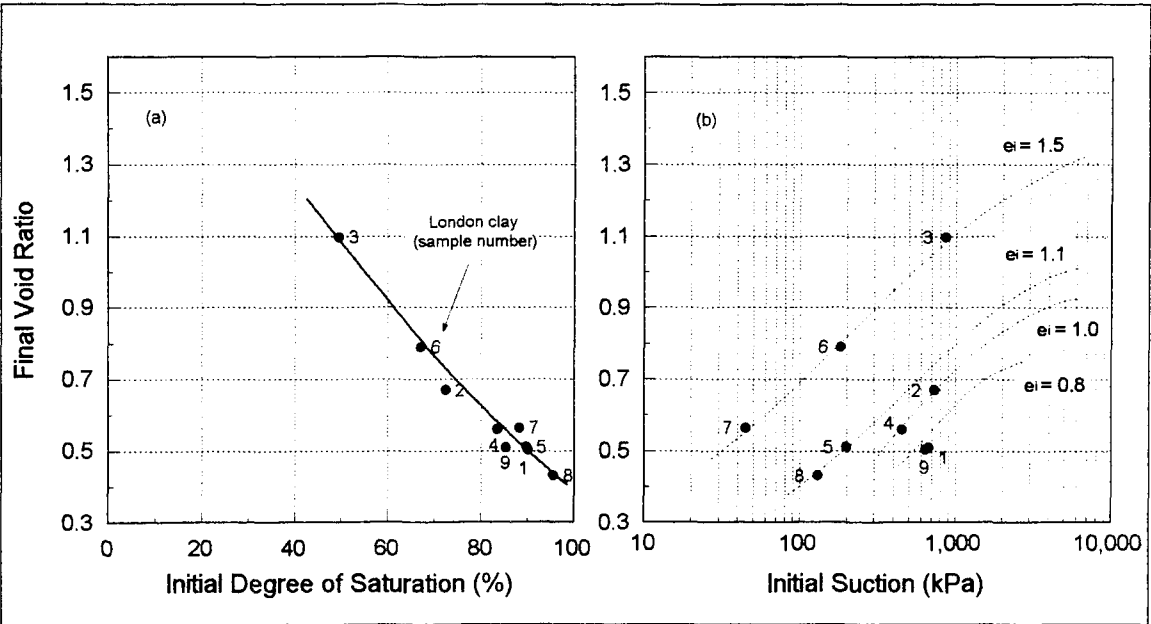


Figure 7.50 - Final void ratio versus degree of saturation and logarithm of suction for London clay.

Figure 7.51 presents a plot showing the relationship between the final void ratio, degree of saturation and the initial suction for another four soils tested. Although the number of samples for each soil is small, it can be seen that the relationship is consistent. It was not possible to define curves of iso-initial-void ratio on the relationship between final void ratio and initial suction. These relationships are probably dependent of the structure of the soil.

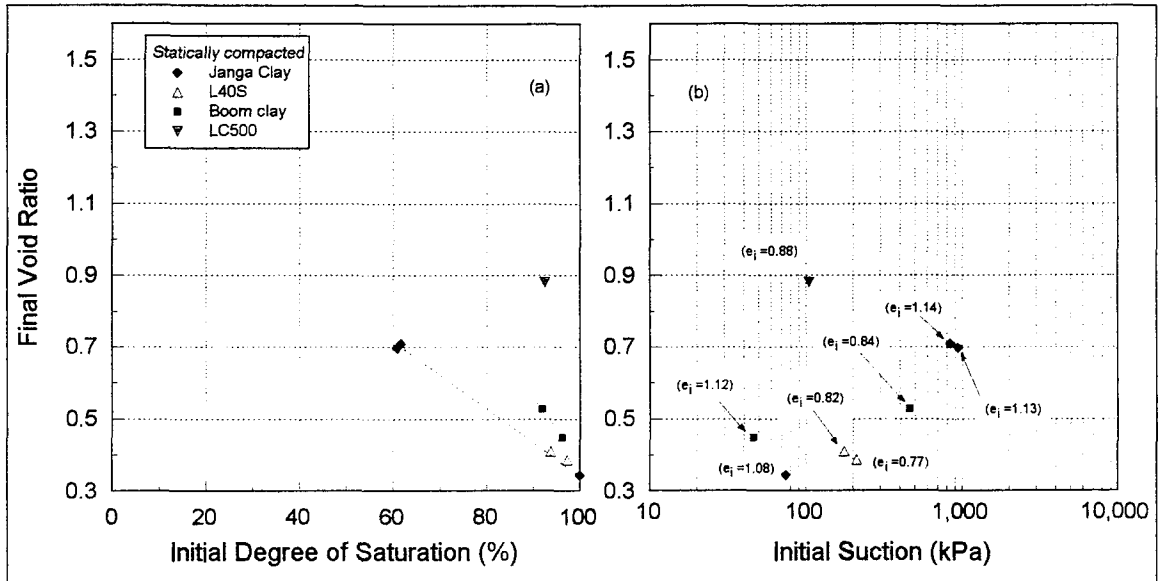


Figure 7.51 - Final void ratio versus degree of saturation and logarithm of suction for four different types of soil.

7.2.2.5. Water Content Versus Suction

Figure 7.52 presents the relationship between water content and suction for all statically compacted soils. The lines showed are the best fit through the data and are represented by the equations previously given.

The relationship between suction capacity (C) and the liquid limit is shown in figure 7.53. The suction capacity of London clay and the LC500 clay are similar (13.1% and 13.6%, respectively). The value of the pore size distribution index (λ) for London clay and LC500 clay are 1.48 and 0.44, respectively. It may be suggested that the pore size distribution, characterized by λ , does not directly affect the suction capacity. However, the heating process to which the LC500 clay was subjected before the tests (see section 6.2.3) may have induced some characteristics that are not usually found in soils, although similar behaviour may be found in some tropical soils such as laterite. Data from literature are also included. The points showed a great scatter that may be due to differences in sample preparation.

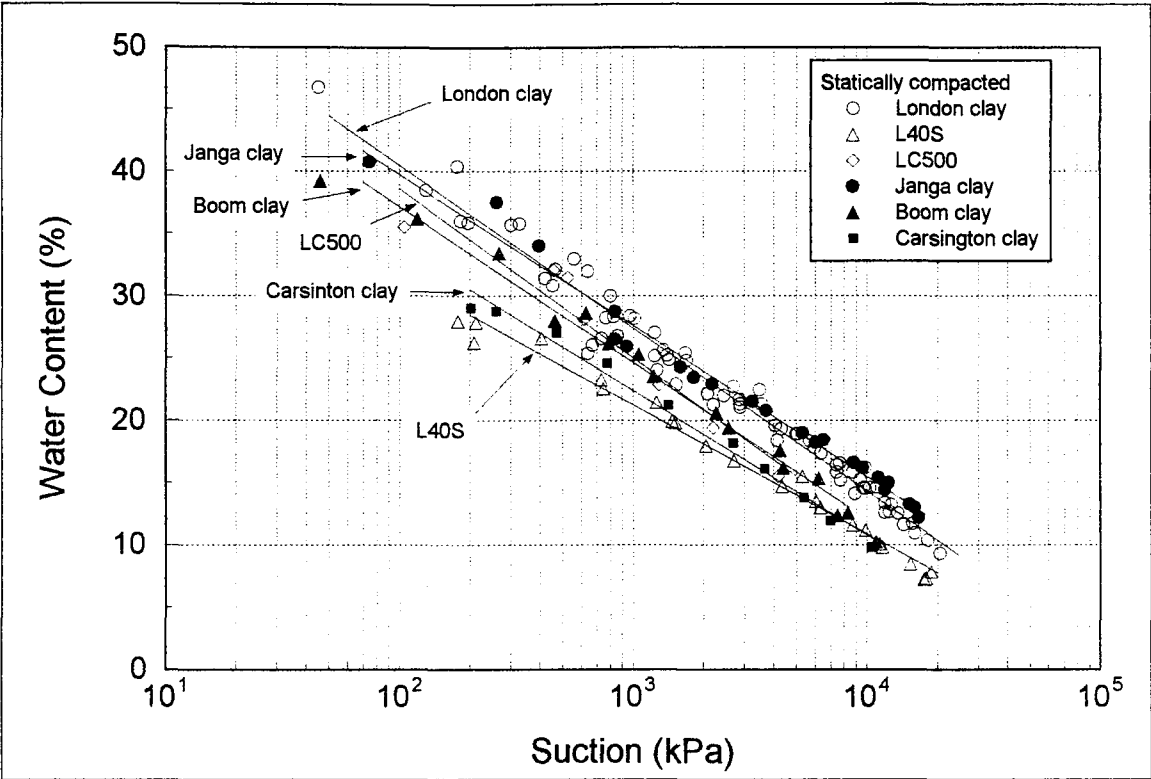


Figure 7.52 - Relationship between water content and suction for all six soils tested.

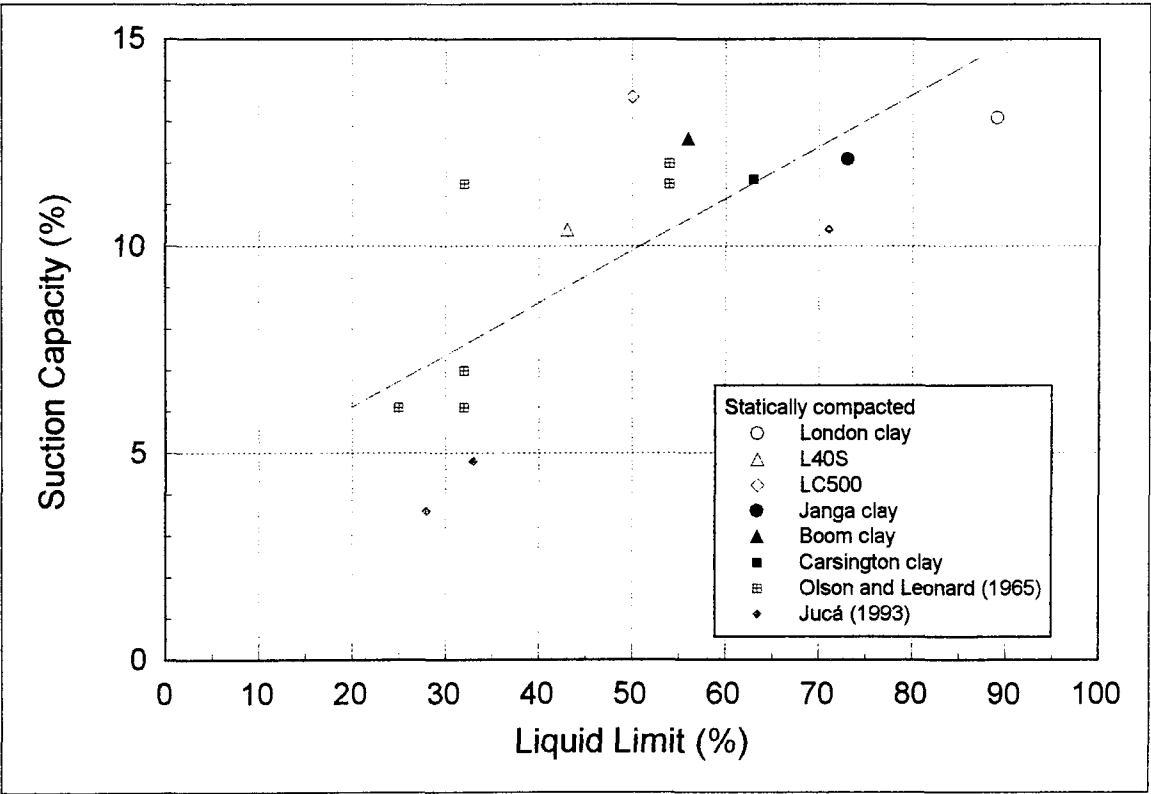


Figure 7.53 - Suction capacity (C) versus liquid limit for statically compacted soils.

Figure 7.54 presents the relationships between water content and suction indicating the GAE point for each soil tested. London clay and Janga clay appear to be capable of sustaining suction of about 10MPa before reaching the general air entry point. Boom clay and the mixture L40S indicate a suction at the GAE point of approximately 4MPa. The LC500 clay shows a very low suction at the GAE point (310kPa). Again, the behaviour of this soil is anomalous in comparison with the other soils tested, since it has a high suction capacity. This soil has a wide range of pore sizes which, associated with the low plasticity of the soil, may indicate that the pore-size distribution is not only greater than that of the other soils, but also that the pore sizes are bigger. This can only be inferred from the GAE point.

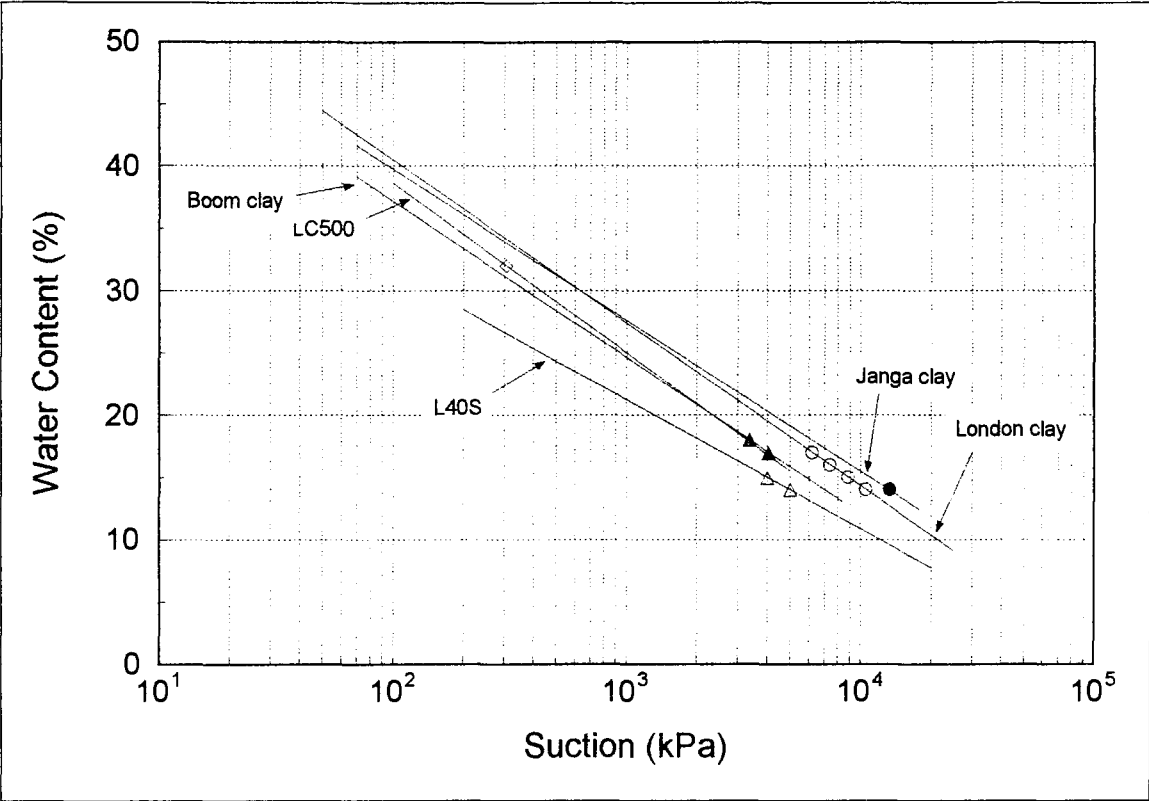


Figure 7.54 - Suction at the general air entry point for the statically compacted samples.

Figure 7.55 shows the relationship between water content normalized by the suction capacity, versus suction. The results showed a good correlation suggesting an unique relationship for the soils tested. The best fit though all points is represented by the equation,

$$\frac{w}{C} = 4.97 - 0.97 \log(\text{suction}) \quad \{7.13\}.$$

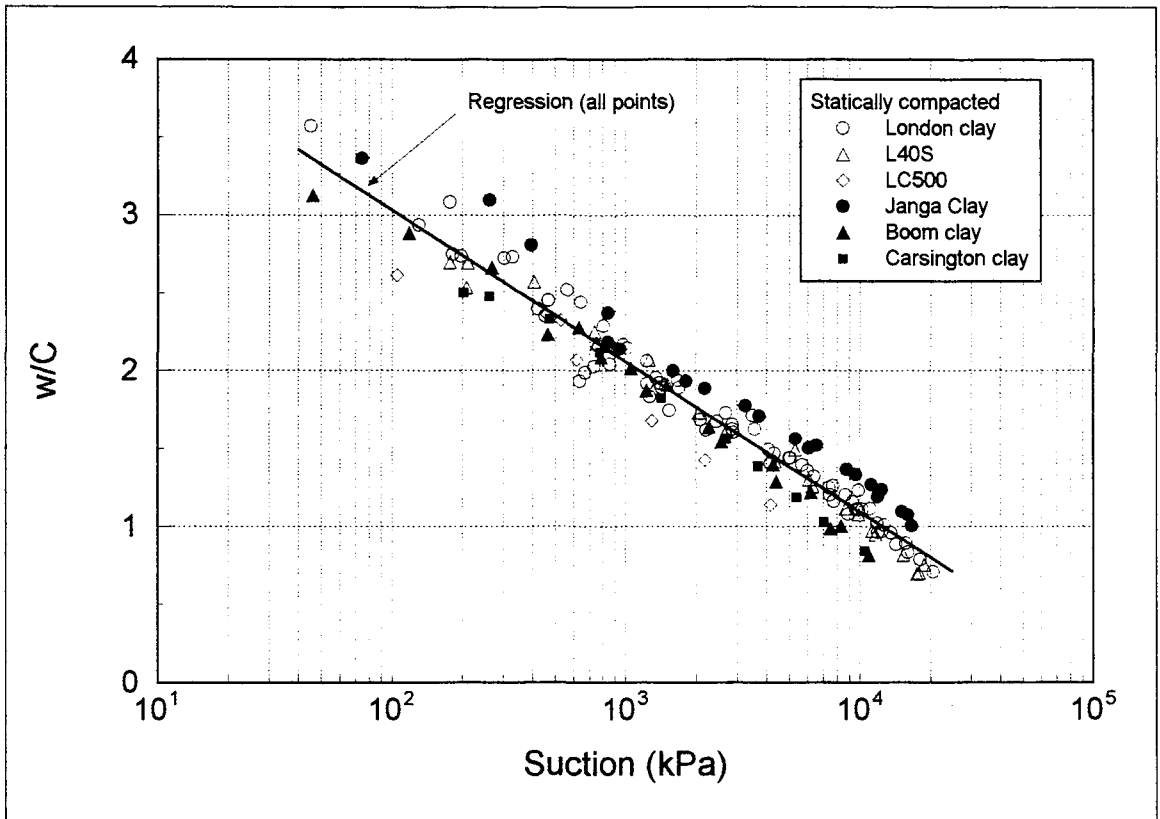


Figure 7.55 - Relationships from figure 7.52, with water content normalized by suction capacity.

7.3 Drying Test on Slurried Soils

7.3.1. General Behaviour

7.3.1.1. Volume Change Versus Water Content

This section presents and discusses the results obtained with samples prepared with a water content well above their liquid limits. The preparation of most of the samples followed the recommendations made by Burland (1990). The procedures followed are described in section 6.2.2. A series of samples were prepared using London clay from Chattenden, and mixtures of this clay and silt. In all, five different mixtures were used, ranging from 100% London clay to 40% clay and 60% silt (L60S). A total of 8 samples were prepared. All samples were consolidated in the oedometer up to 100kPa to allow the sample to be handled. The initial characteristics of the samples (after consolidation) are presented in Table 7.6.

Sample	e_i	S_i	Initial suction (kPa)
L00S	1.248	100	62
L00S2	1.3	99	55
L20S	1.119	96	54
L30S	1.039	98	56
L40S	0.882	98	134
L40S - PP	0.917	93	100
L60S	0.788	94	67
L60S - PP	0.74	92	100
50% kaolin+50% silt	0.57	98	416
Blue clay	1.022	99	294
HD bentonite	1.557	88	1180

Table 7.6 - Initial characteristics of slurried samples after the consolidation.

A mixture of 50% kaolin and 50% silt was also tested. This sample was obtained after consolidation and was kindly donated by Mr. C. Menkiti. The other two soils tested were an Italian blue clay and bentonite. One sample of bentonite was prepared by allowing the slurry to consolidate by gravity drainage, and the other is a industrial material (HD bentonite).

The Experimental drying curves are plotted in Figures 7.56 to 7.60. In Figure 7.56 the results obtained with the mixtures of London clay and silt are shown. It can be observed that the soils are saturated or very near saturation at the beginning of the drying process. The $S=100\%$ line indicated refers to a specific gravity (G) of 2.75. The mixtures with larger silt contents diverge early from the saturation line. The behaviour of the mixture L20S is very similar to the London clay samples (L00S and L00S2). The dominance of the silt in the behaviour of the samples seems to start at a silt content of approximately 30%.

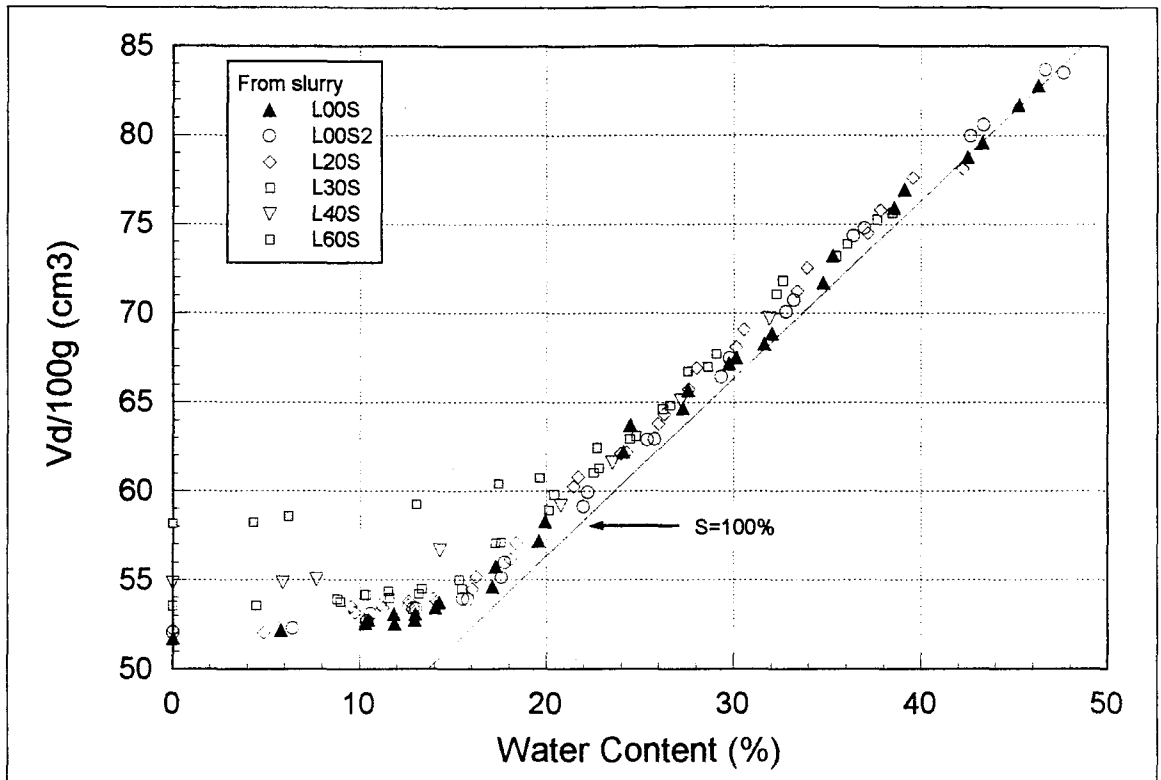


Figure 7.56 - Drying behaviour of slurried mixtures of London clay and silt; $V_d/100$ is the volume per 100g of soil solids.

Figure 7.57 presents the results obtained with mixtures L40S and L60S, where for each mixture two samples were tested. One sample of each mixture was dried by allowing the water to evaporate to the laboratory atmosphere, while the other was dried in the pressure plate apparatus. The pressure plate used was only able to apply a maximum suction of 500kPa, which limited the volume reduction of the sample. A difference is observed in the samples of L60S mixture, which seems to be due to different initial characteristics of the samples L40s and L40S-PP (see table 7.6). The mixture L60S showed a very good agreement in the range tested.

The sample composed of 50% kaolin and 50% silt showed a very small volume change during drying (see figure 7.58). Only residual shrinkage is observed. The sample started from an unsaturated state and diverges from the saturation line, increasing the volume of air present. This behaviour may be influenced by the initial characteristics of the sample, the initial water content being lower than the general air entry point, thus reducing the shrinkage of the sample during drying.

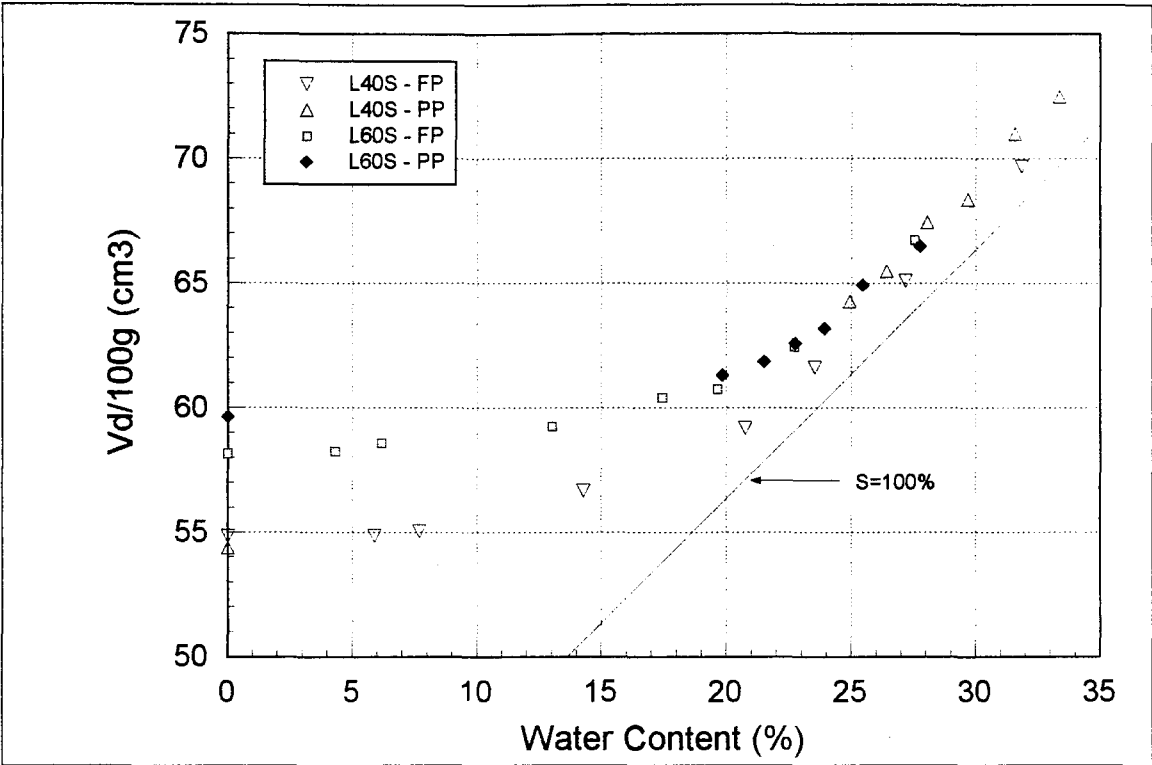


Figure 7.57 - Comparison between drying the soil to the atmosphere and in the pressure plate for two slurried mixtures of London clay and silt; Vd/100 is the volume per 100g of soil solids.

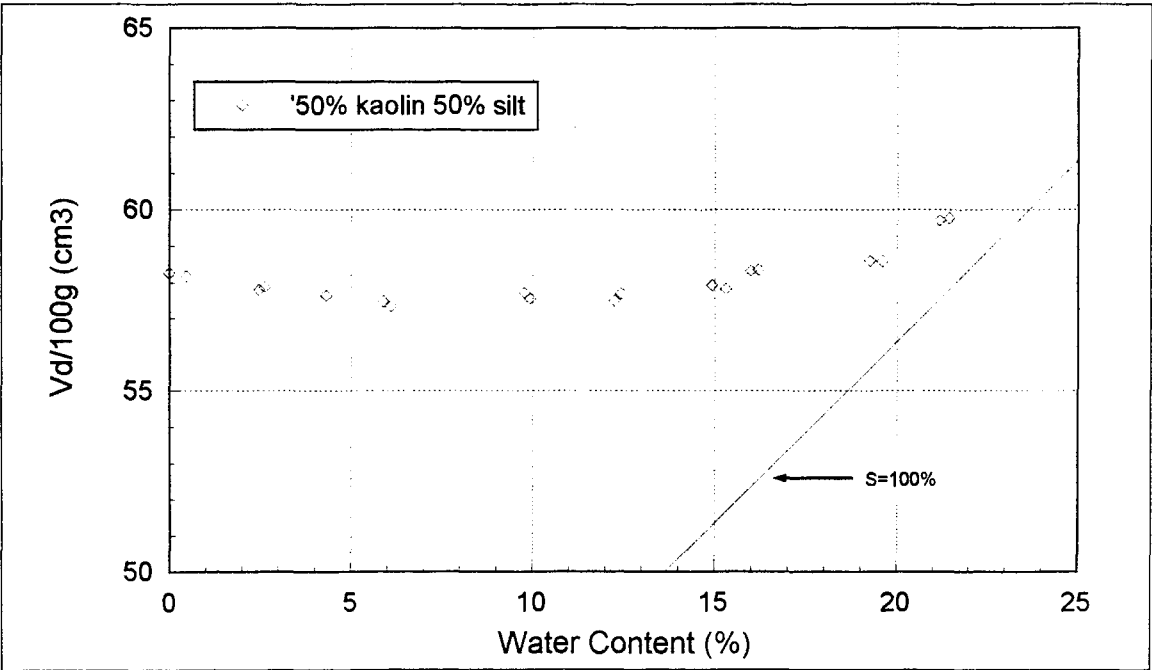


Figure 7.58 - Drying behaviour of the mixtures of 50% kaolin and 50% silt; Vd/100 is the volume per 100g of soil solids.

The blue clay sample had an initial degree of saturation of 99% and its behaviour during the drying process is presented in figure 7.59. The drying curve followed a path parallel to the S=100% line (normal shrinkage) up to approximately 24% of water content. It can be observed that the soil reduced in volume continuously after the normal shrinkage phase (residual shrinkage) until reach zero water content, *i.e.* the shrinkage continued until the soil dried completely.

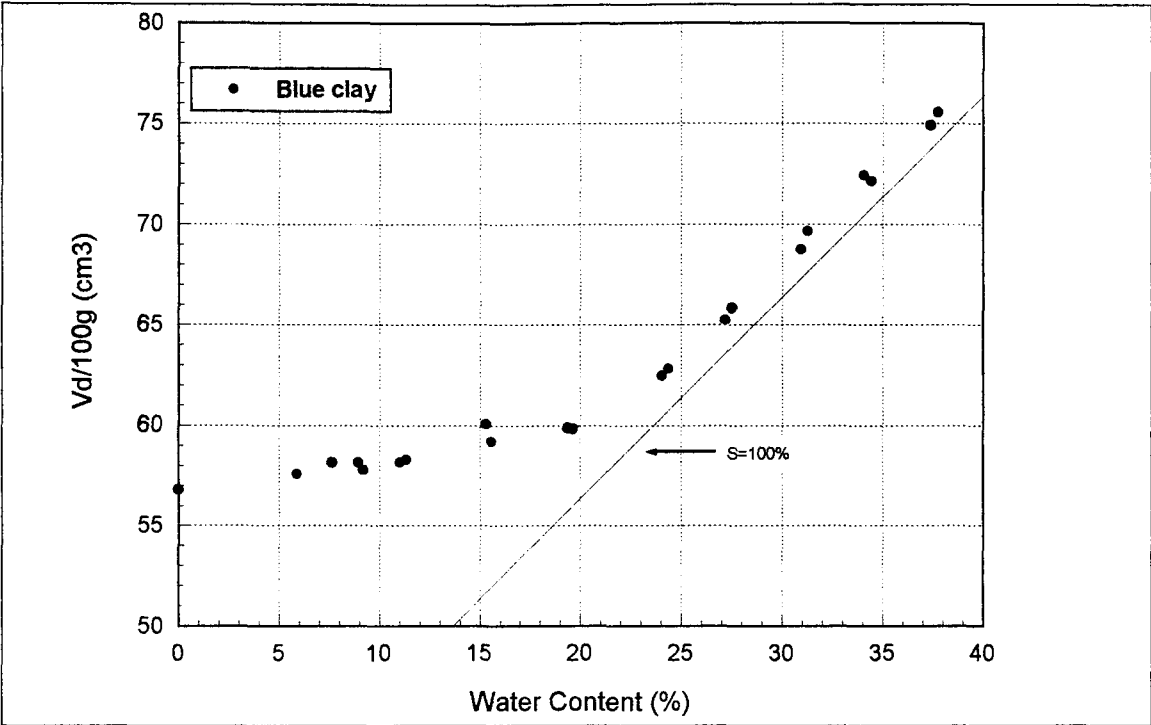


Figure 7.59 - Drying behaviour of the slurried Blue clay; $V_d/100$ is the volume per 100g of soil solids.

The results obtained from the high density bentonite also suggested that the shrinkage limit, as defined, may not be an appropriate index by which to infer the end of shrinkage. From the air dry state to the oven dry state the sample reduced in water content by 25% and volume change was 30% of the total reduction (see figure 7.60). In order to dry the soil beyond the air dry state the use of salt solution is necessary.

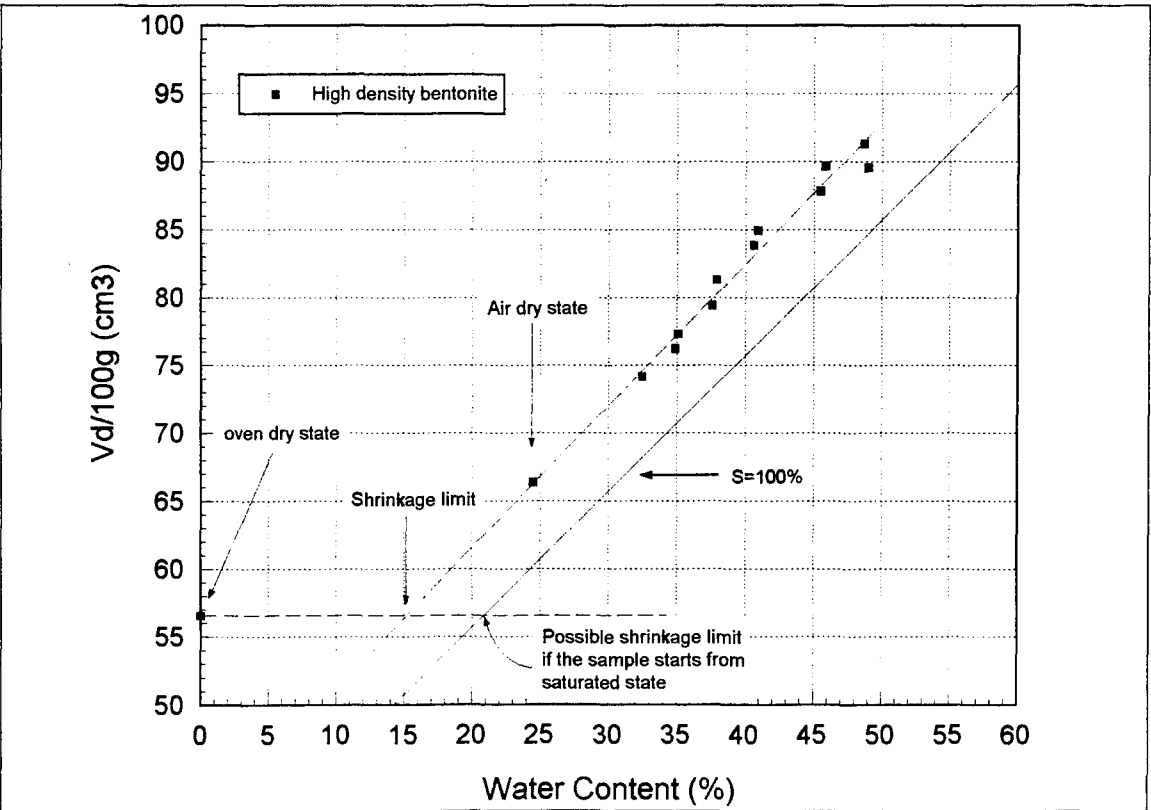


Figure 7.60 - Drying behaviour of the high density bentonite; $V_d/100$ is the volume per 100g of soil solids.

7.3.1.2. Water Content, Volume Change and Suction

The interrelation between void ratio, degree of saturation, water content and suction are presented in figures 7.61 to 7.66.

The results obtained with the London clay and the clay/silt mixtures are plotted in Figure 7.61. The relationship between void ratio and water content is equivalent to that shown in Figure 7.56. In Figure 7.61b a change in the general air entry (GAE) point can be observed when the silt content increases, particularly between the L00S and L60S samples. The relationship between degree of saturation and suction, presented in figure 7.61d, demonstrates clearly the reduction in suction at the GAE point with the increase of silt content. The relationship between water content and suction (figure 7.61e) is a log-linear one in the range tested. The following equations define this relationship.

L00S $w = 71.99 - 14.28 \log(\text{suction})$

L20S $w = 62.42 - 12.5 \log(\text{suction})$

L30S $w = 60.09 - 12.18 \log(\text{suction})$

L40S $w = 59.56 - 12.95 \log(\text{suction})$

L60S $w = 48.38 - 10.69 \log(\text{suction})$

{7.14}.

{7.15}.

{7.16}.

{7.17}.

{7.18}.

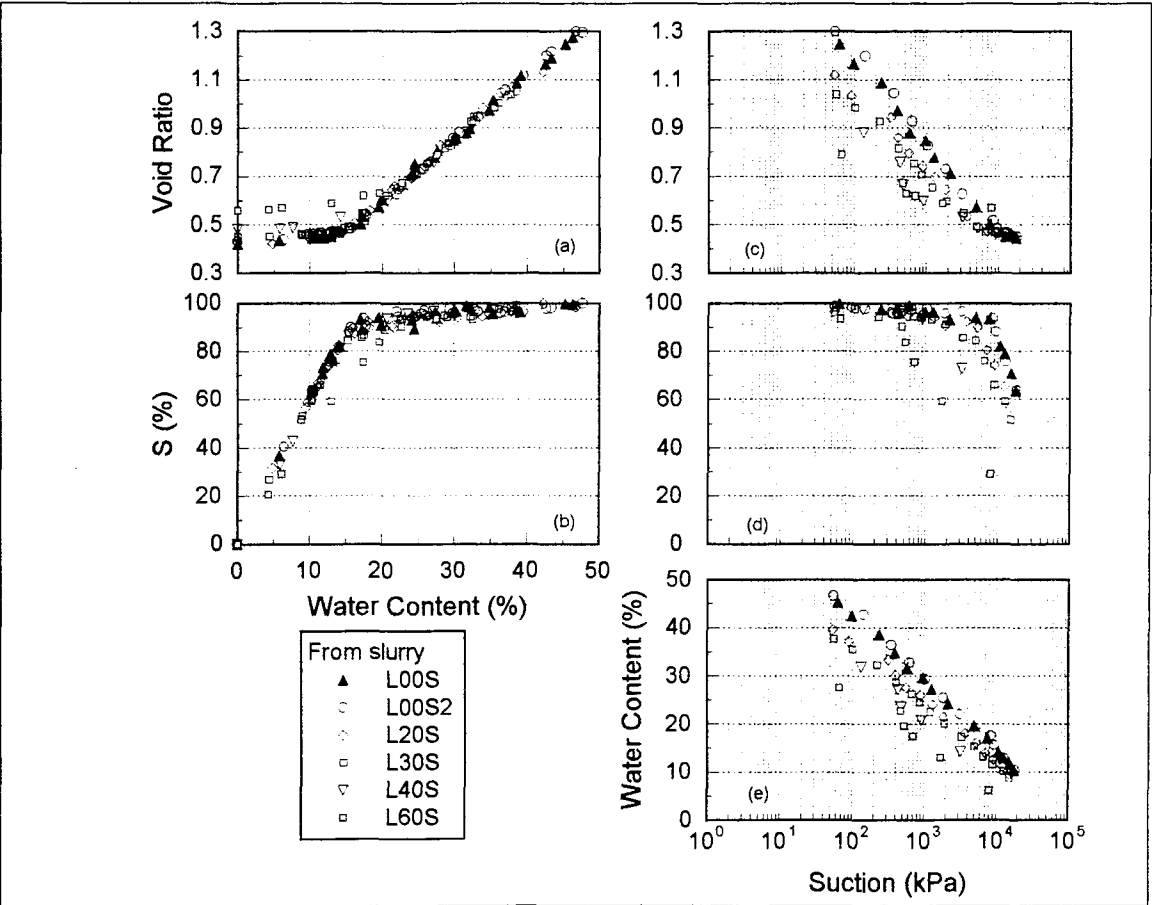


Figure 7.61 - Drying behaviour of the clay/silt mixtures plotted against common axes of water content and suction.

Figure 7.62 presents the results obtained with the mixtures L40S and L60S, for comparison between the process of drying in air and drying in the pressure plate. To some extent these results also show a comparison between the filter paper method and the pressure plate. It is important to point out that in this case the pressure plate does not measure the prevailing sample suction but imposes a defined suction on the soil. A reasonable agreement is observed. The results suggest that, for plastic soils, the drying process performed by allowing the sample to dry to the atmosphere is similar to the drying imposed by the axis translation technique (see section 2.2.5).

Comparing the results obtained using the mixture of 50% kaolin and 50% silt (K50S50) with results from the literature (Ridley, 1993) it can be seen that the initial water content of the sample K50S50 may indeed have been lower than the general air entry point. The results are presented in figure 7.63 and show a very consistent trend. The tests with the pure kaolin and with an 80% kaolin and 20% silt mixture indicate a GAE point respectively higher than the mixture K50S50. The relationship between degree of saturation and suction (part *d* of figure 7.63) show a similar pattern of behaviour for all mixtures. It can be observed that after the GAE point the suction increases very slowly in comparison with the reduction in degree of saturation and water content.

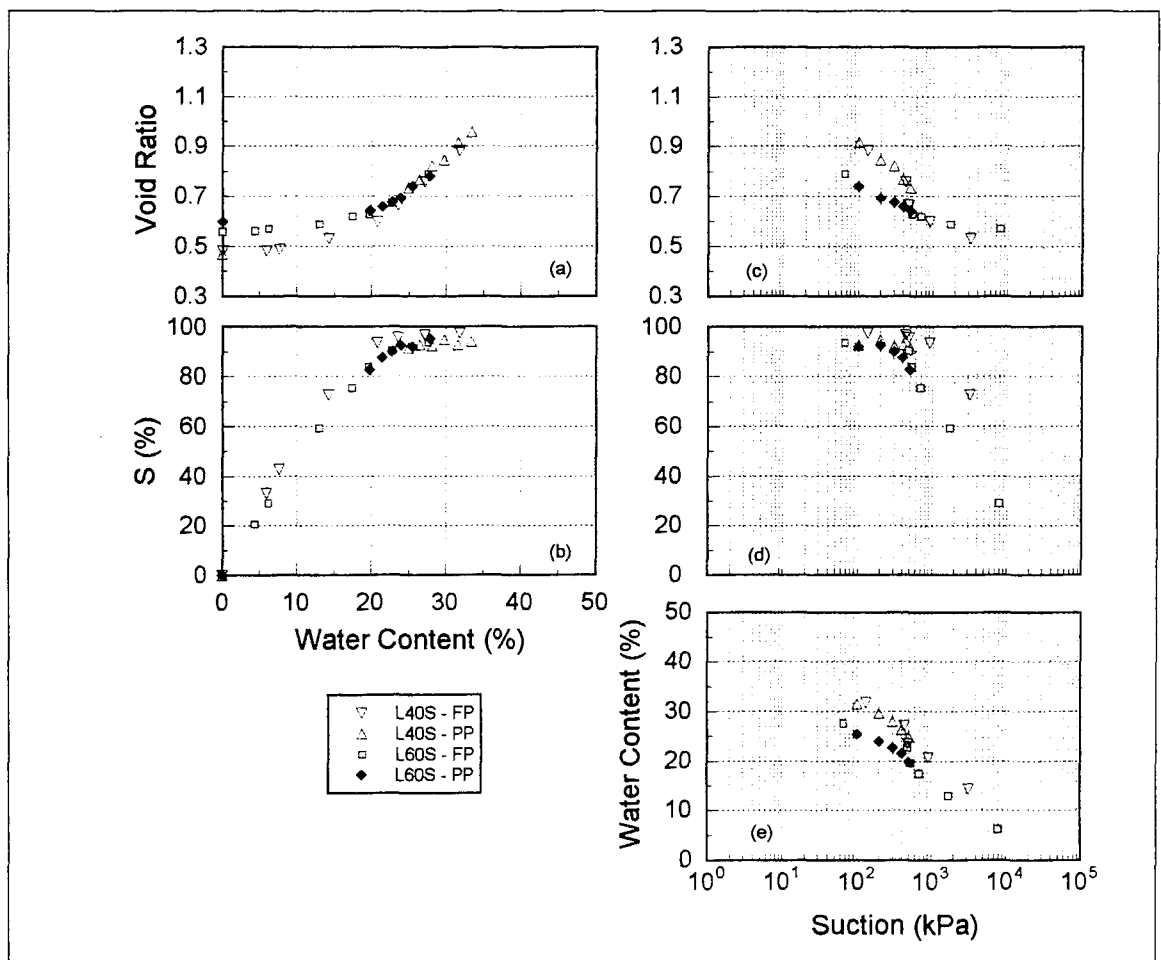


Figure 7.62 - Comparison between drying to the atmosphere and in the pressure plate for two clay/silt mixtures, plotted against common axes of water content and suction.

Figure 7.64 presents the results obtained with the mixture K50S50, including one test where only the water content and suction were obtained. The sample called 'second drying' in figure 7.64 was re-wetted from a air dry condition by submerging it in water, and dried from this state. There is a tendency for the second drying to display overconsolidated behaviour, probably due to its first drying. This characteristic is represented by the diversion of the curves presented in figure 7.64e at a suction of about 1.5MPa.

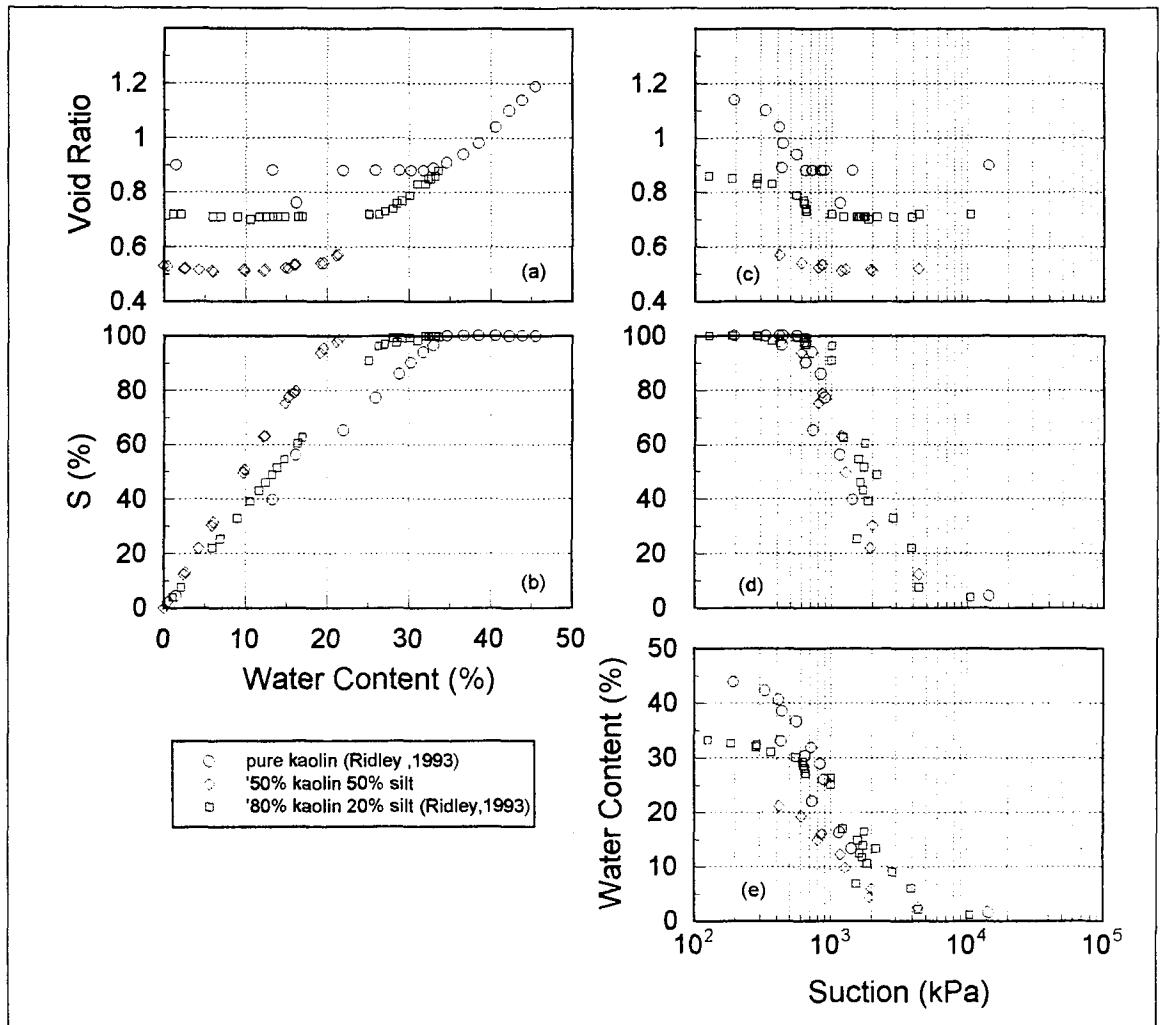


Figure 7.63 - Drying behaviour of the kaolin and the kaolin/silt mixtures plotted against common axes of water content and suction.

As can be seen in figure 7.65, the blue clay sample continues to shrink beyond the shrinkage limit. The general air entry point is clearly observed and can be identified either in figure 7.65b or 7.65d, but is not apparent in the relationship between water content and suction. The relationship between water content and suction for blue clay can be represented by the log-linear equation:

$$w = 82.75 - 18.53 \log(\text{suction})$$

{7.19}.

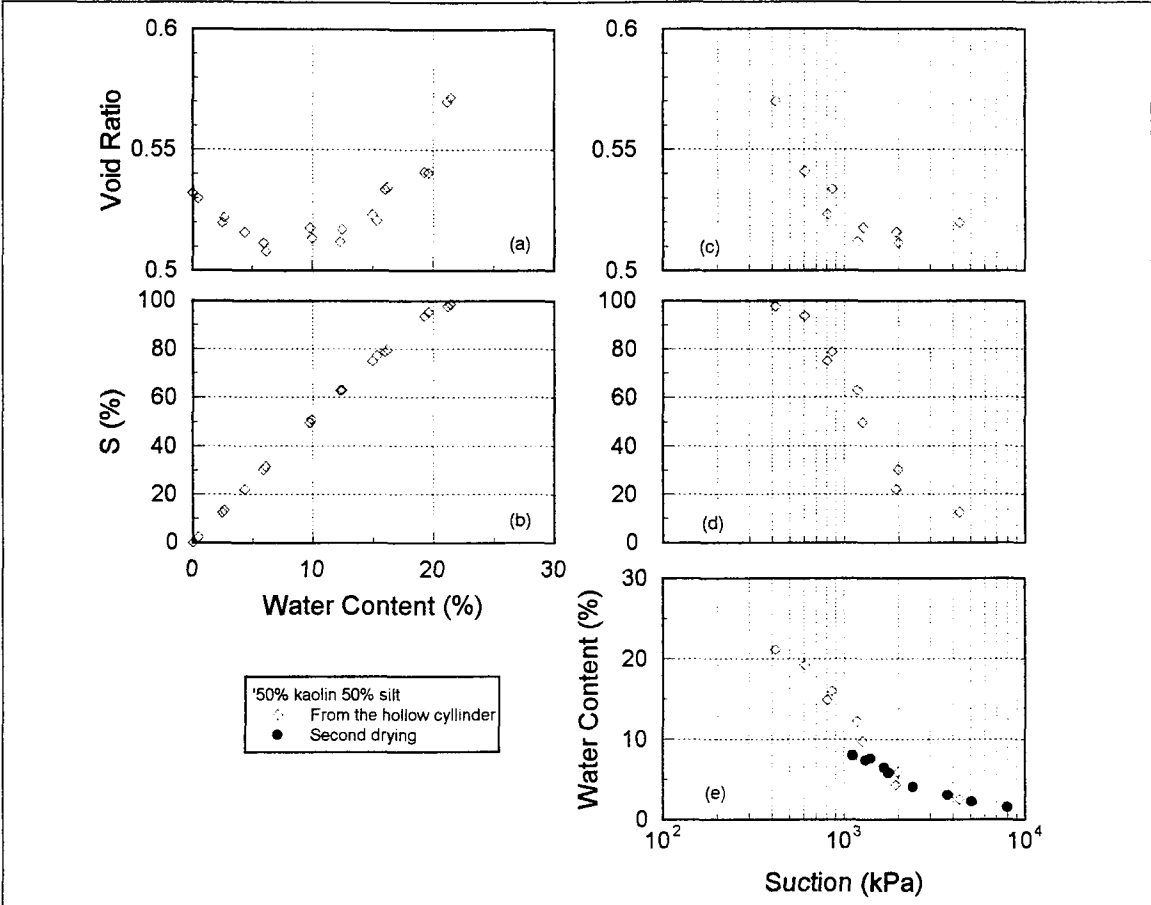


Figure 7.64 - Drying behaviour of mixture 50% kaolin and 50% silt plotted against common axes of water content and suction.

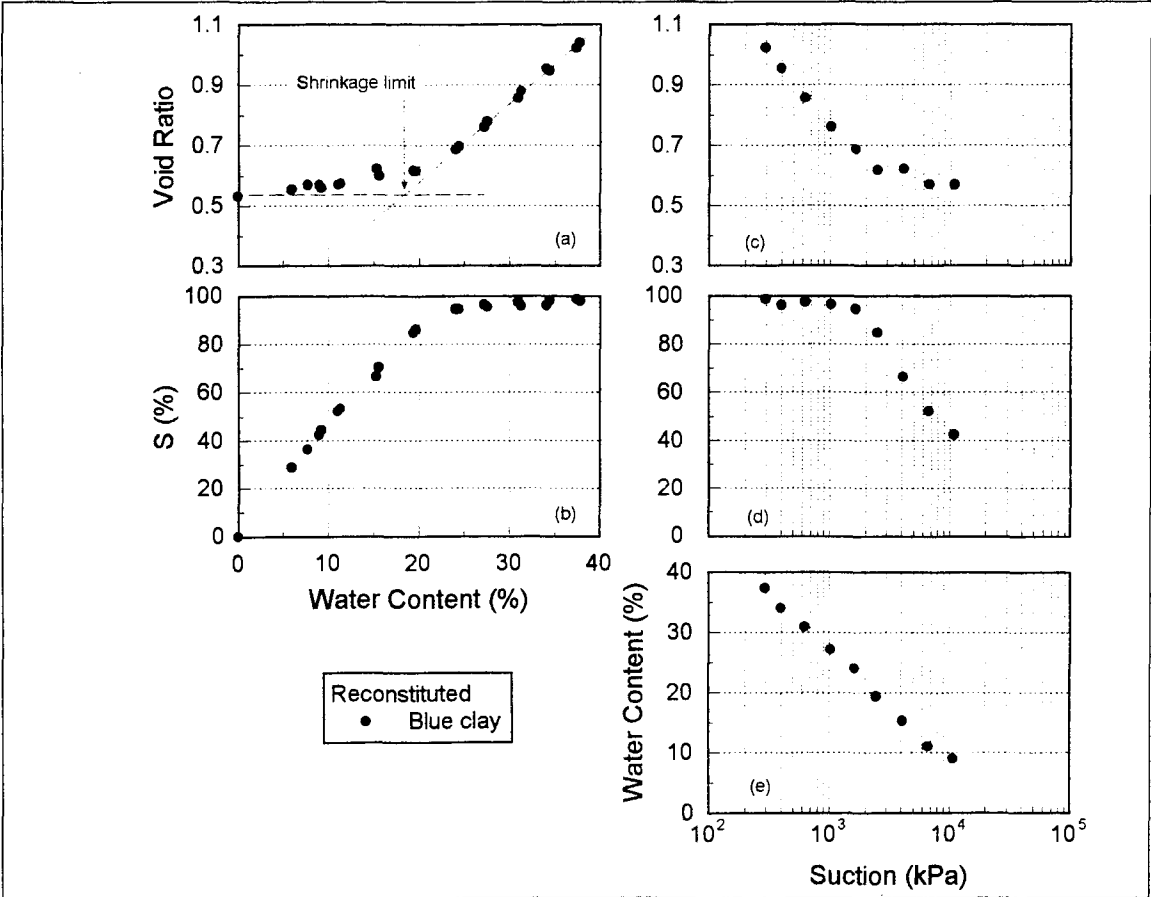


Figure 7.65 - Drying behaviour of the Blue clay plotted against common axes of water content and suction.

The bentonite sample, which had an high initial density showed a very high initial suction (see table 7.6). Figure 7.66 presents the results obtained showing that the degree of saturation remained fairly constant during the test. It was not possible to detect the GAE point since the test was stopped before this point was reached. The relationship between water content and suction showed a bi-linear behaviour. The first part of the curve is probably due to its over consolidated characteristics. After the inflection point is reached the sample follows the "virgin desaturation line" (see section 5.3). This behaviour is also observed in part c of figure 7.66, where the relationship between void ratio and suction is shown. Since the GAE point was not reached and the sample had a degree of saturation higher than 80%, the relationship between void ratio and suction may be compared with an isotropic consolidation curve (see section 5.3.1). The high density bentonite is a commercial material whose the process of preparation is not fully known. In part e of Figure 7.66 is also showed the results obtained using bentonite consolidated by gravity drainage. The curve water content versus suction is well defined at the low range of suctions. At high suctions the sample start to crack and became difficult to handle the soil. The results sugest a bi-linear relationship and also indicate that at high suction the bentonite tends to converge to the high density bentonite.

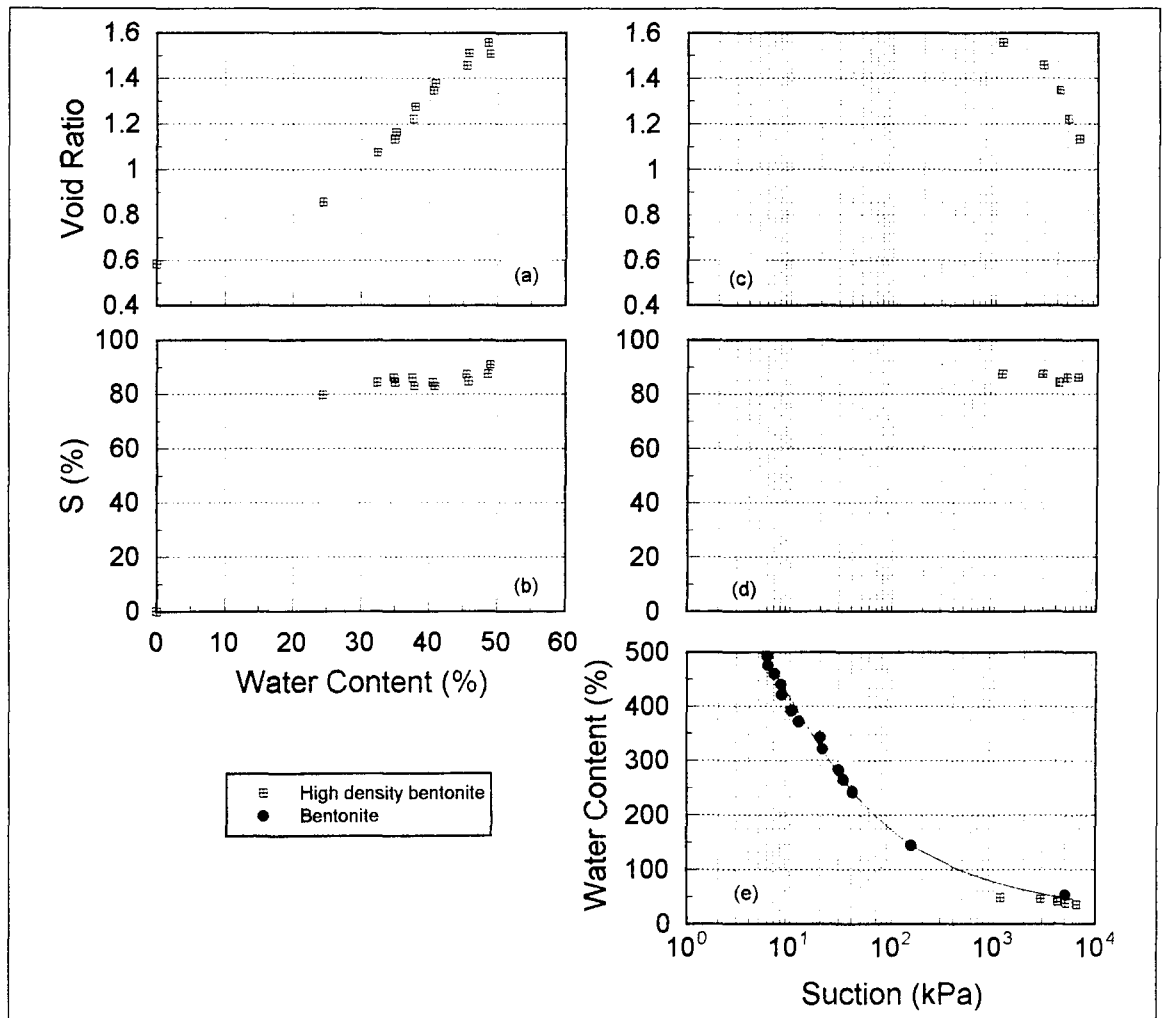


Figure 7.66 - Drying behaviour of the high density bentonite and bentonite plotted against common axes of water content and suction.

7.3.2. Using a Model for Inferring the Pore-size Distribution

In order to evaluate the pore size characteristics of the London clay and the clay/silt mixtures, the model proposed by Books and Corey (1966) is used (see section 5.3.3.3). Figure 7.67 presents the relationship between the effective degree of saturation (S_e) versus suction. It was possible to determine the pore size distribution index (λ) and the suction at the air entry point ($(u_a - u_w)_b$) as described by Brooks and Corey (1966), for the five mixtures. Again the residual degree of saturation was assumed to be at the air dry state, since it was not possible to determine its value with the data available. Table 7.7 presents the values of λ and $(u_a - u_w)_b$ for London clay (L00S) and three other mixtures, where it was possible to apply the model.

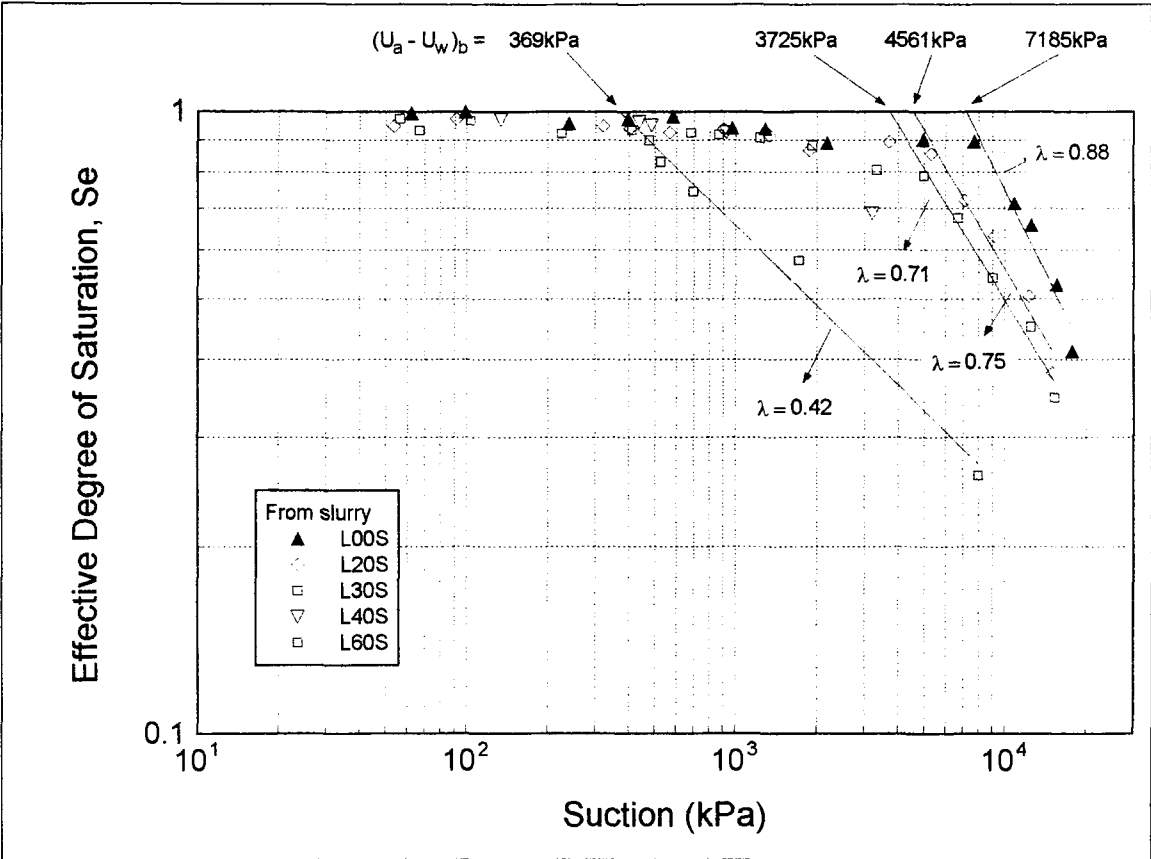


Figure 7.67 - Relationship between the effective degree of saturation (S_e) and suction showing the air entry value and the pore size distribution index (λ) for the clay/silt mixtures.

Soil	λ	$(u_a - u_w)_b$ (kPa)
L00S	0.88	7185
L20S	0.75	4561
L30S	0.71	3725
L60S	0.42	369

Table 7.7 - Pore size distribution index and suction at the air entry value for London clay and clay/silt mixtures.

The uniformity in the pore size distribution decreases from London clay to the L60S mixture, and the suction at the air entry value also decreases with decrease in uniformity of the pore size distribution curve. The latter behaviour is due to the appearance of large voids probably due to the increase in the silt content. Performing similar comparisons for the kaolin and kaolin/silt mixtures, it can be observed that the addition of 20% silt seems to change the pore size distribution in comparison with the pure kaolin. However, the addition of 50% silt does not appear to alter the shape of the pore-size distribution curve (see figure 7.68). Table 7.8 presents the values of λ and $(u_a - u_w)_b$ obtained.

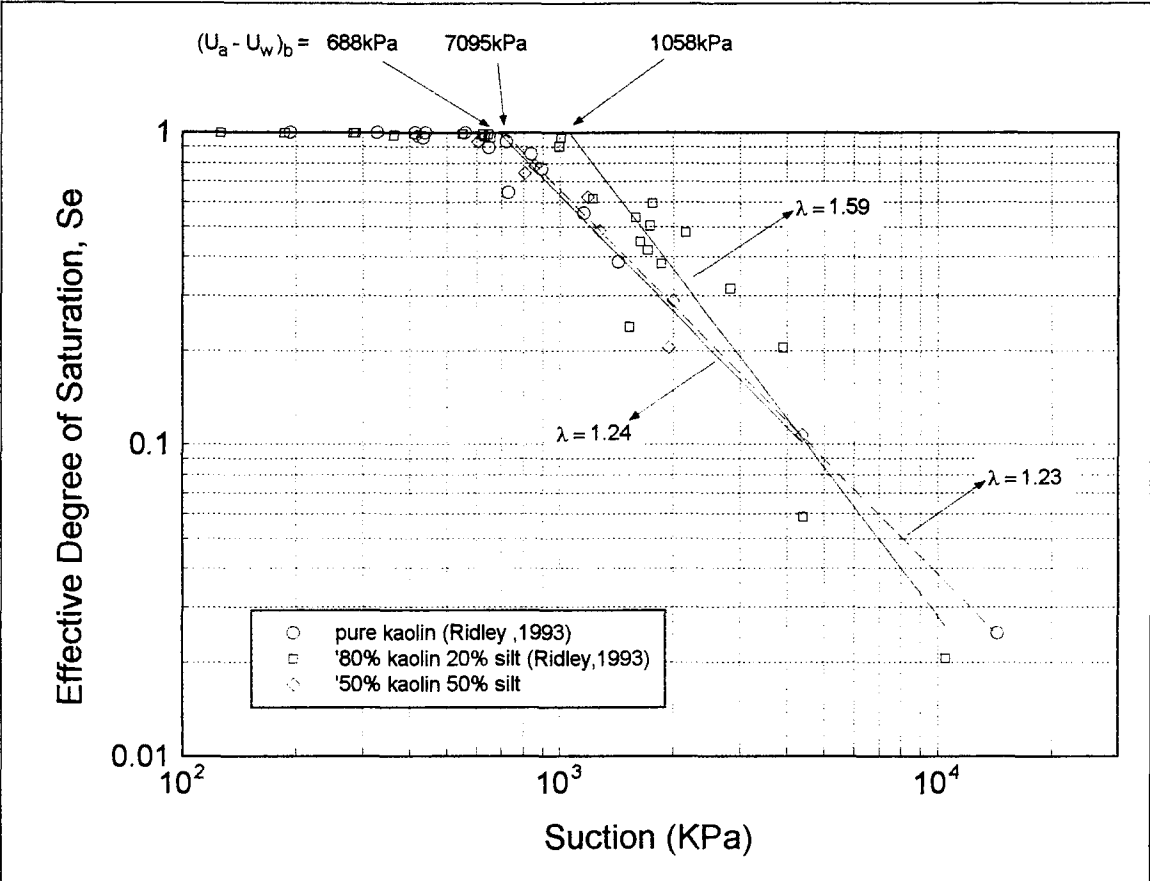


Figure 7.68 - Relationship between the effective degree of saturation (S_e) and suction showing the air entry value and the pore size distribution index (λ) for the kaolin/silt mixtures.

Soil	λ	$(u_a - u_w)_b$ (kPa)
kaolin	1.23	7095
80% kaolin + 20% silt	1.59	1058
50% kaolin + 50% silt	1.24	688

Table 7.8 - Pore size distribution index and suction at the air entry value for kaolin and kaolin/silt mixtures.

Although the pore size distribution index are similar for the kaolin and for the K50S50 mixture, the suction at the air entry value is very different, which may be due to an increase in pore size, not range of pore sizes.

The relationship between effective degree of saturation and suction for blue clay is presented in figure 7.69. The value of λ is 0.76 and the $(u_a - u_w)_b$ is 1910 kPa. In terms of pore size distribution index the blue clay is comparable with the mixture L20S. The suctions at the air entry values are different, which suggests that the blue clay may have larger pores.

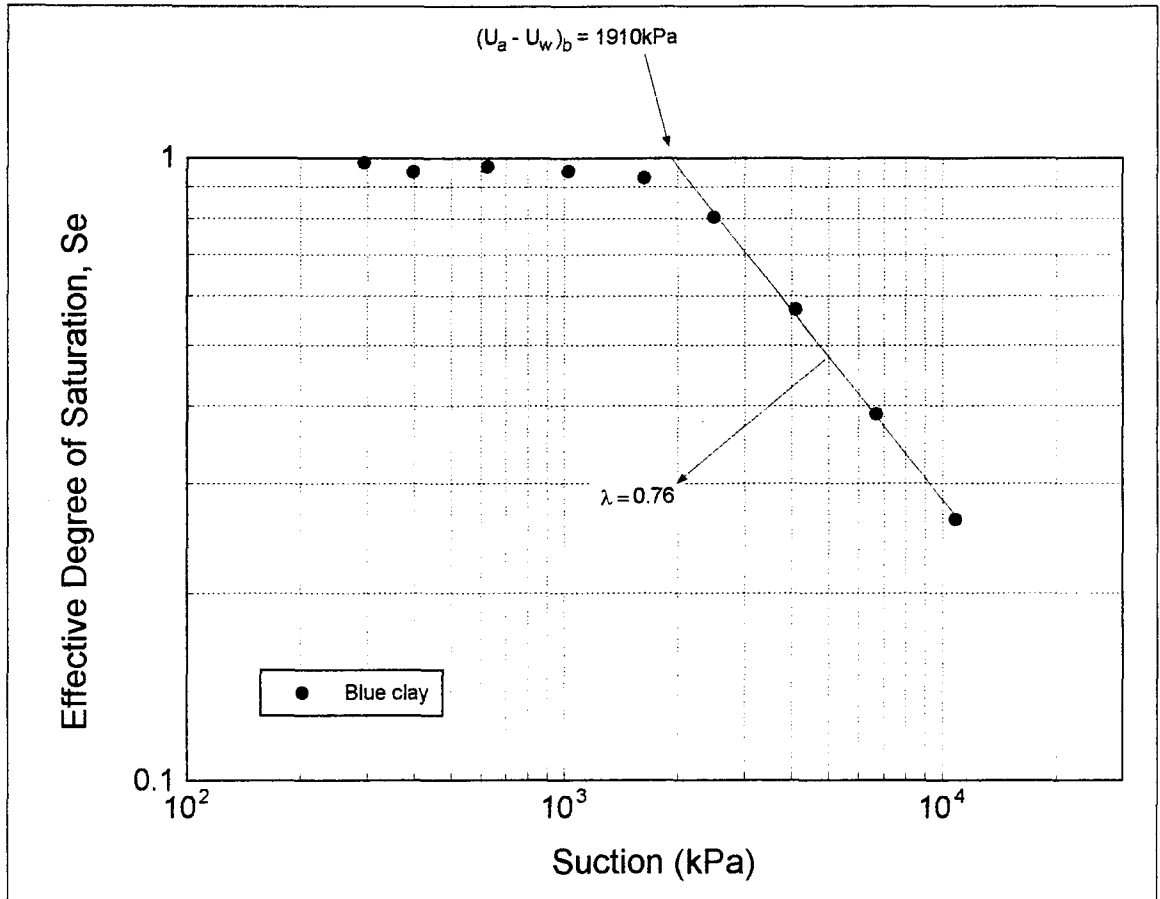


Figure 7.69 - Relationship between the effective degree of saturation (S_e) and suction showing the air entry value and the pore size distribution index (λ) for the Blue clay.

7.3.3. Water Content Versus Suction

Plotting the relationship between water content and suction for the London clay, clay/silt mixtures and for blue clay, it can be observed (see figure 7.70) that the blue clay intersects the line for the L20S. This may be a reflection of the pore sizes.

Figure 7.71 presents the relationship between suction capacity (C) and liquid limit. The suction capacity obtained for the high density bentonite was determined using the second line of the bi-linear behaviour observed (see figure 7.66e). Together with the data from this work is presented data from the literature. The value of suction capacity obtained from the data presented by Burland (1990) was determined assuming a degree of saturation of 100% and using the effective vertical stress. A regression line obtained using the data presented by Burland (1990) is shown. There is reasonable agreement for liquid limits up to 80%. The high

density bentonite seems to differ from the envelop for saturated soils (Burland data). The liquid limit for the high density bentonite is 279%.

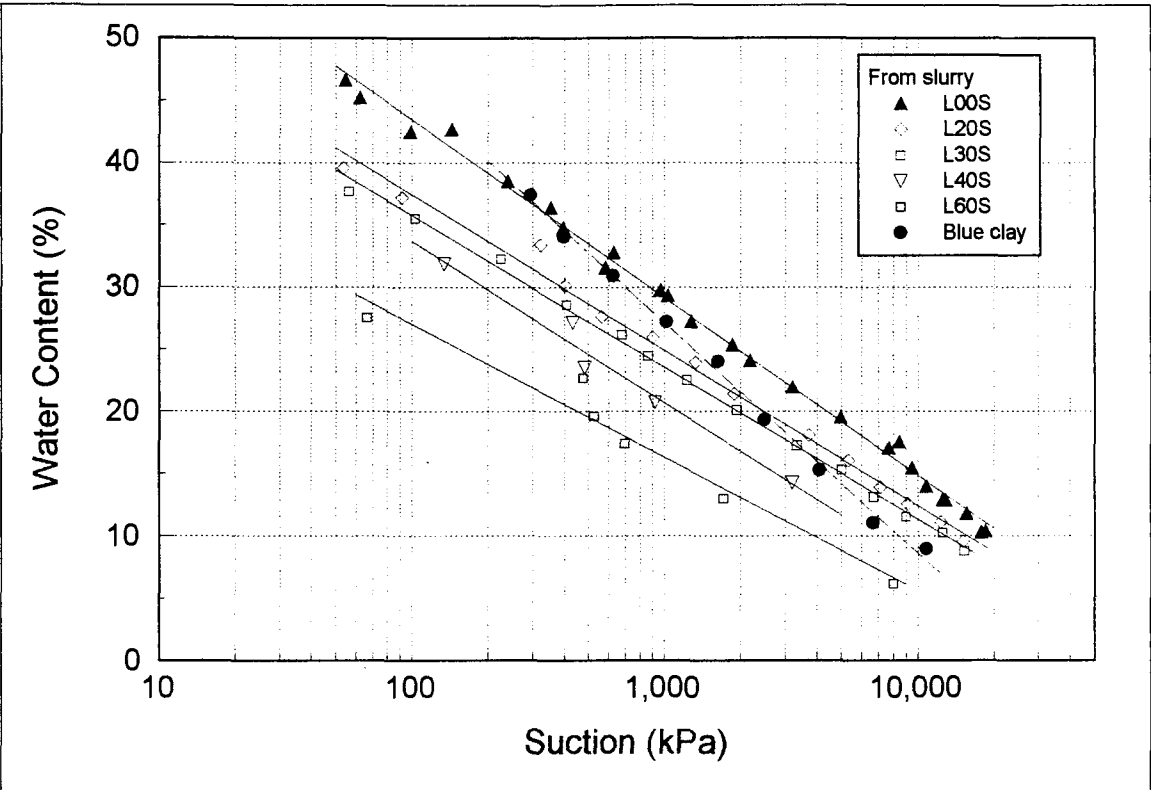


Figure 7.70 - Relationship between water content and suction for all clay/silt mixtures and for Blue clay.

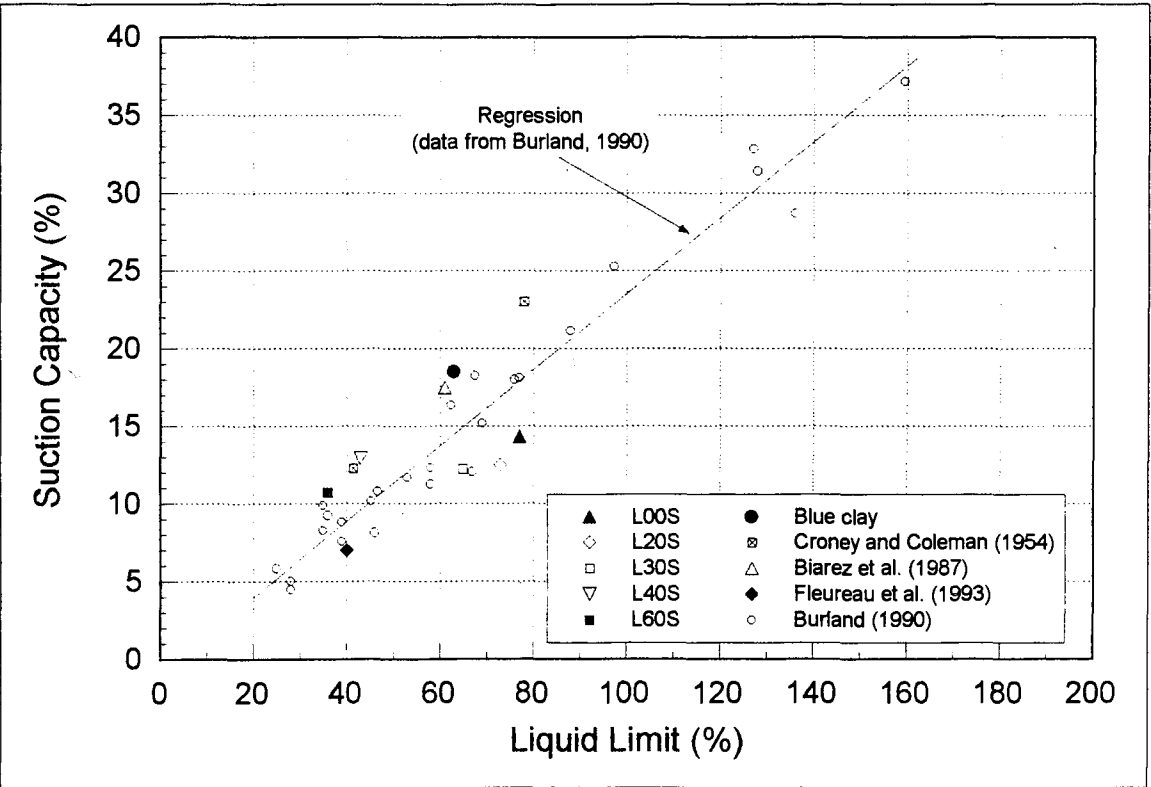


Figure 7.71 - Suction capacity (C) versus liquid limit for slurried soils.

Figure 7.72 presents the lines representing the relationship between water content and suction. In the lines are indicated the point of general air entry, giving the water content and suction at that point. There is a tendency for the suction at the GAE point to reduce with the decrease in plasticity. However, the sample of blue clay seems to diverge from that, showing a low suction at the GAE point considering its suction capacity. An increase in suction reduces the volume of shrinkable clays, though there may be cases where an increase in suction is not accompanied by a decrease in pore sizes, inducing early general air entry. The L30S mixture has a lower liquid limit than the blue clay and both samples started the drying process from approximately the same point (see table 7.6). Comparing these two samples it can be observed that the L30S mixture is more shrinkable than the blue clay. The ability to shrink allows the pore size to be reduced further when suction is increased.

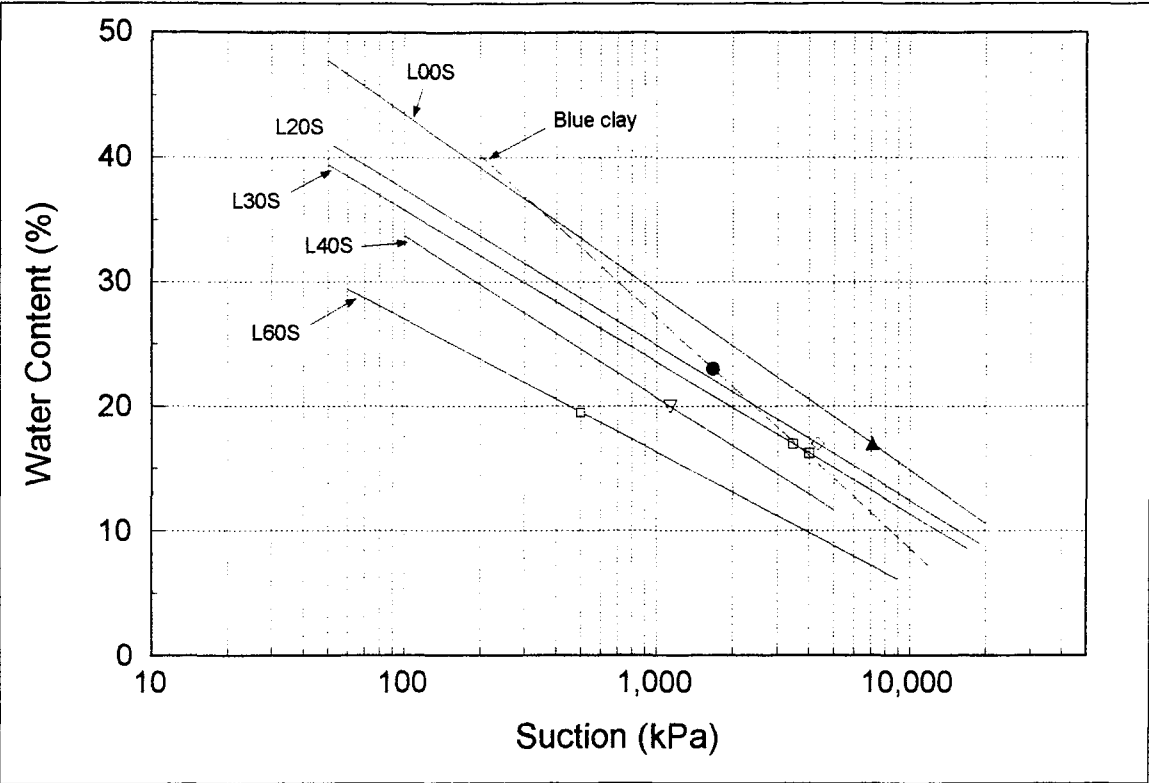


Figure 7.72 - Suction at the general air entry point for the slurried soils.

The water content normalized by the suction capacity versus suction is presented in figure 7.73. Although there is a consistent relationship it can be seen that the samples are separated into two groups. The samples with lower suction at the GAE (L40S, L60S and blue clay) are located below the regression line and the other three samples located above. These results seem to reflect a structure dependence that could not be clarified.

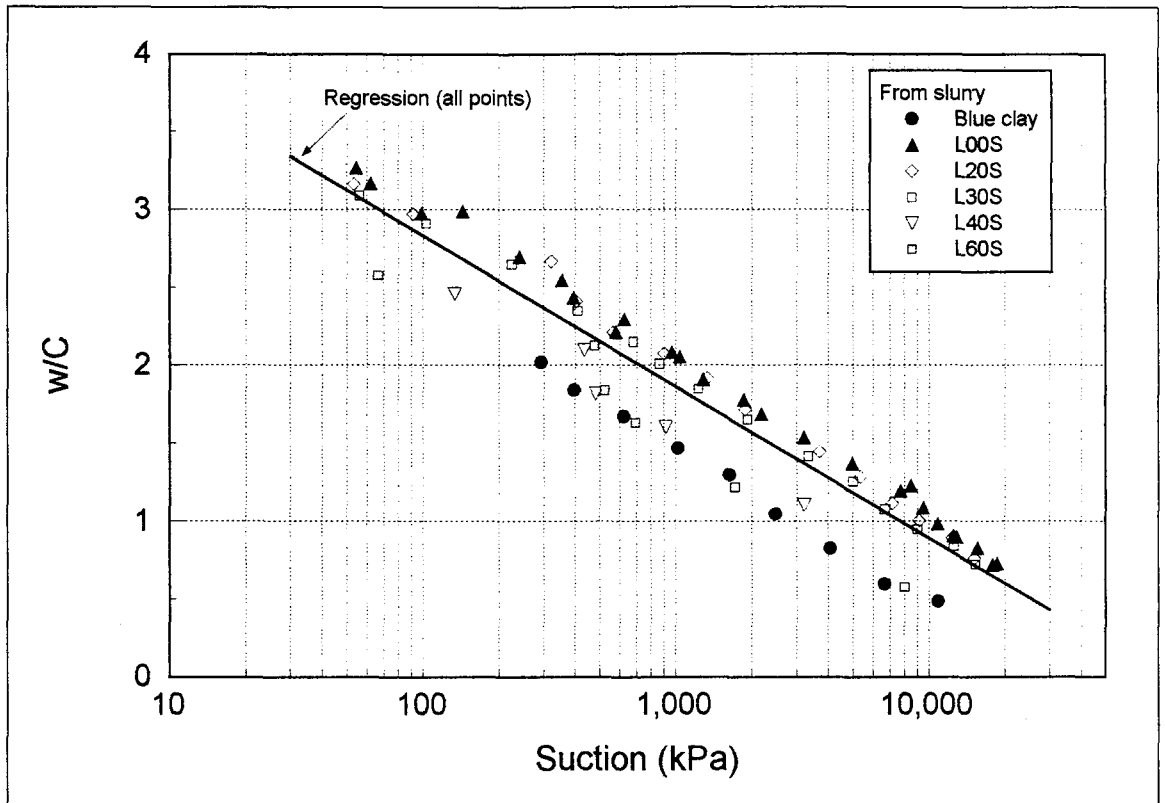


Figure 7.73 - Relationships from figure 7.70, with water content normalized by suction capacity(C).

7.4 - Drying Test on Undisturbed Soils

This section presents and discusses the results obtained with undisturbed samples.

As part of a joint program between Imperial College and the Building Research Establishment, samples of London clay were obtained from Chattenden, Kent. The samples were taken from two bore holes. One of the bore holes (BH-51) was subjected to an 'injection' of a chemical product which claims to stabilize expansive/shrinkable clays. In order to investigate the effectiveness of the product *in situ*, tests were carried out in a 'treated' area and in an untreated area.

Figure 7.74 presents the water content and suction profile for the samples tested. In terms of water content the profile in the two bore holes are the same. However, below approximately 2 meters the suction in the bore hole BH-51 is higher than in bore hole BH-52. The upper layer shows a lower suction. The initial characteristics of the samples used in the drying tests are presented in table 7.9.

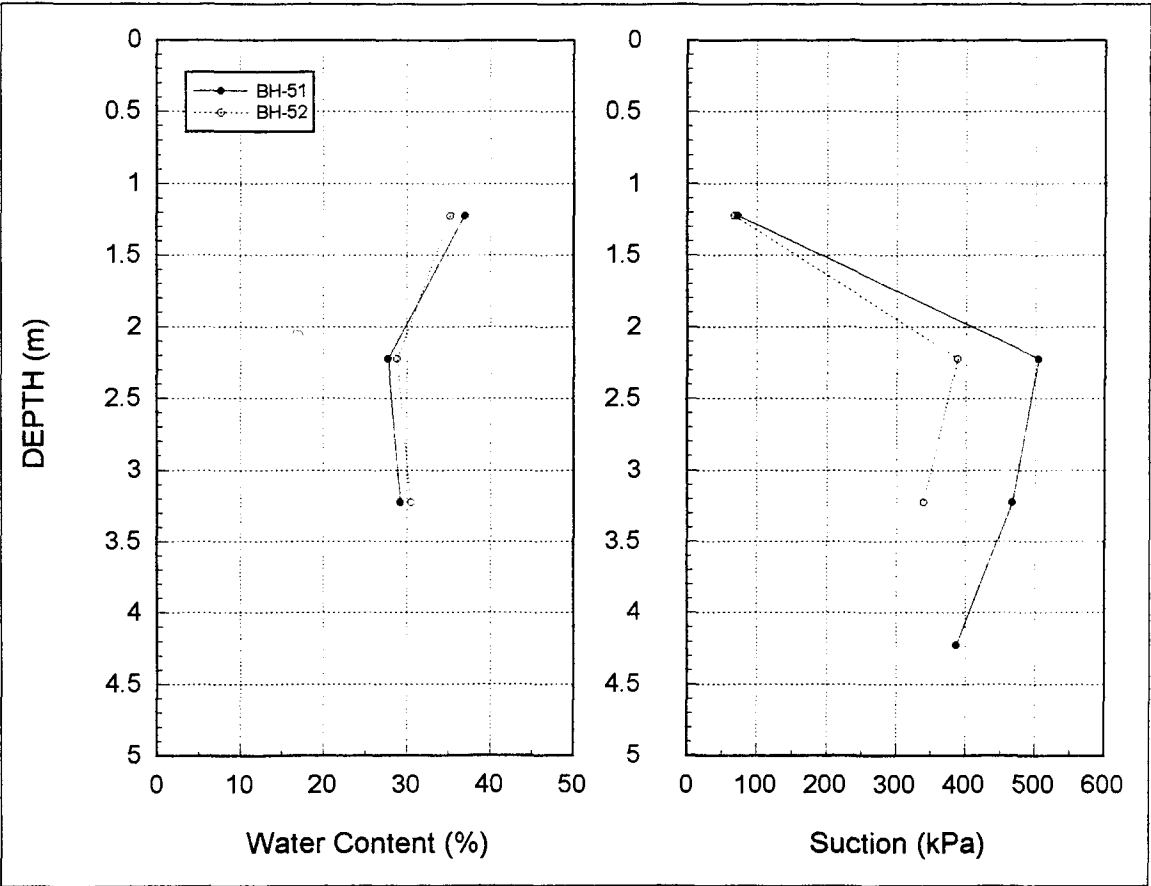


Figure 7.74 - Profile of water content and suction at Chattenden.

Sample	ei	Si	suction (kPa)
D-51a1	1.03	96	72
D-52a1	0.99	97	67
D-51b1	0.79	94	505
D-52b1	0.81	95	388
D-51c1	0.8	96	467
D-52c1	0.8	99	339
D-51d1	0.85	96	387

Table 7.9 - Initial characteristics of the undisturbed London clay samples from Chattenden.

7.4.1. General Behaviour

7.4.1.1. Volume Change Versus Water Content

Figure 7.75 shows the results of oedometer tests in samples at three depths, from the 'treated' and untreated bore holes. The results do not show significant differences between the samples from the 'treated' and untreated areas. The two samples from the upper layer had different initial void ratios. Figure 7.76 shows the value of the coefficient of compressibility (C_c) versus average vertical pressure. No apparent differences were observed between the two boreholes. Though it is not the aim of this thesis discuss the stabilization aspect of expansive soils, it can be concluded that the attempt to inject the chemical product (soil-STA) into the *in situ* London clay was not successful. Hence, the samples from the two boreholes will be hereafter considered as not having been treated.

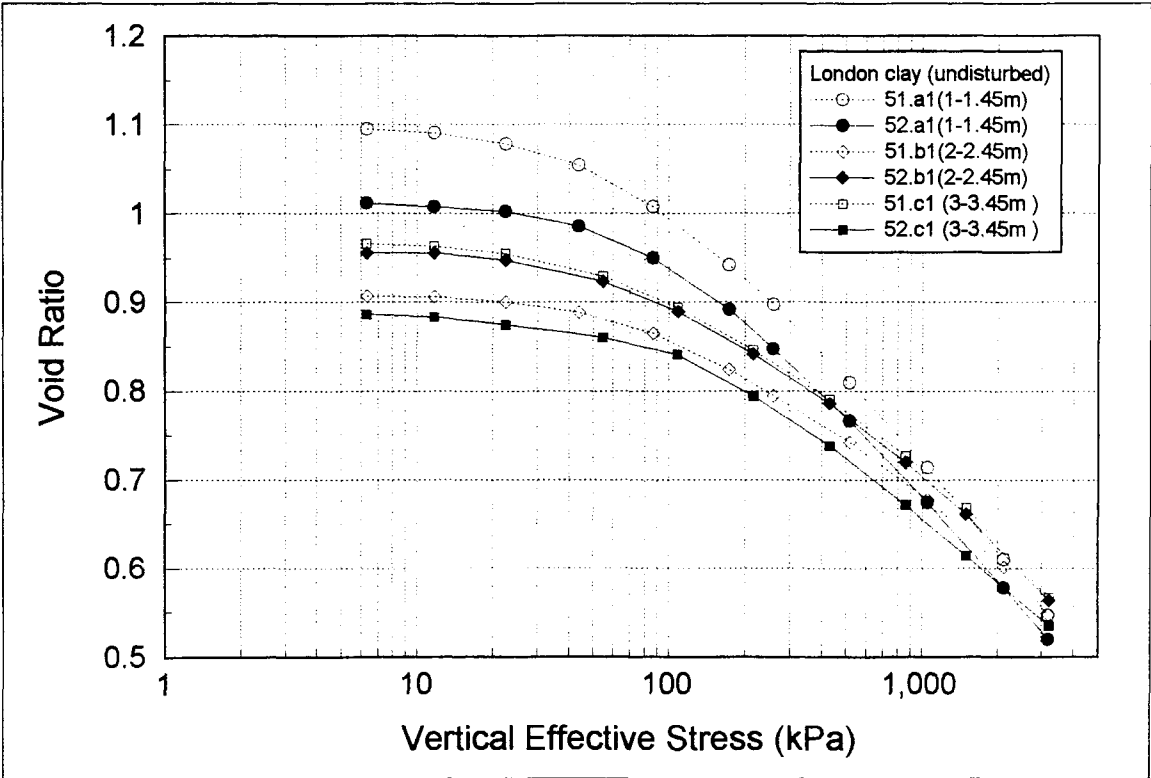


Figure 7.75 - Results of oedometer tests on London clay from Chattenden.

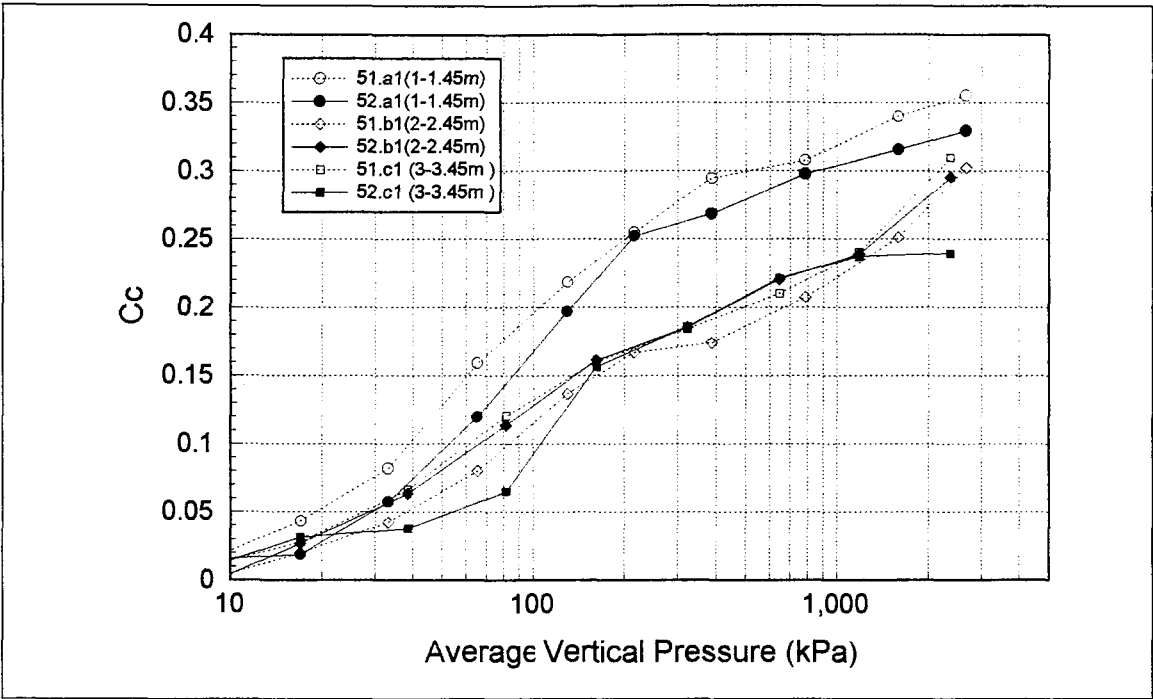


Figure 7.76 - Coefficient of compressibility for London clay from Chattenden.

The drying curves for this series of samples are presented in Figures 7.77 to 7.79. This figure also confirms that the soil-STA does not alter the characteristics of the London clay. Figure 7.77 shows the results obtained with samples obtained from a depth between 1 and 1.45m. During the drying process the samples followed the line parallel to $S=100\%$. The samples from a depth between 2 and 2.45m, shown in Figure 7.78, indicate a difference in final volume per 100g of dry soil ($V_d/100$) but this is not significant enough to justify the conclusion that of the soil-STA has any effect. The behaviour at a depth 3-3.45m did not show any apparent difference between the two boreholes (see Figure 7.79).

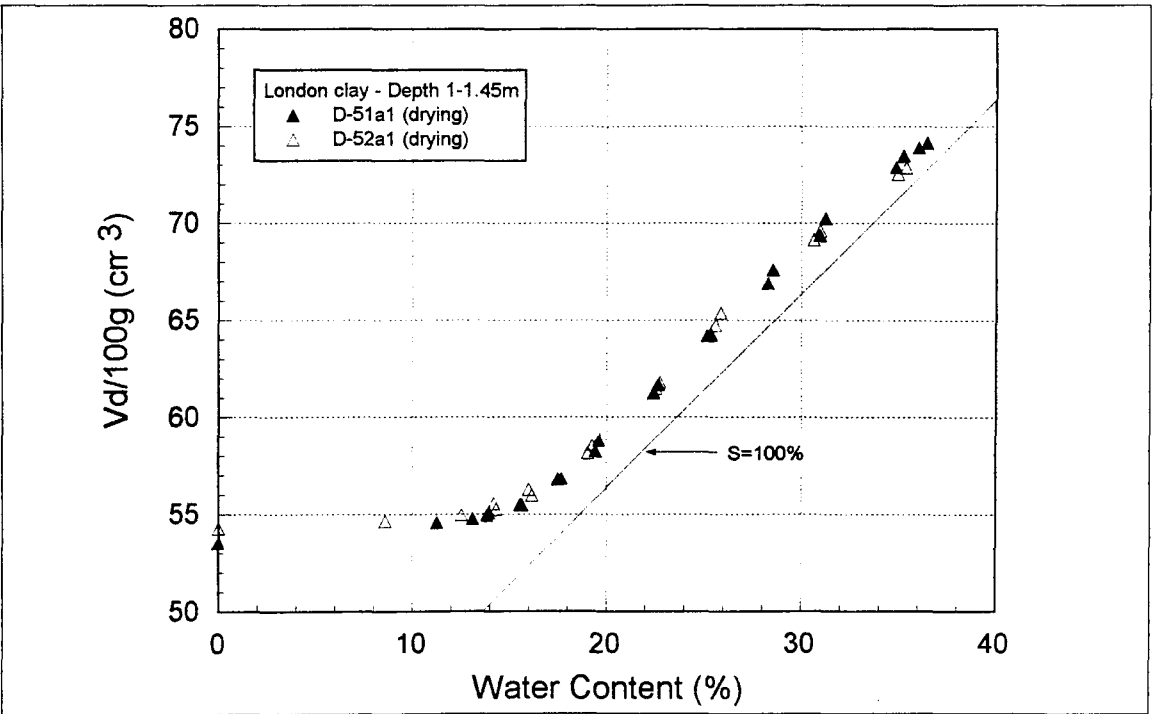


Figure 7.77 - Drying behaviour of undisturbed London clay from Chattenden (Depth 1-1.45m).

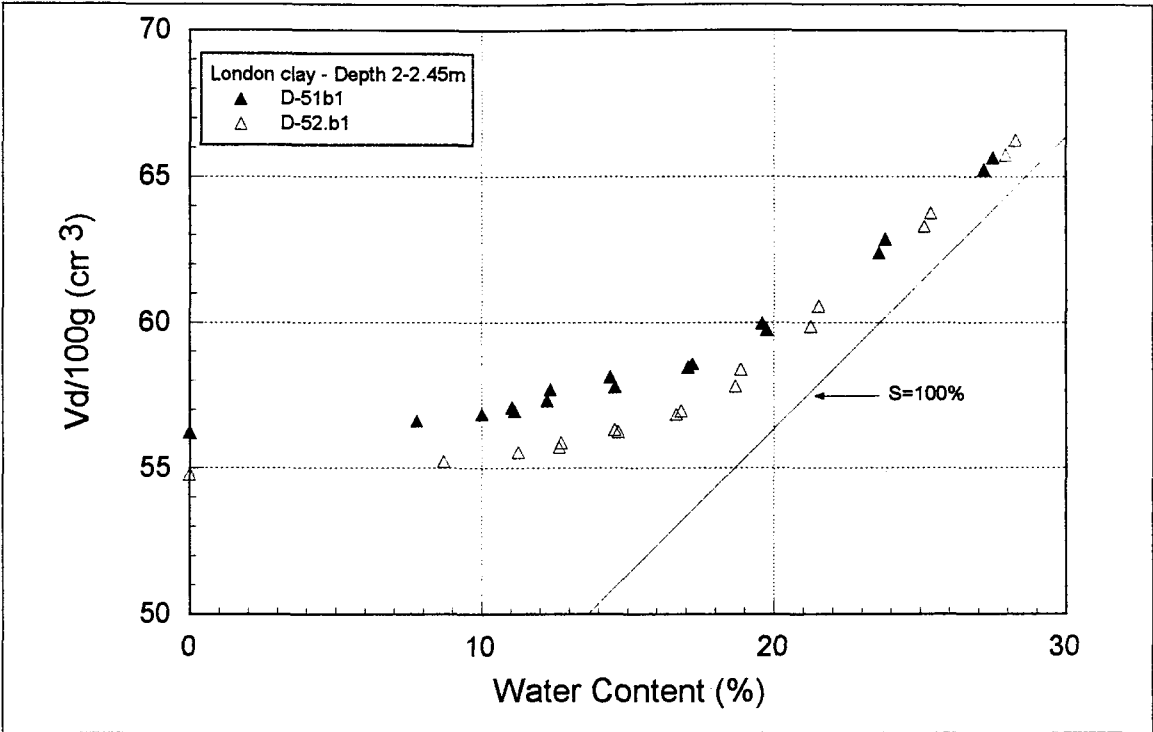


Figure 7.78 - Drying behaviour of undisturbed London clay from Chattenden (Depth 2-2.45m).

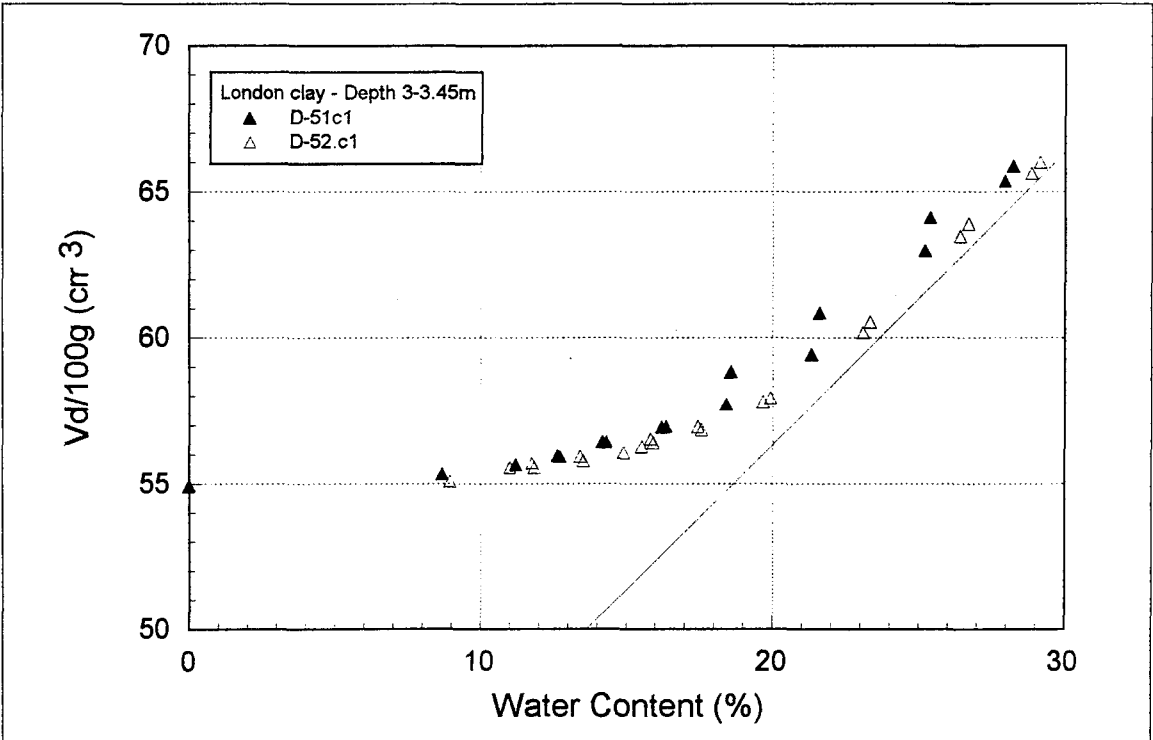


Figure 7.79 - Drying behaviour of undisturbed London clay from Chattenden (Depth 3-3.45m).

Drying tests were also carried out on 'old' undisturbed samples from Chattenden (approximately 4 years old). The results are presented in figure 7.80 and the initial characteristics of the samples are shown in table 7.10.

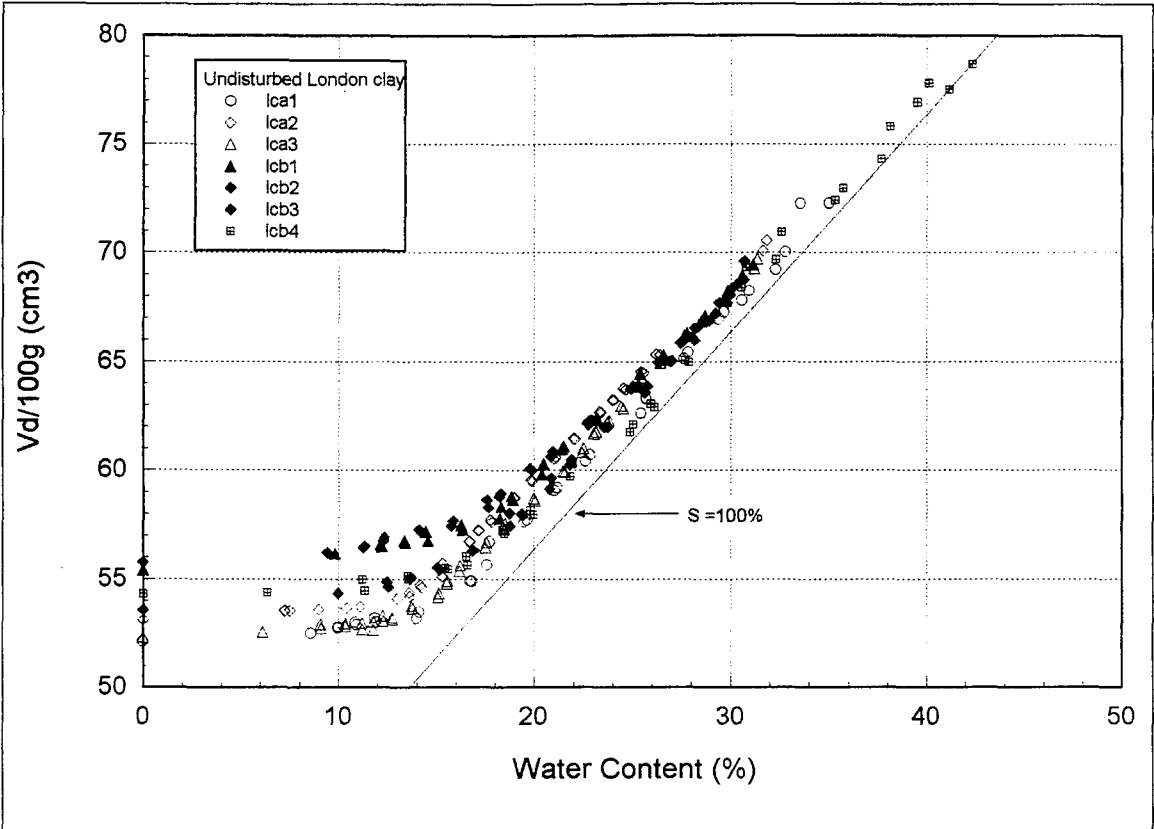


Figure 7.80 - Drying behaviour of 'old' undisturbed London clay from Chattenden.

In Figure 7.81 the drying curves of two samples of London clay (Cross Rail) are presented. The samples were kindly given by Mr. J. Standing. The initial characteristics of these samples are presented in table 7.10.

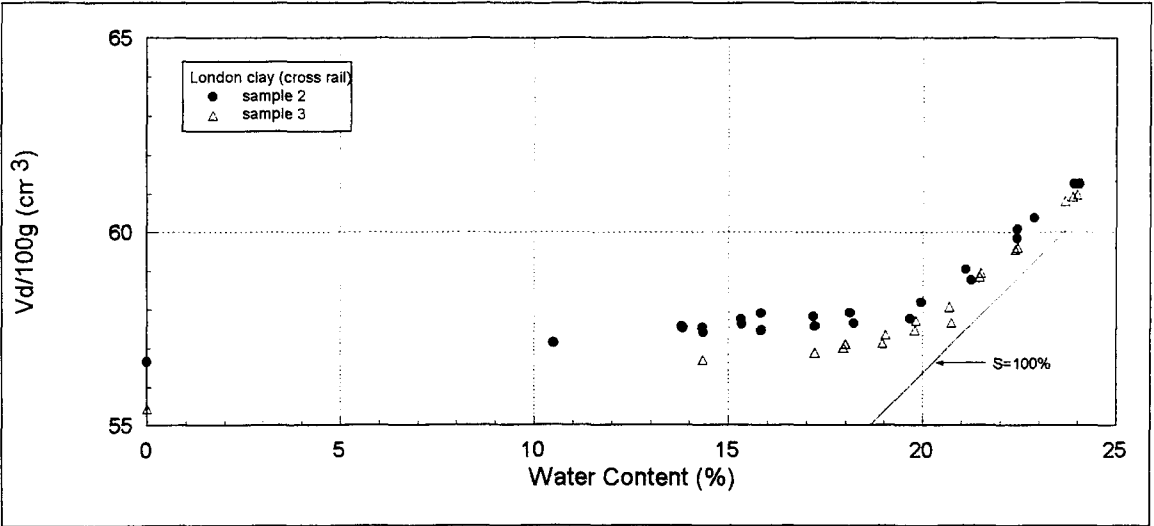


Figure 7.81 - Drying behaviour of undisturbed London clay from cross rail.

Samples	ei	Si	suction (kPa)
lca1	0.988	93	9
lca2	0.928	94	104
lca3	0.905	95	99
lcb1	0.897	94	229
lcb2	0.891	95	211
lcb3	0.88	94	222
lcb4	1.132	100	6
Cross rail - S2	0.654	99	463
Cross rail - S3	0.645	100	481

Table 7.10 - Initial characteristics of 'old' undisturbed London clay and undisturbed London clay from cross rail.

The results obtained from an undisturbed sample of Queensborough clay is presented in figure 7.82. The sample started from a very wet condition ($w=71\%$). It can be observed that the sample followed a line parallel to $S=100\%$, up to approximately 30% water content. Table 7.11 presents the initial conditions of the sample.

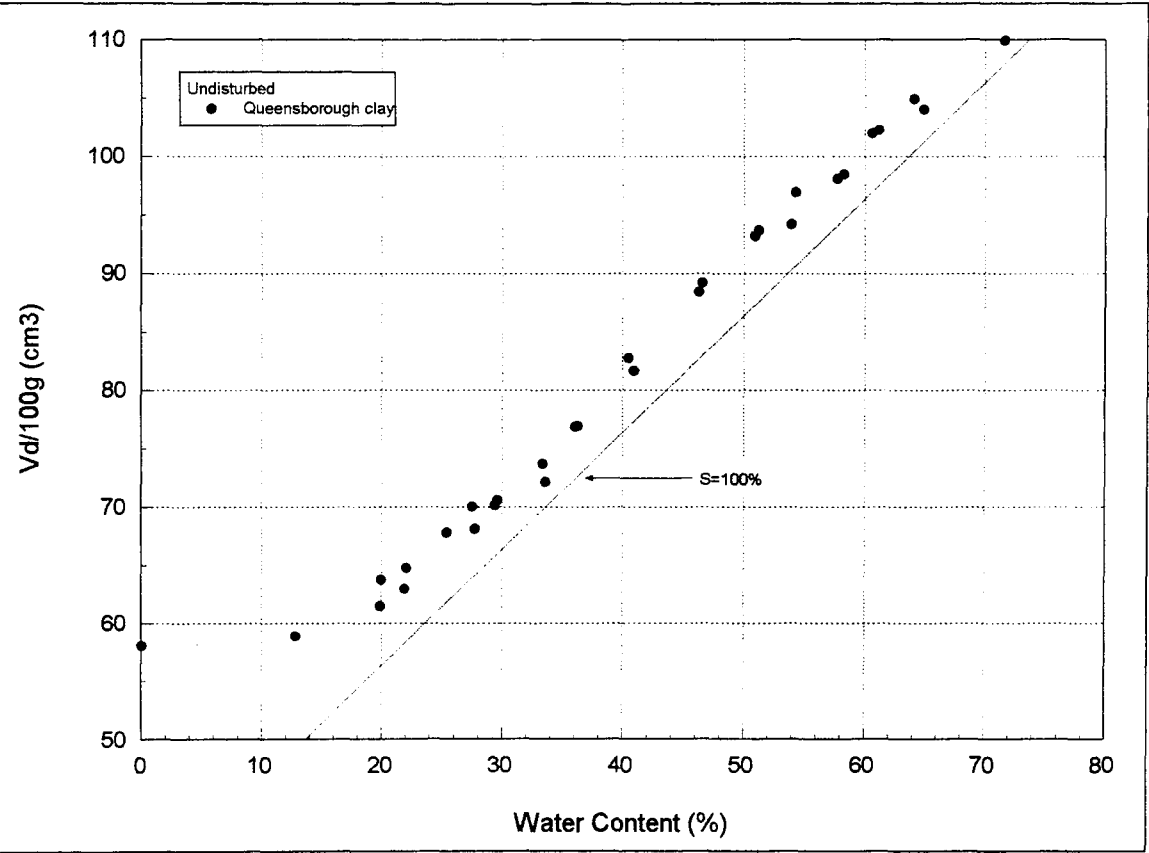


Figure 7.82 - Drying behaviour of undisturbed Queensborough clay.

In figure 7.83 the drying curve obtained for the Blue clay is presented. As can be seen the sample diverge from the $S=100\%$ line since the beginning of the test, although it was near saturation, showing only residual shrinkage. The initial characteristics of this sample are presented in Table 7.11.

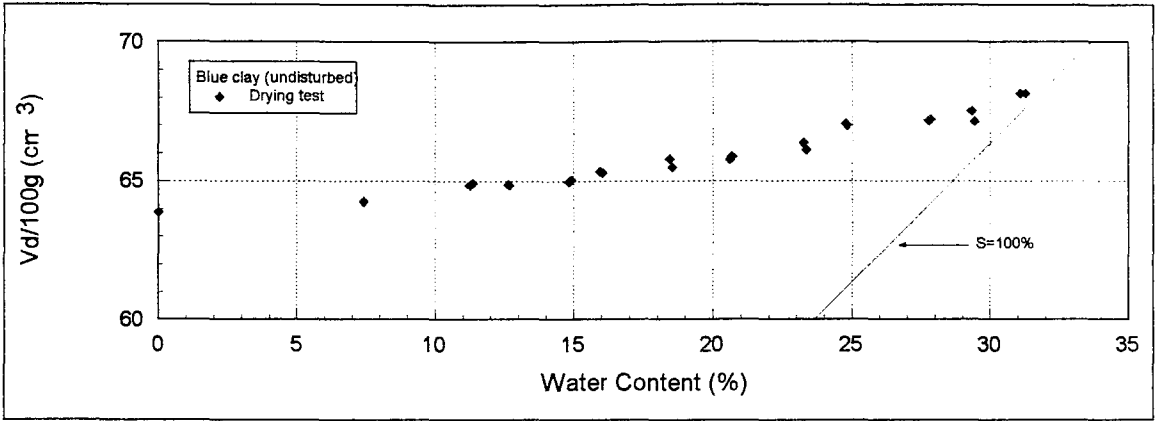


Figure 7.83 - Drying behaviour of undisturbed blue clay.

Sample	ei	Si	suction (kPa)
Queensborough clay	1.967	98	10
Blue clay	0.909	96	1119

Table 7.11 - Initial characteristics of Queensborough clay and blue clay.

In figure 7.84 is presented the results obtained with a chalk sample. There were two aims in using this type of material, firstly to characterize the drying curve for a non expansive material, and secondly to evaluate the use of water vapour to wet soil samples. The sample was initially submerged in water for several days and placed under vacuum for 24 hours. After that a drying test was performed. As can be seen in the figure, the sample was not fully saturated at the beginning of the test ($S=88\%$). At the end of the first drying the sample was slowly wetted by using water vapour (see section 6.5). The sample was then submitted to a second drying and finally wetted again by submerging it in water.

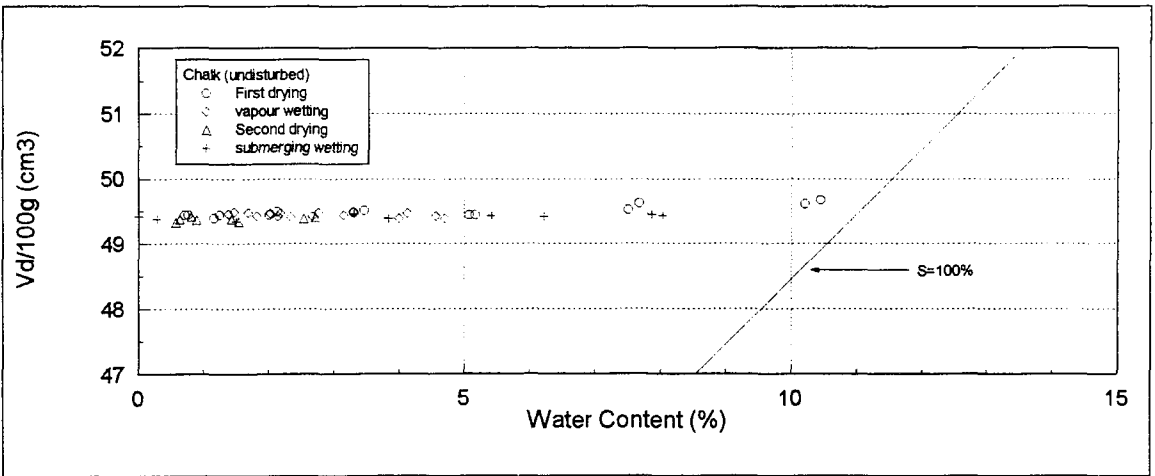


Figure 7.84 - Drying behaviour of undisturbed chalk, showing the wetting and drying path.

7.4.1.2. Water Content, Volume Change, Suction and Compressive Index

Figure 7.85 shows the interrelated parameters of void ratio, degree of saturation, water content and suction for London clay from Chattenden, obtained from boreholes 51 and 52 at 1-1.45m. The relationship between degree of saturation and suction shows very similar behaviour for the two samples. For these two samples a few wetting points were obtained, which show some agreement with the general trend but appear to suggest some hysteresis (see figure 7.85e). Part e of figure 7.85 presents the relationship between water content and suction, which is not a straight line. There are two distinct suction capacities in this case, one for suctions below 2.5MPa ($C=8.2\%$) and another for suctions above this value ($C=13\%$). This yielding point is due to the overconsolidation of the sample, above which the suction capacity tends to follow the "virgin desaturation line" (see section 5.3.1). Figure 7.86 presents the value of the compressive index with respect to matrix suction (C_m) (for definition see section 5.3.3.1). The value of C_m increases with suction up to a maximum value of about 0.3, which corresponds to approximately 2MPa of suction, and thereafter decreases with increasing suction.

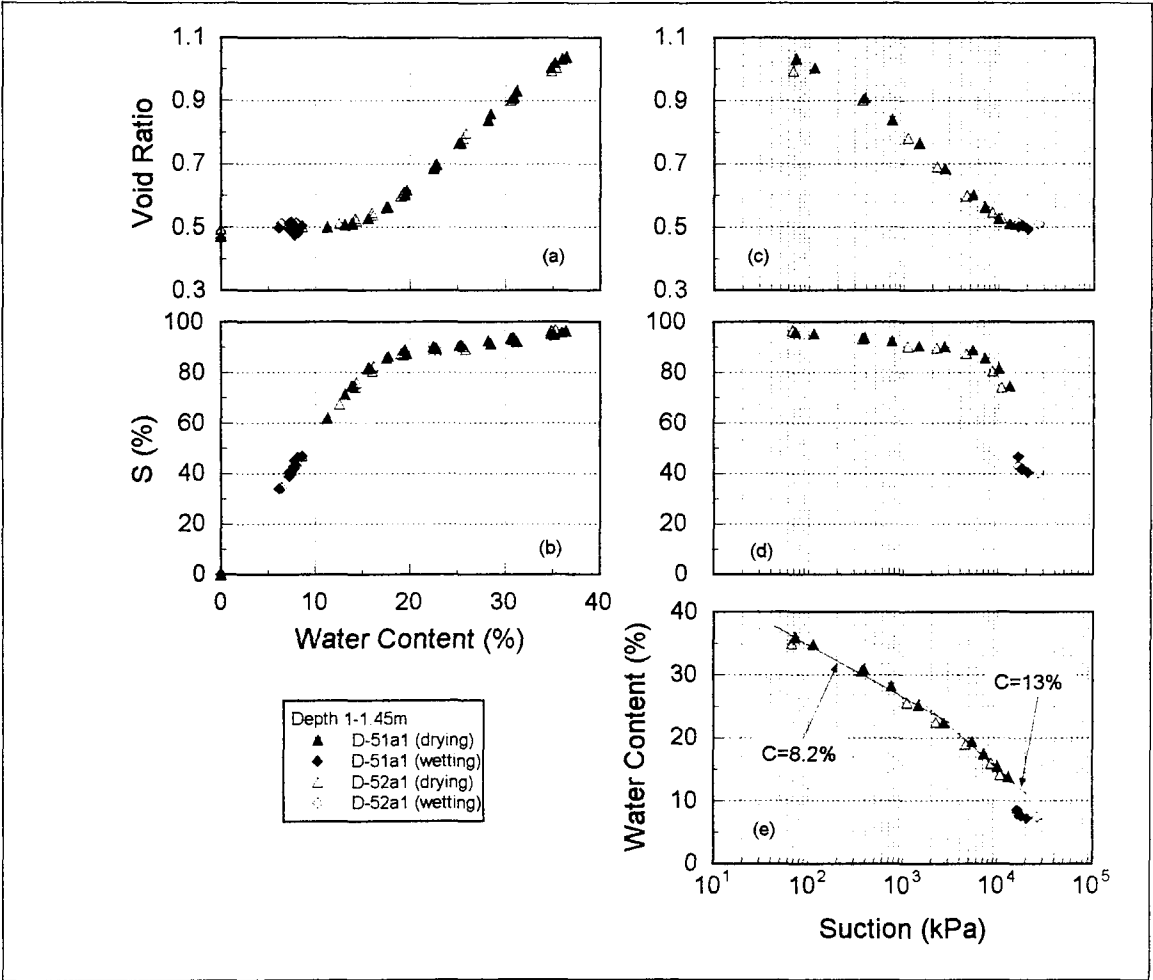


Figure 7.85 - Drying behaviour of London clay from 1-1.45 metres plotted against common axes of water content and suction.

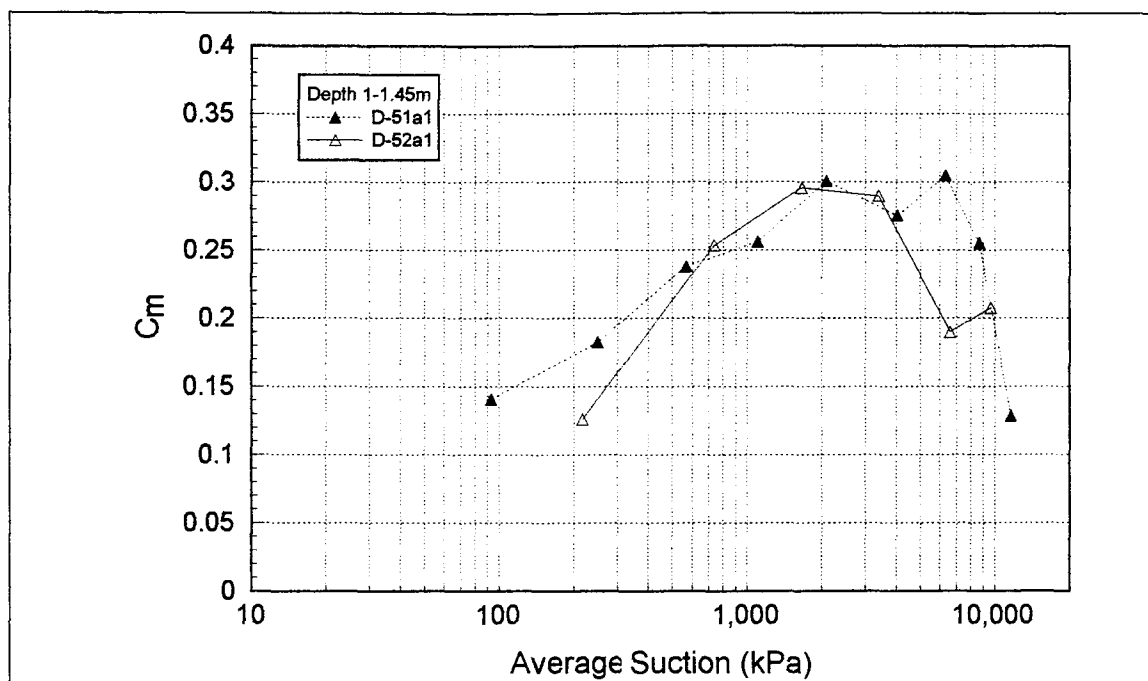


Figure 7.86 - Compressive index in terms of matrix suction versus average suction for London clay at 1-1.45 m.

Figure 7.87 shows results obtained with samples from 2-2.45 metres depth. The sample from borehole 51 seems to start desaturation slightly before the sample from borehole 52. The relationship between water content and suction again shows bi-linear behaviour. The suction capacity obtained below 4.5MPa is 8%, and thereafter is 22.5%. The relationship between C_m and average suction in Figure 7.88 shows that the reduction in the compressive index (C_m) occurred at approximately 5MPa, which seems to coincide with the suction at the general air entry point.

The results obtained with samples from 3-3.45m showed similar behaviour to the samples from upper layers (Figures 7.89 and 7.90). Yet again a bi-linear trend can be observed, the suction capacity for suctions below 4MPa being 8.5% and above that value is 18.5%.

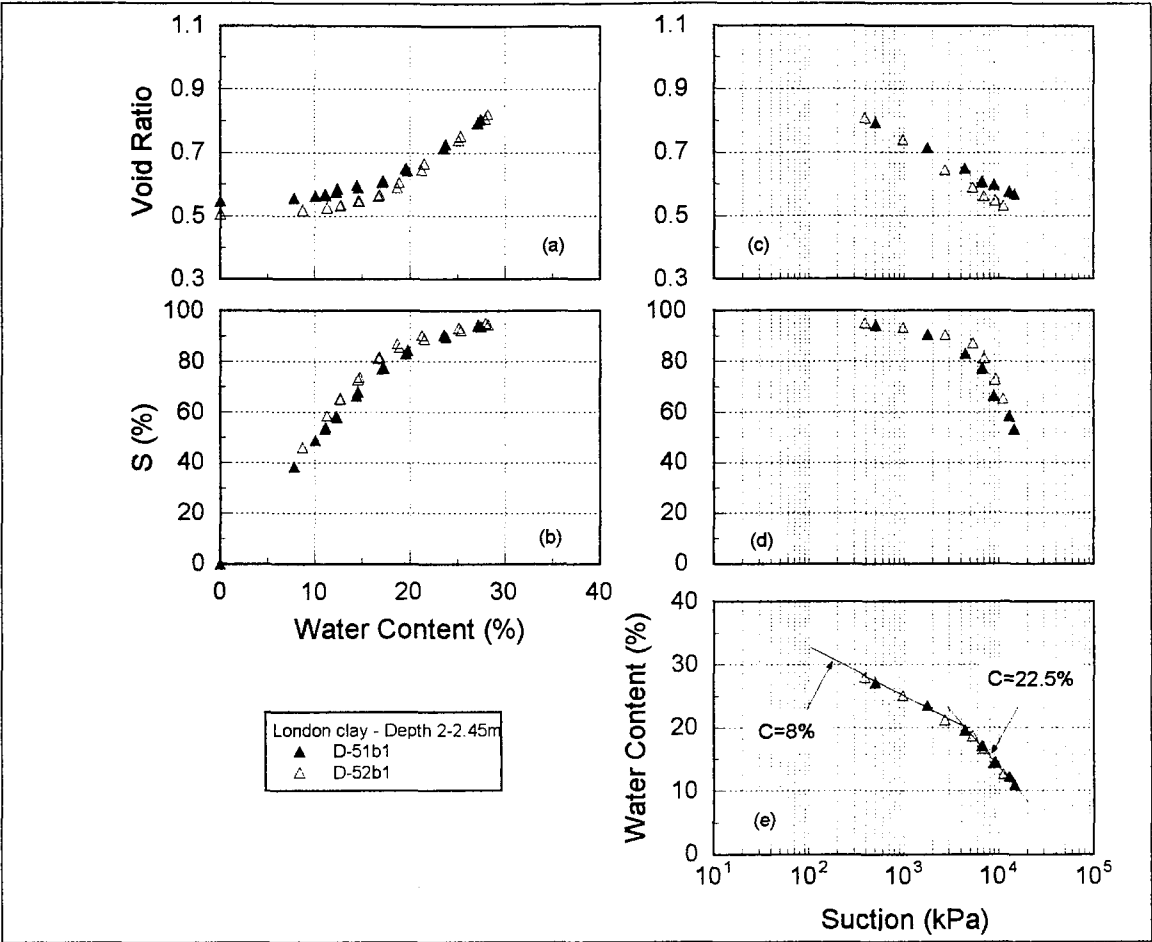


Figure 7.87 - Drying behaviour of the London clay at 2-2.45 meters plotted against common axes of water content and suction.

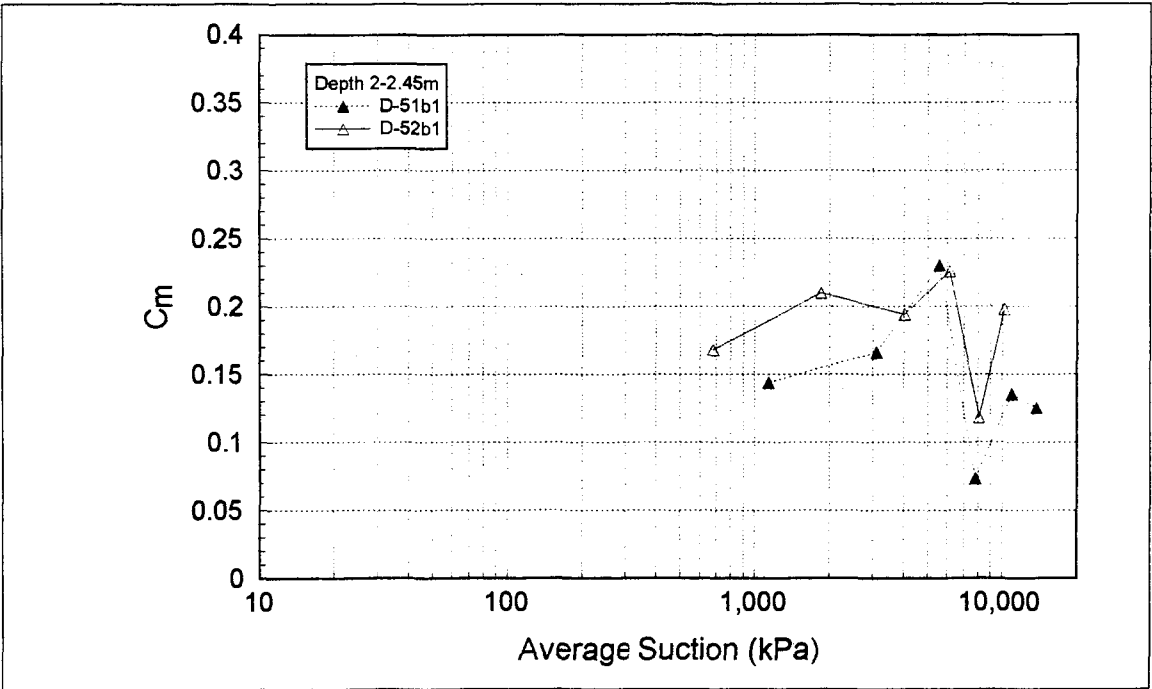


Figure 7.88 - Compressive index in terms of matrix suction versus average suction for London clay at 2-2.45 m.

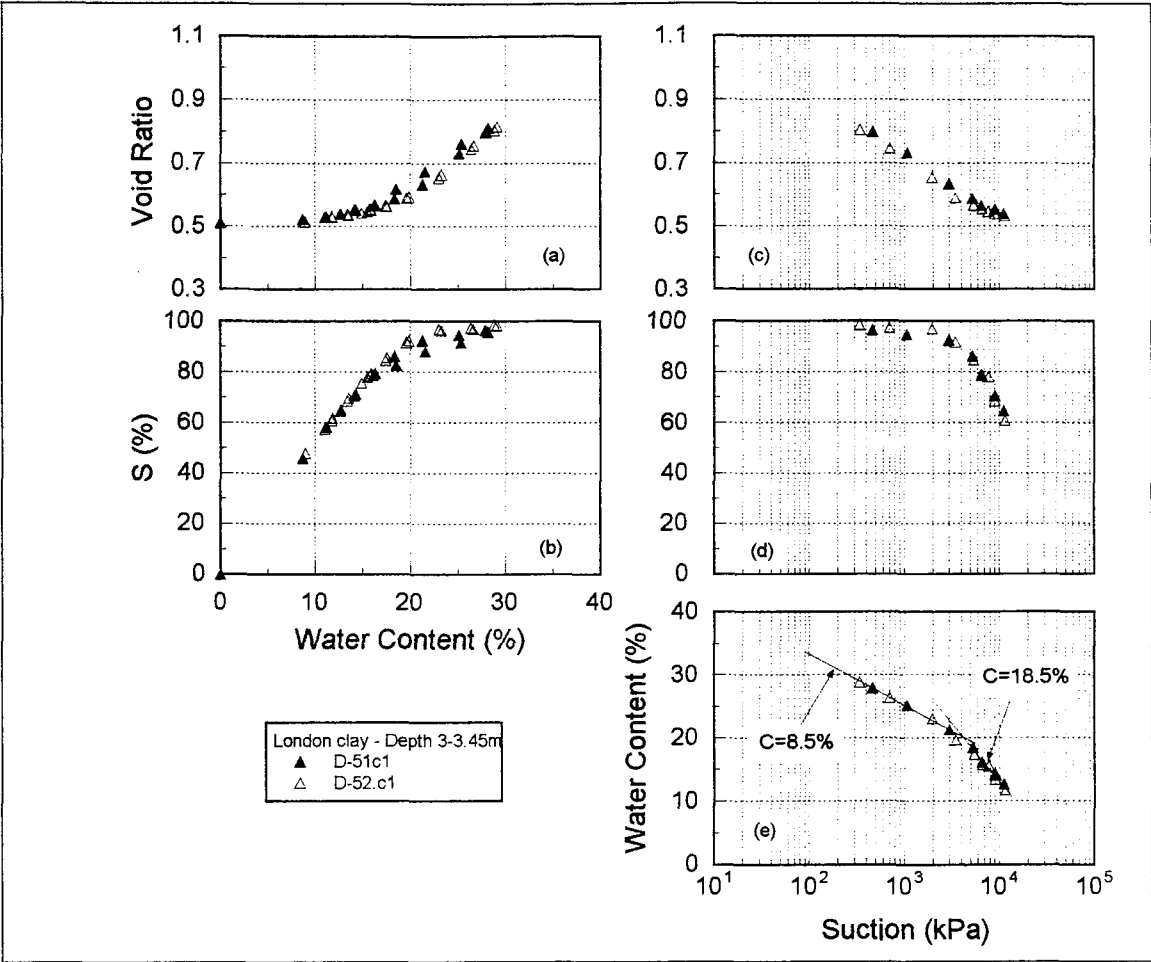


Figure 7.89 - Drying behaviour of the London clay at 3-3.45 meters plotted against common axes of water content and suction.

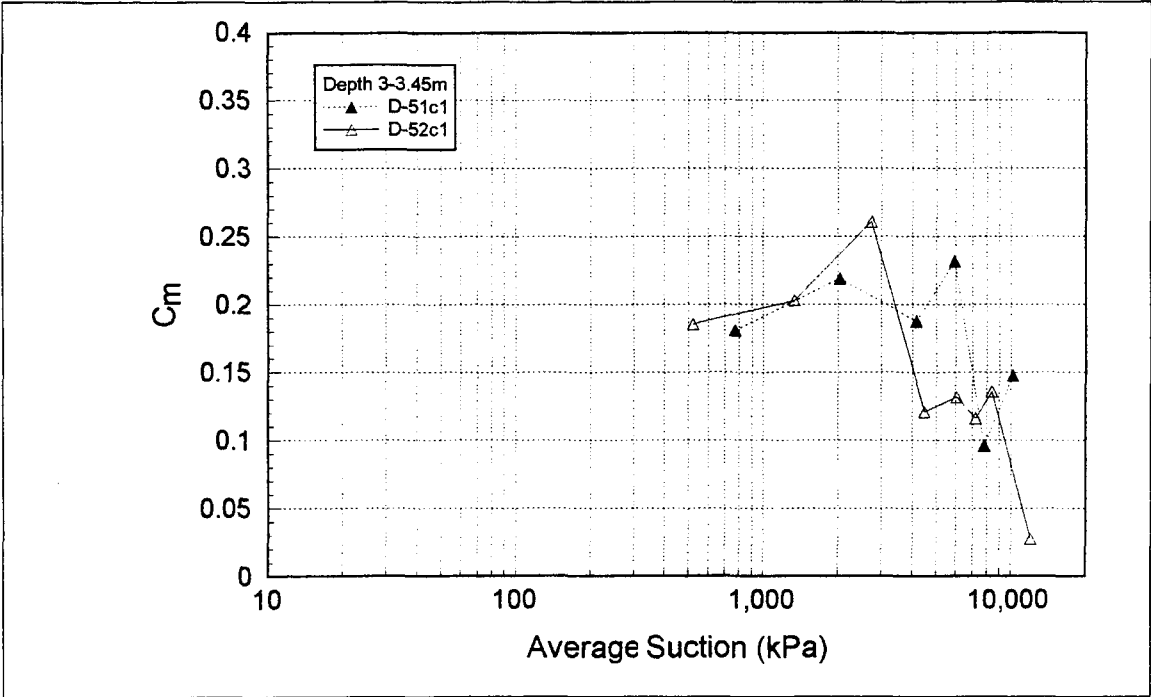


Figure 7.90 - Compressive index in terms of matrix suction versus average suction for London clay at 3-3.45 m.

Figure 7.91 presents the interrelated parameters of void ratio, water content, degree of saturation and suction for the 'old' undisturbed samples of London clay. In part c of figure 7.91 it can be seen that sample lca1 showed a different behaviour in relation to the other samples, indicating a less compressive characteristic at low suction. The same behaviour is observed in part e of the same figure, where water content is plotted against suction. As indicated in figure 7.91 the value of suction capacity below 3MPa is 7.5% for sample lcb4 and 3.9% for all other samples. Above 3MPa a common suction capacity of 16% is obtained.

Figure 7.92 presents the results obtained with London clay samples (cross rail). Samples 2 and 3 started from a near saturation state and with a low void ratio. The general air entry point is observed very clearly in both samples. For Sample 1, water content and suction only were determined. The relationship between water content and suction (part e of Figure 7.92) shows a bi-linear characteristic. Sample 1 is located above sample 2 and 3. The suction capacity for sample 1 is 6.3% for suctions below 2.2MPa and 19% for suctions above this value. For samples 2 and 3 suction capacity is equal to 4.8% for suctions below 3MPa and 15.2% above that value. Table 7.12 presents the values of C and the correspondent level of suction for all samples tested.

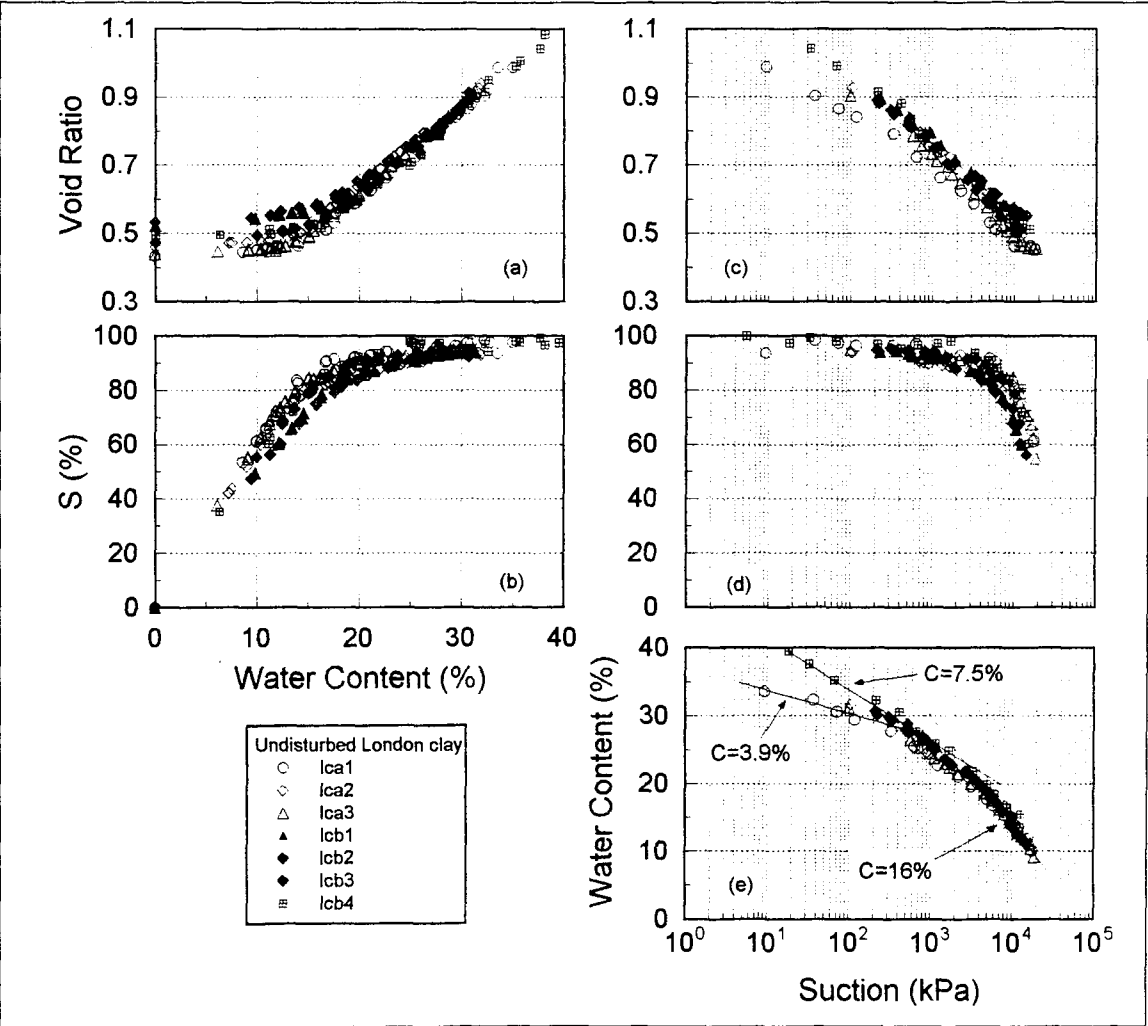


Figure 7.91 - Drying behaviour of 'old' undisturbed London clay samples from Chattenden plotted against common axes of water content and suction.

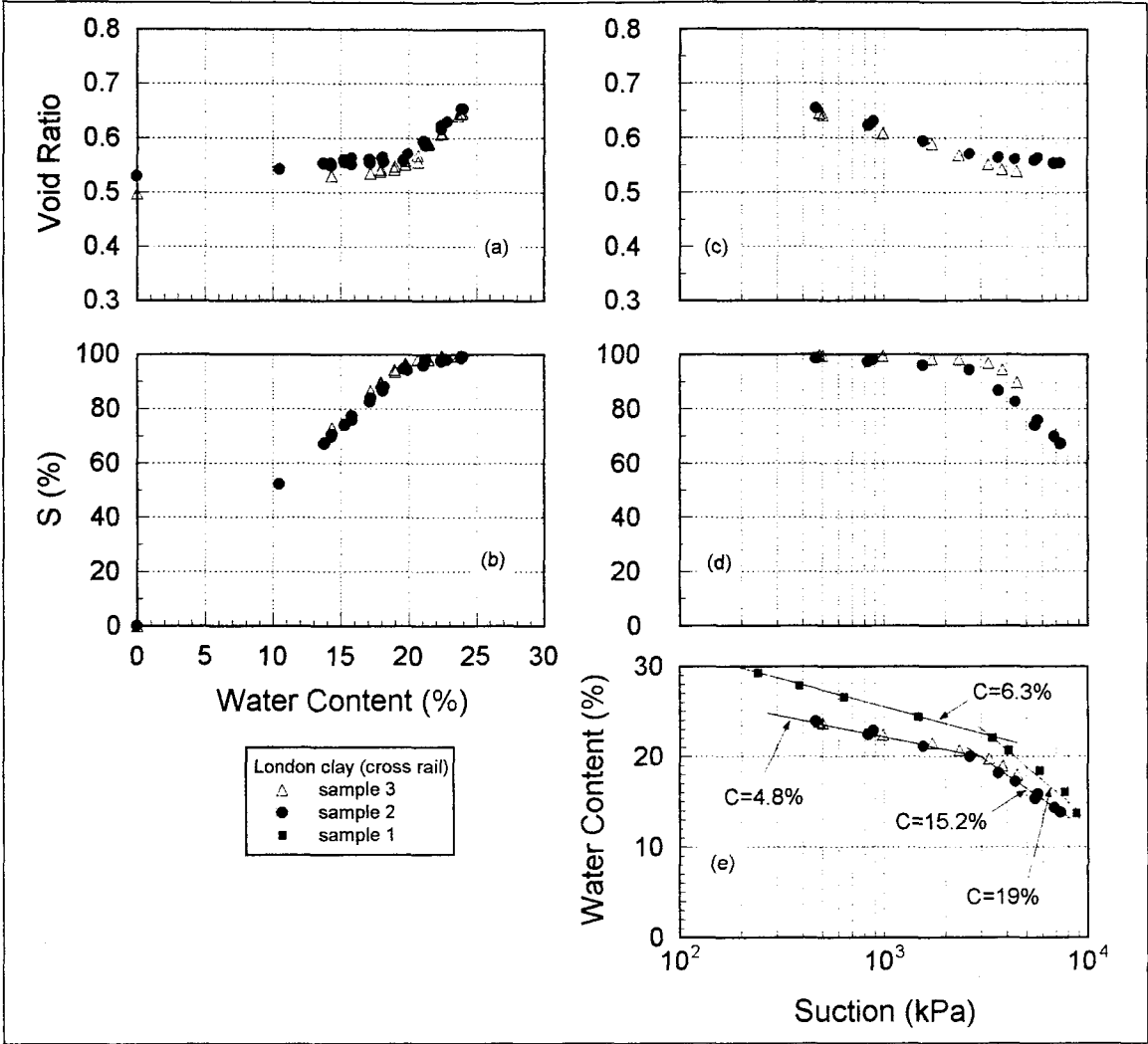


Figure 7.92 - Drying behaviour of London clay samples from cross rail plotted against common axes of water content and suction.

Sample	C(%)	Level of suction
D-51a1 and D-52a1	8.2	< 2.5 MPa
	13	> 2.5 MPa
D-51b1 and D-52b1	8	< 4.5 MPa
	22.5	> 4.5 MPa
D-51c1 and D-52c1	8.5	< 4.0 MPa
	18.5	> 4.0 MPa
LCU-T1, LCU-T2 and LCU-H1	8.1	< 3.5 MPa
	19.4	> 3.5 MPa
lca1,lca2,lca3,lcb1,lcb2,lcb3	3.9	< 500 kPa
	-	-
lcb4	7.5	Above 3.0 MPa
Cross rail - S.2 and S.3	4.8	Below 3.0 MPa
	15.2	Above 3.0 MPa
Cross rail - S.1	6.3	Below 2.2 MPa
	19	Above 2.2 MPa

Table 7.12 - Values of suction capacity (C) for undisturbed London clay samples according with the suction level.

In Figure 7.93 is presented the results obtained with Queensborough clay. A sample of calcarenite was tested and the results is presented in the same figure for comparison. The calcarenite sample was kindly provided by Dr. R. Lagioia. The sample of Queensborough clay maintained a very high degree of saturation (>80%) up to a suction of 7MPa. The relationship between water content and suction shown in part e of Figure 7.93 can be expressed using a linear equation for this type of graphic, shown below,

$$w = 88.97 - 17.79 \log(\text{suction})$$

{7.20}

The calcarenite sample, which is a non plastic granular soft rock, shows a completely different patten in terms of water content versus suction, which is a reflection of the pore sizes and its inability to shrink during the increase of suction. Similar behaviour is observed for the Pentre silt, where the volume change is also shown.

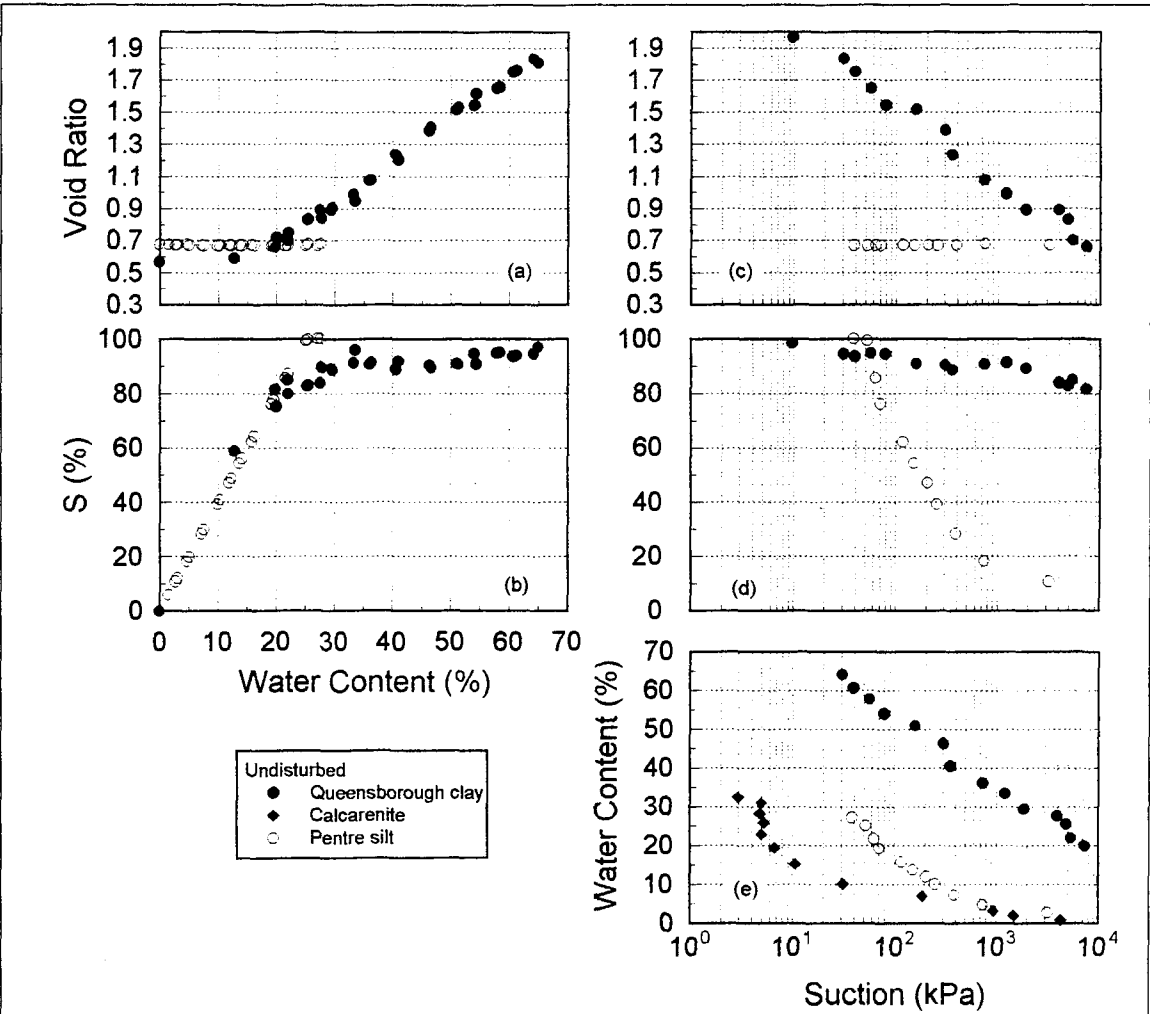


Figure 7.93 - Drying behaviour of Queensborough clay, calcarenite and Pentre silt samples plotted against common axes of water content and suction.

Figure 7.94 presents the results obtained with a undisturbed sample of Blue clay. The sample started from a high degree of saturation, and the general air entry point seems to be on the start point of the test (*i.e.* only residual shrinkage is observed). This can be seen on part b and d of figure 7.94 (see also figure 7.83). In part c is plotted two oedometer tests (Cotecchia, 1994)

for reference. It can be observed that the mechanical compression is more effective in reducing the volume than the increase in suction (see also section 5.3.1). The relationship between degree of saturation versus log suction showed a linear relationship in the range of suction presented. Assuming a linear relationship the equation below can represent the water content versus log suction relationship, for undisturbed Blue clay.

$$w = 110.88 - 26.24 \log(\text{suction})$$

{7.21}.

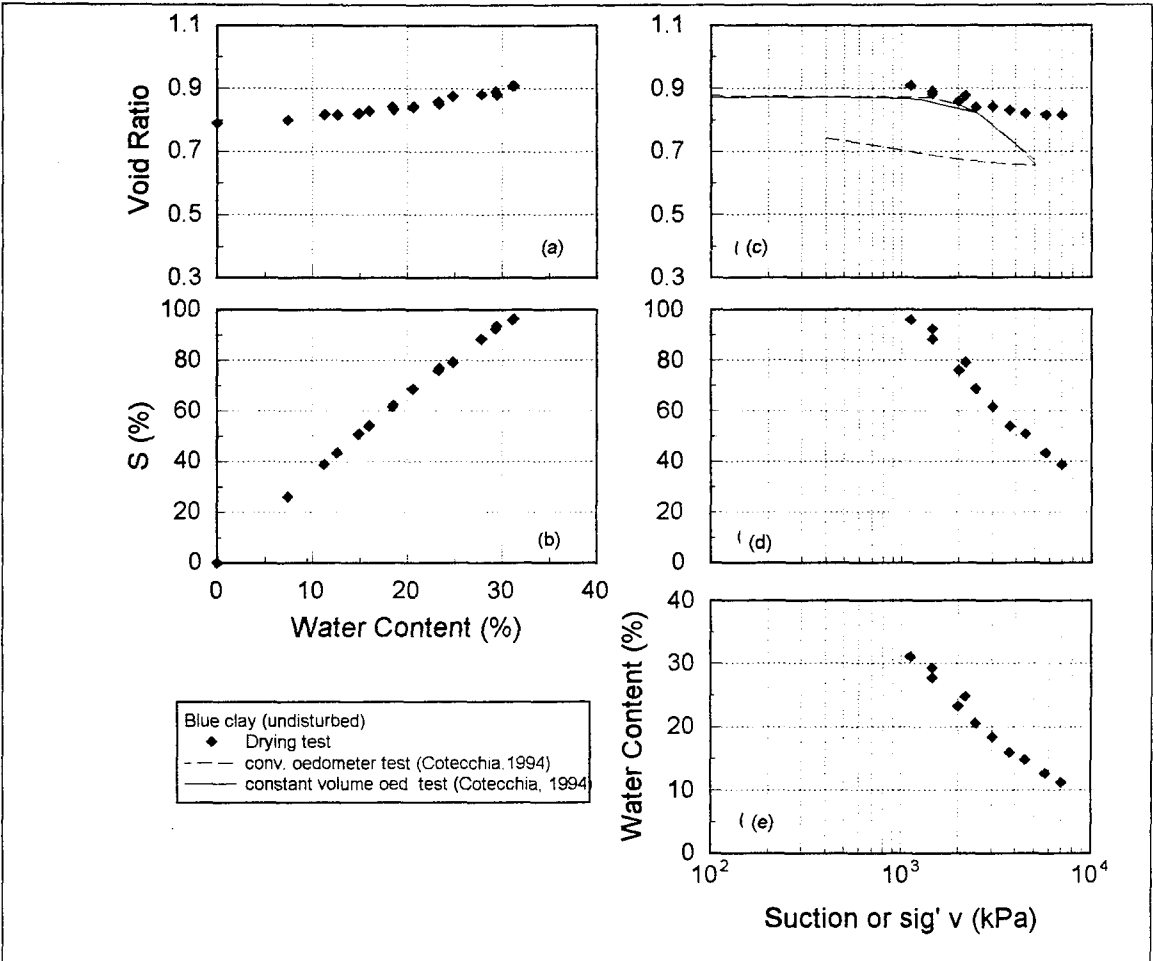


Figure 7.94 - Drying behaviour of a blue clay sample plotted against common axes of water content and suction.

The test on the Blue clay started with a suction which is higher or equal to the suction at the general air entry (GAE) point. In this case a suction capacity of 26% may refer to the virgin desaturation line. For lower values of suction the suction capacity is expected to be lower if the sample is over consolidated with an overconsolidation pressure equivalent of the suction at the GAE point.

Since shrinkable soils can sustain very high suctions without desaturation occurring, it is expected that mechanical consolidation up to the desaturation pressure is equivalent to overconsolidation due to drying. In this case the "virgin desaturation line" may be unique for the soil. When the "effectiveness" of the suction differs from the effective mechanical pressure the

"virgin desaturation line" will not be the same. Similar conclusion may be drawn from results using kaolin, presented by Ridley (1993).

7.4.1.2.1. Matrix and Total Suction

Both total and matrix suction were measured in two samples of undisturbed London clay from Chattenden. The results are presented in Figures 7.95 and 7.96. The initial osmotic suction obtained was 110kPa and 250kPa for samples LCU-T1 and LCU-T2, respectively. The suction capacity for each of those samples is presented in the figures. Figure 7.97 presents the relationship between water content and suction for two previously discussed samples (LCU-T1 and LCU-T2) and also the results obtained with the sample (LCU-H1) used for evaluation of the contact effect with the filter paper (see section 7.1.1.2). Using the results from these three samples two values of suction capacity are obtained, 8.1% for suctions below 3.5MPa and 19.4% for suctions above 3.5MPa.

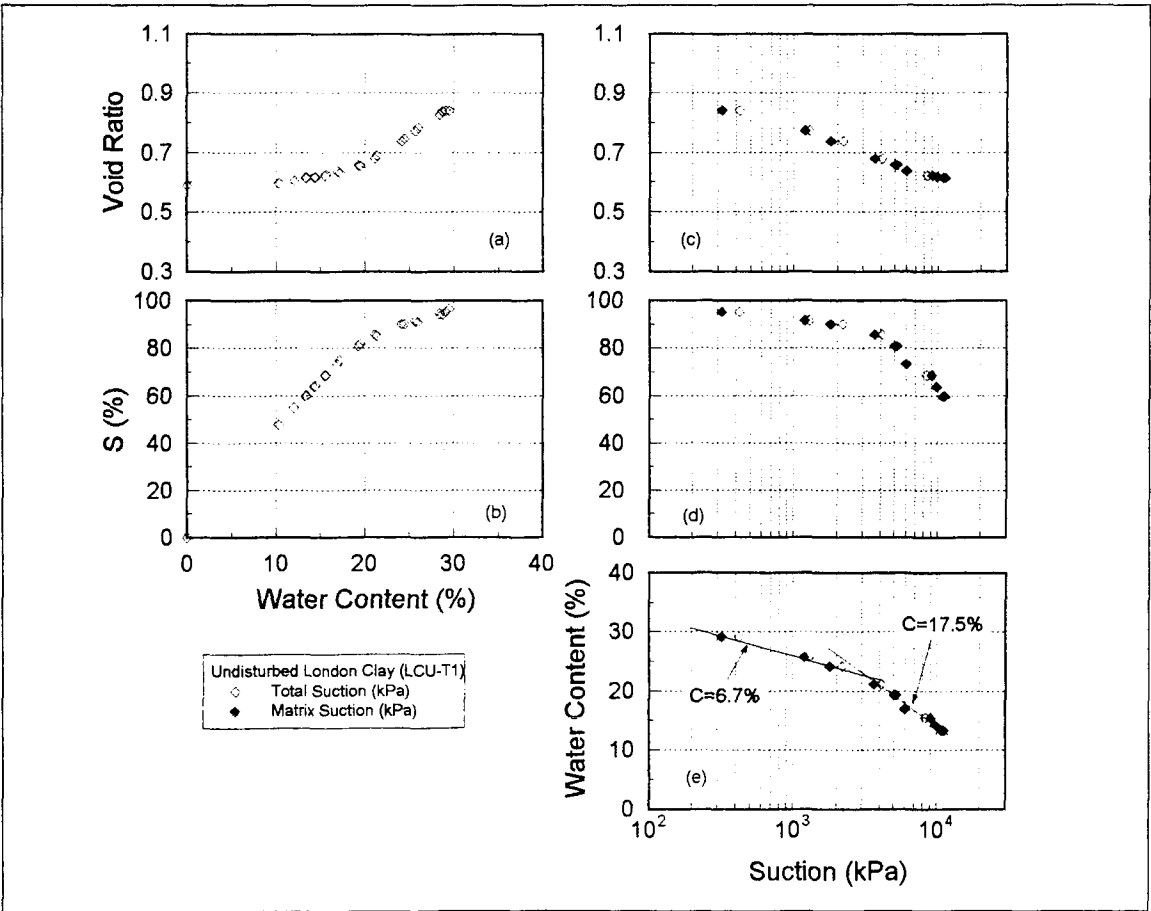


Figure 7.95 - Drying behaviour of undisturbed London clay plotted against common axes of water content and matrix and total suction.

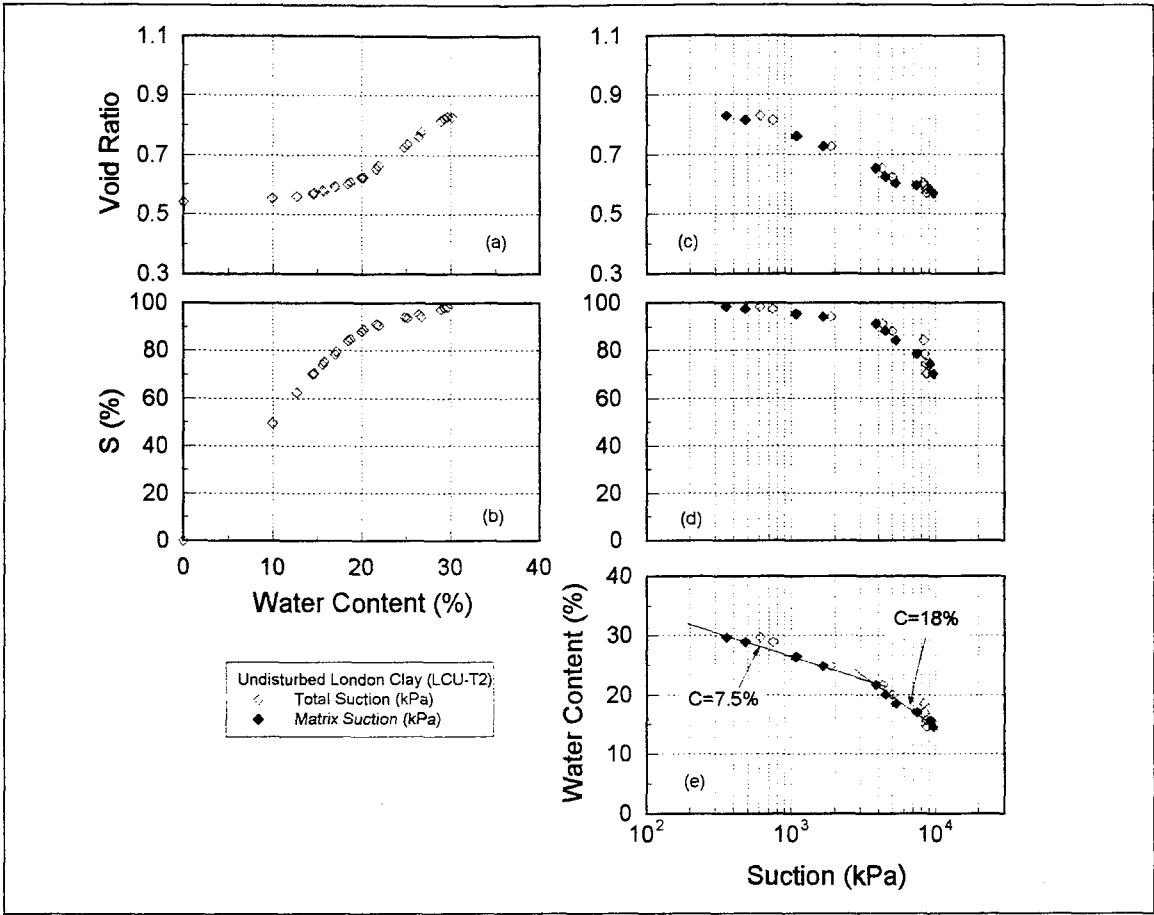


Figure 7.96 - Drying behaviour of undisturbed London clay plotted against common axes of water content and matrix and total suction.

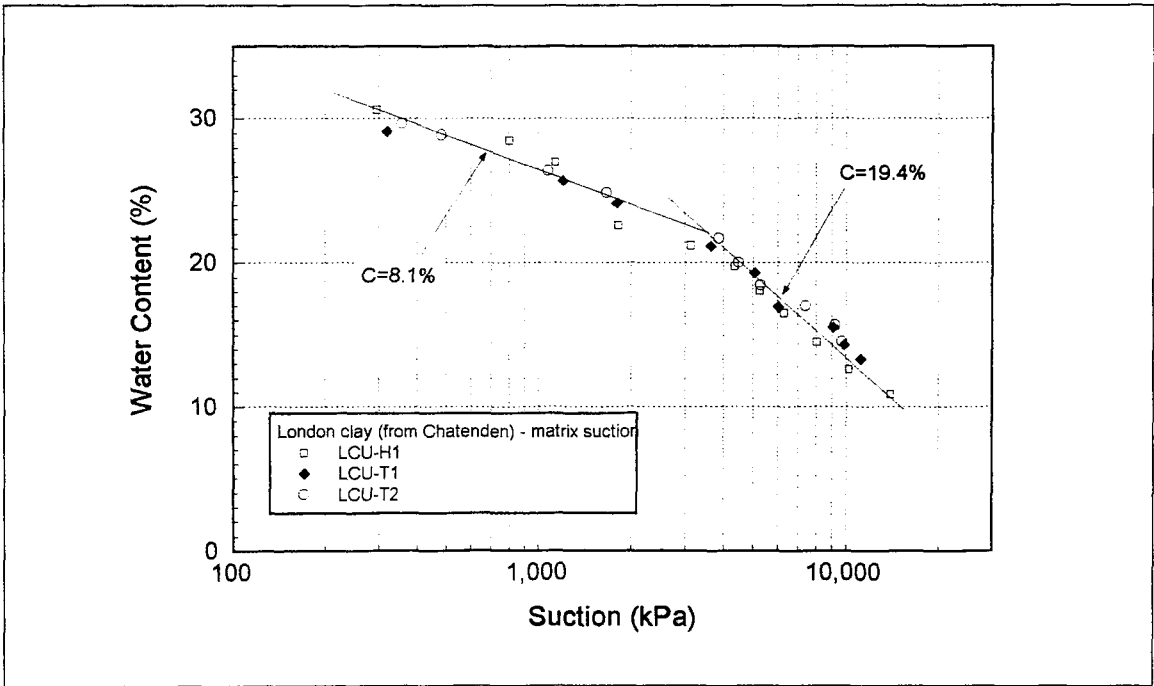


Figure 7.97 - Relationship between water content and suction from London clay samples.

7.4.1.2.2. Wetting Using Water Vapour

The results of suction measurements on the chalk sample are presented in figure 7.98. The sample exhibits practically no volume change during the wetting and drying processes. The relationship between degree of saturation and suction shows a steep gradient for suctions below 1MPa, reducing, in the log plot, with increase in suction. The residual degree of saturation (S_r) of the sample is close to zero, which means that the effective degree of saturation (S_e) is equal to the degree of saturation (S) (see equation 5.11). The wetting process using water vapour gave results similar to the submerging technique. The penetration and condensation of the water vapour into the soil pores appeared to be equivalent to the penetration of water by capillary penetration. Although it was expected that a reduction in hysteresis would be observed using the water vapour technique for wetting, it was not possible to identify this.

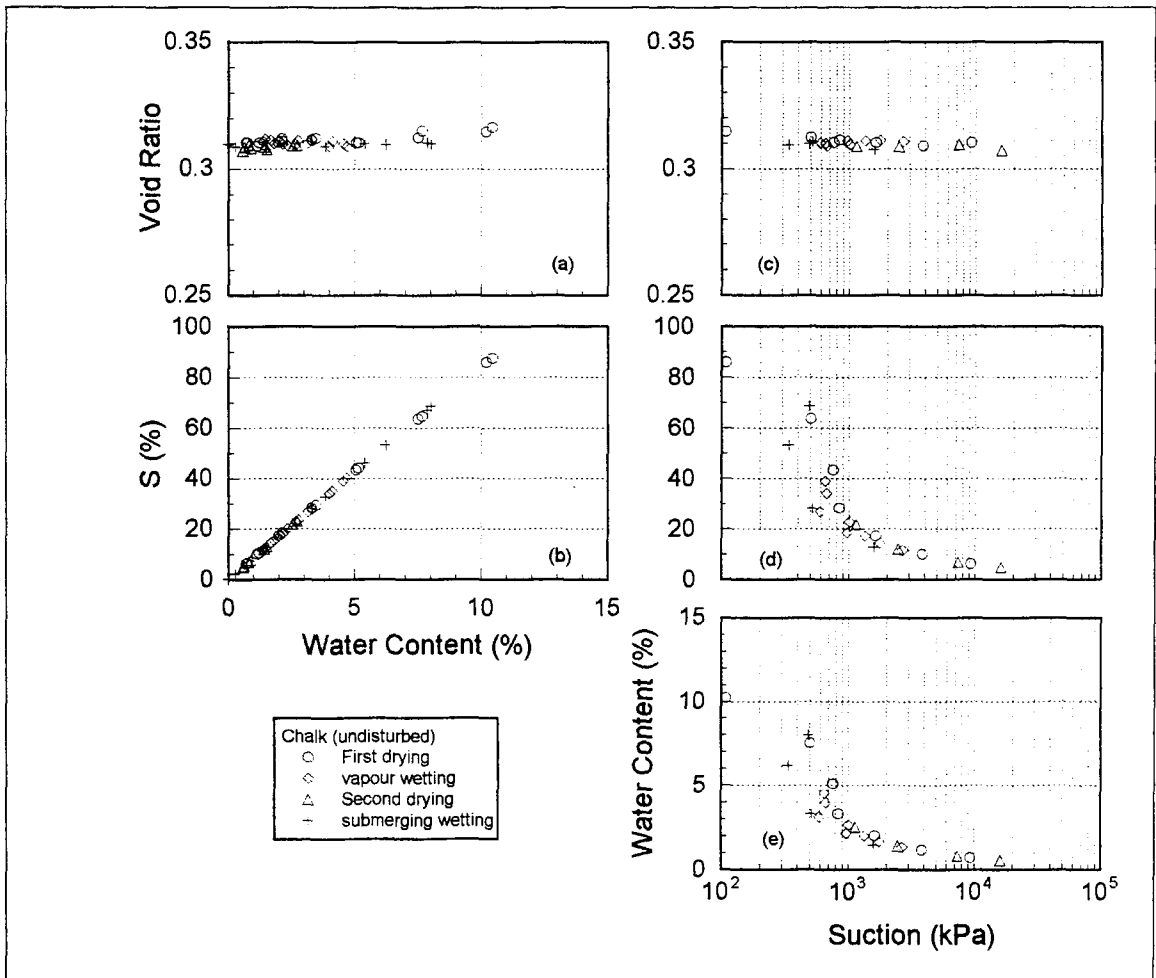


Figure 7.98 - Drying behaviour a chalk sample plotted against common axes of water content and suction.

7.4.2. Using a Model for Inferring the Pore-size Distribution

The model proposed by Books and Corey (1966) is used (see section 5.3.3.3) in order to evaluate the pore size distribution of some of the soils tested,

Figure 7.99 presents the relationship between effective degree of saturation and suction, for samples of London clay from Chattenden obtained at 2-2.45m in bore hole 51 and 52. Again the residual degree of saturation was assumed to be at the air dry state. The pore size distribution index (λ) and the suction at the air entry point ($(u_a-u_w)_b$), as defined by Books and Corey, is 1.76 and 6815kPa, respectively. It was not possible to use the model for the depth 1-1.45m due to the small number of experimental points obtained at high suction.

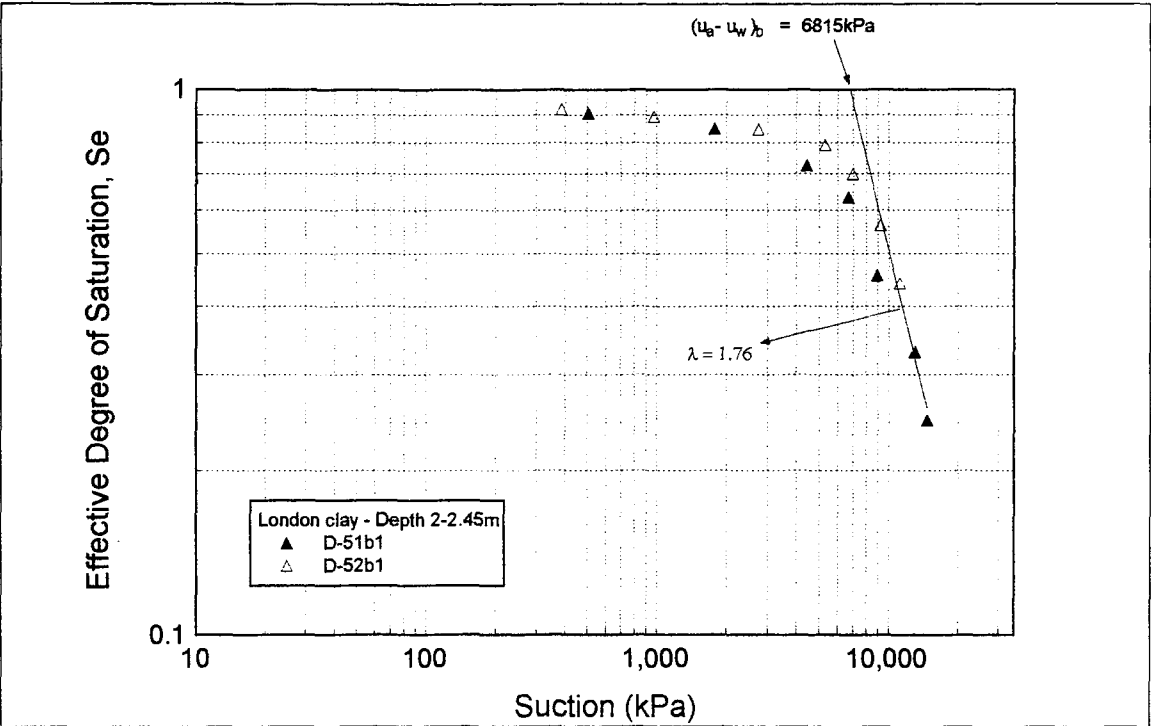


Figure 7.99 - Relationship between the effective degree of saturation and suction showing the air entry value and the pore size distribution index (λ) for London clay at 2-2.45m.

Figure 7.100 presents the same relationship as figure 7.99 for the sample obtained at 3-3.45m. The pore size distribution index (λ) and the $(u_a-u_w)_b$ are, 1.24 and 4652kPa, respectively.

Figure 7.101 presents the results obtained with the 'old' undisturbed samples of London clay. The samples were divided in two groups according with their pattern observed in the plot. For samples lca1, lca2 and lca3, $\lambda = 1.21$ and $(u_a-u_w)_b = 7755 \text{ kPa}$. For samples lcb1, lcb2 and lcb3 $\lambda = 1.06$ and $(u_a-u_w)_b = 5510 \text{ kPa}$. The sample lcb4 was not considered in the analysis.

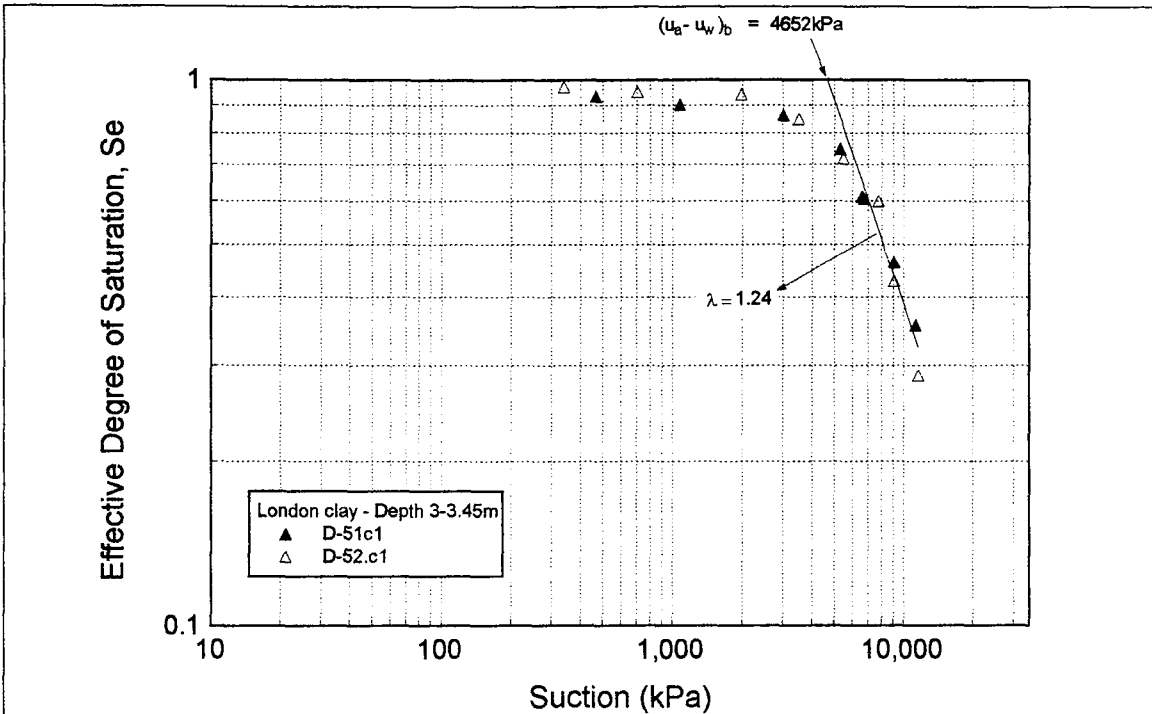


Figure 7.100 - Relationship between the effective degree of saturation and suction showing the air entry value and the pore size distribution index (λ) for London clay at 3-3.45m.

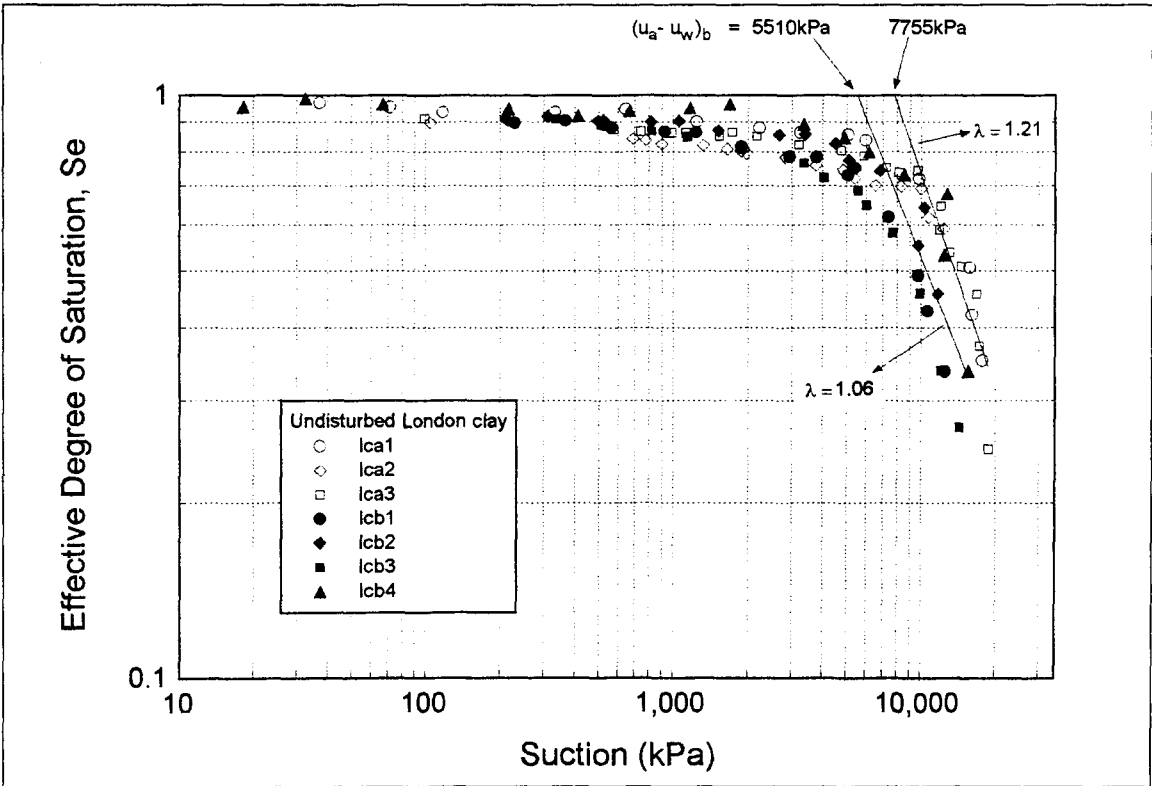


Figure 7.101 - Relationship between the effective degree of saturation and suction showing the air entry value and the pore size distribution index (λ) for the 'old' London clay samples.

The pore size distribution index (λ) for Blue clay was 1.14 and the suction at the air entry point was 1580kPa. (see figure 7.102).

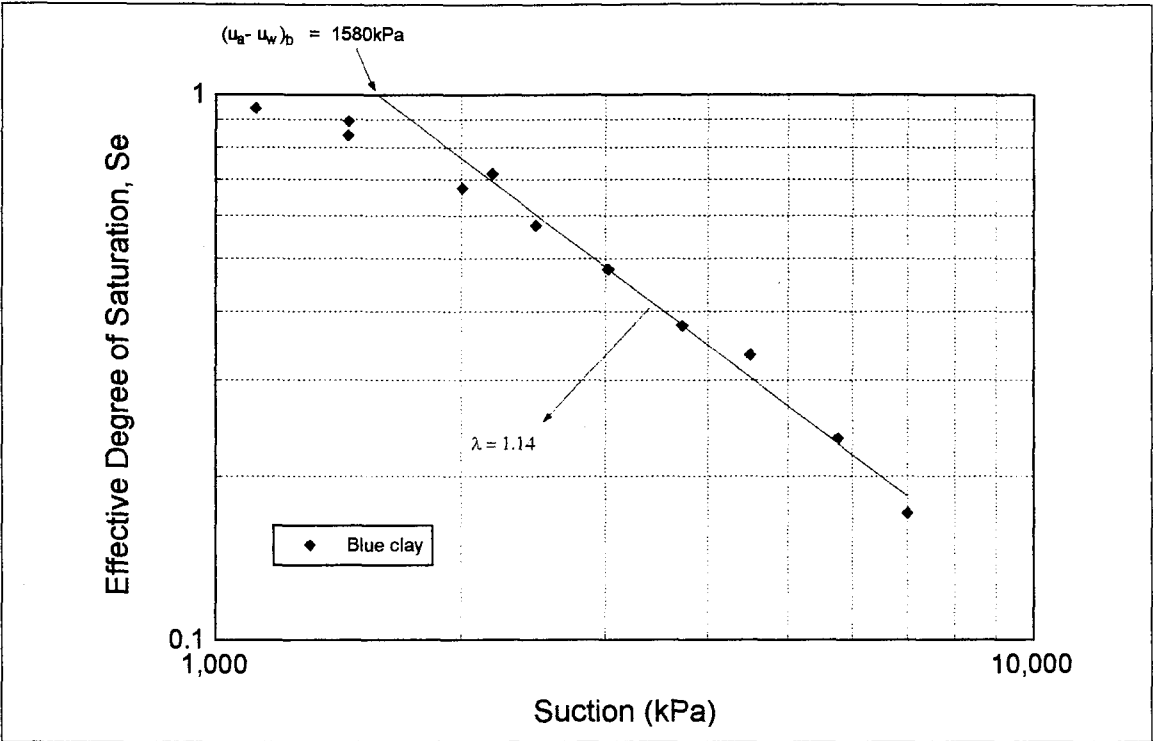


Figure 7.102 - Relationship between the effective degree of saturation and suction showing the air entry value and the pore size distribution index (λ) for the blue clay sample.

Table 7.13 presents the values of λ and $(u_a - u_w)_b$ obtained. It can be seen that the suction at the air entry point varies considerably and is not related to the pore size distribution index. The suction at the air entry point seems to indicate the dominant pore size of the samples. Blue clay has a much wider range of pore sizes than the London clay from Chattenden, and it yielded the lowest value of $(u_a - u_w)_b$.

Sample	λ	$(u_a - u_w)_b$ (kPa)
London clay D-51b1 D-52b1	1.76	6815
London Clay D-51c1 D-51c1	1.24	4652
London clay lca1, lca2, lca3	1.21	7755
London clay lcb1, lcb2, lcb3	1.06	5510
Blue clay	1.14	1580

Table 7.13 - Pore size distribution index and suction at the air entry point for undisturbed samples.

7.4.3. Suction Capacity

Figure 7.103 shows the relationship between the suction capacity, obtained in the first linear segment of the relationship between water content and suction, and liquid limit. It is also presents some results from the literature. The Croney and Coleman results refers to London clay (LL = 78%) and a silt (LL= 41.5%). It can be observed that overconsolidated soils tend to present lower suction capacities. The samples of Blue clay and Queensborough clay gave very high suction capacities, more comparable to those obtained from slurried samples.

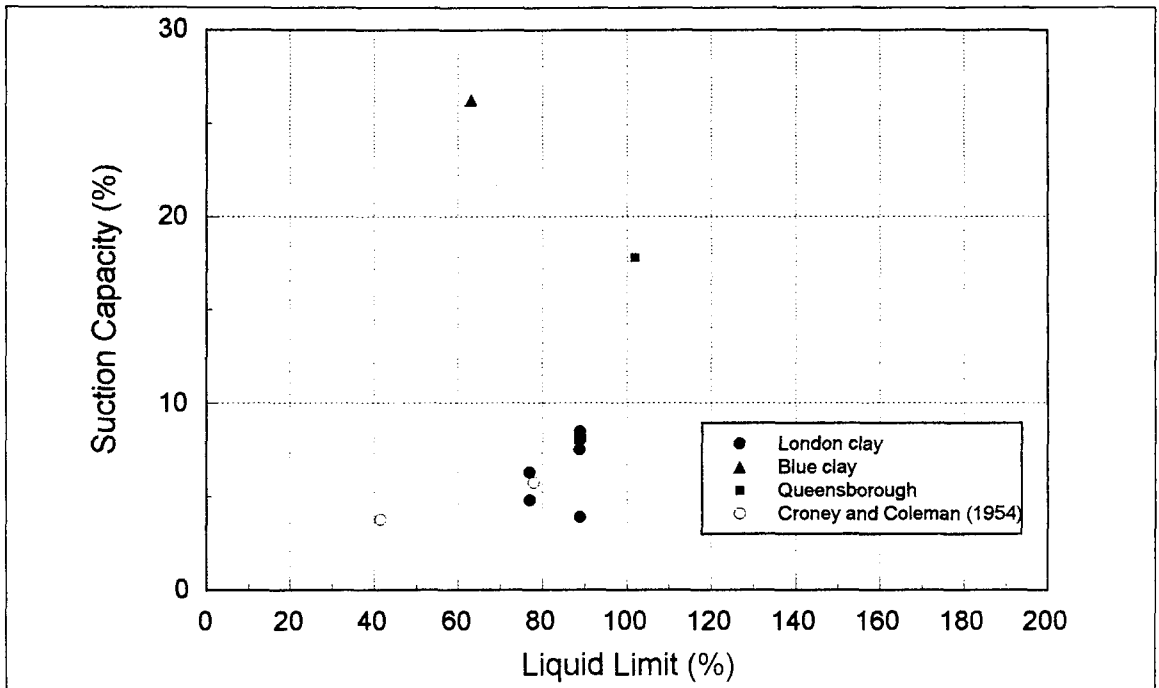


Figure 7.103 - Relationship between suction capacity and liquid limit for the undisturbed samples.

7.4.4. Initial Degree of Saturation, Final void ratio and Suction

Figure 7.104 presents the relationship between final void ratio versus initial degree of saturation and initial suction. The samples started from a high degree of saturation showing a high sensitivity to the initial degree of saturation. The relationship between final void ratio and suction showed an increase in the final void ratio with the increase in the initial suction.

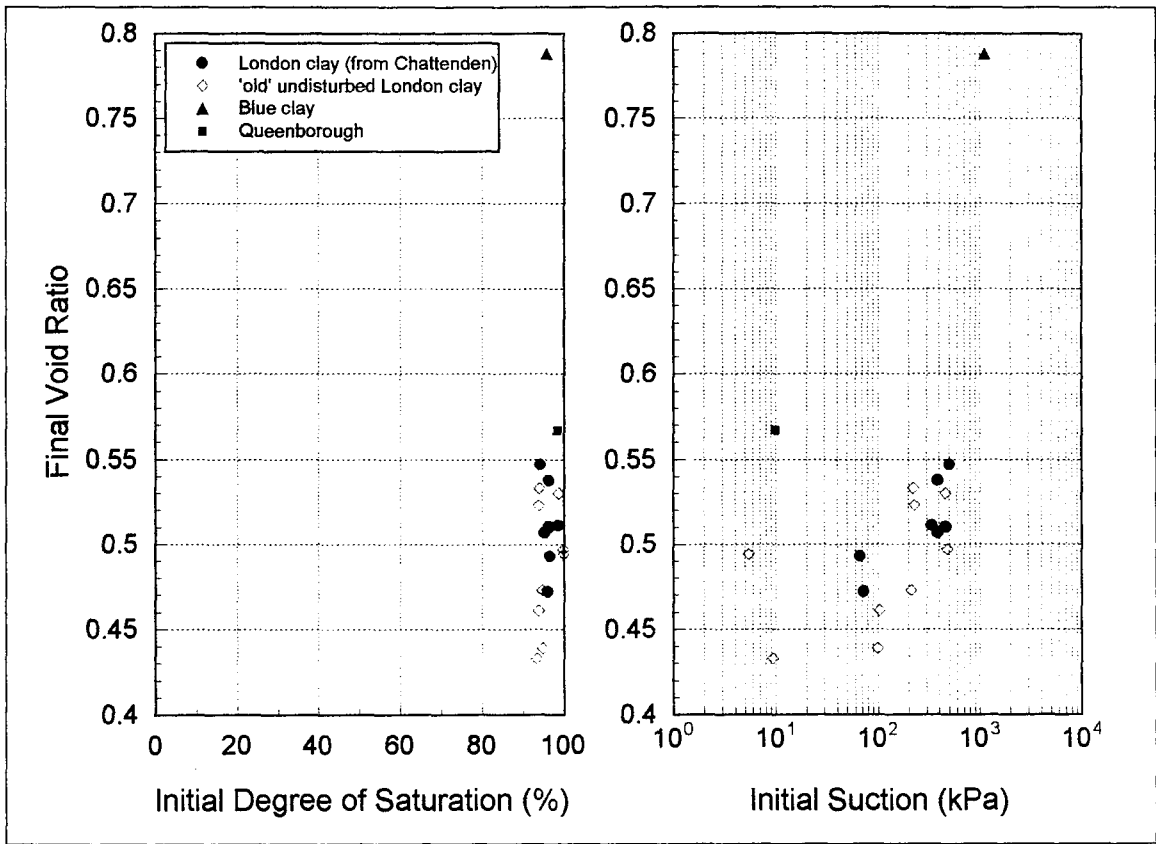


Figure 7.104 - Relationship between final void ratio, initial degree of saturation and initial suction for the undisturbed samples.

7.5 Drying Test on Continuously Disturbed Soils

In order to investigate the relationship between water content and suction on samples with a high degree of disturbance, as suggested by Croney and Coleman (1954), drying tests were carried out on continuously disturbed samples. Disturbance was imposed before each suction measurement was taken. After reworking the samples (Section 6.2.5) they were left to equalise for 7 days.

Figure 7.105 presents the results obtained with a sample of kaolin. Data from Ridley (1993) are also included for comparison. Ridley performed a series of unconfined compression tests on statically compacted samples of kaolin, and the pre-shear and failure conditions for each sample are shown. The drying curve for kaolin (Ridley, 1993) is from a slurried sample. The initial conditions of the sheared samples are very close to the drying curve of the slurried sample.

In part *e* of figure 7.105 the drying curve of the continuously disturbed sample is shown. It can be seen that the continuously disturbed curve tends to converge to the drying curve of the slurried sample at high suctions (approx. 1MPa), and that the suction for the continuously disturbed sample is much lower than the suction for the drying curve of the slurried sample at the same water content. This is in accordance with the observations of Croney and Coleman (1954). Although the suctions at failure reported by Ridley are lower than the initial suctions; they are still very different from the continuously disturbed curve.

The measurement of the suction of the sheared samples were made with the probe tensiometer (Ridley, 1993; Ridley and Burland, 1993), located at the base of the sample; so thus the suction recorded may not be the suction at the failure plane. This will be particularly the case for samples with a degree of saturation below 80%.

Figure 7.106 presents similar results for samples of Queensborough clay. The drying curve for the continuously disturbed sample is located to the left of the drying curve for the undisturbed samples. For suctions up to 100kPa the two curves are approximately parallel. There is a tendency for the two curves to converge at a suction of approximately 5MPa.

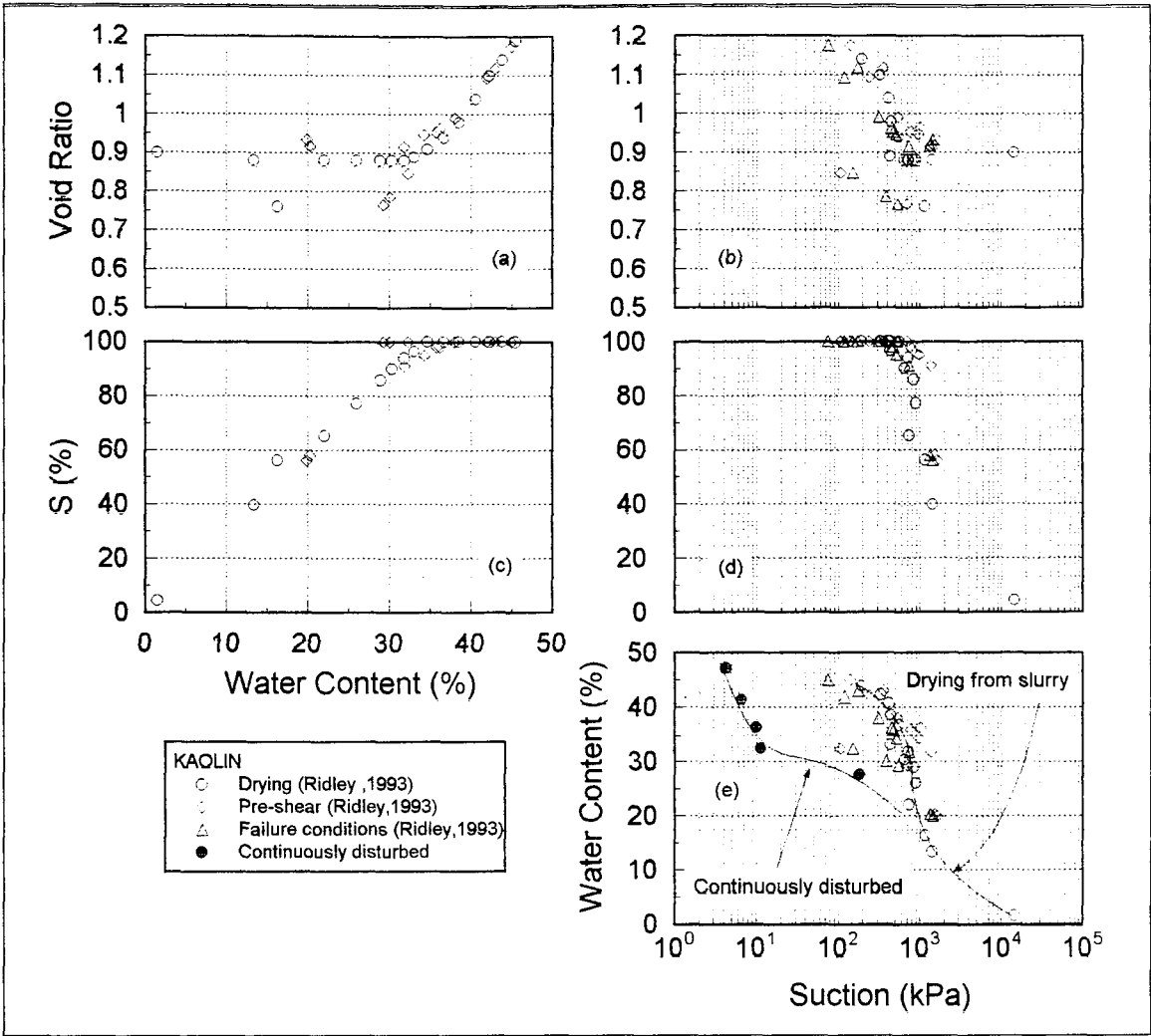


Figure 7.105 - Drying curves of continuously disturbed sample and slurried sample of kaolin and results from literature showing the pre-shearing and at failure conditions.

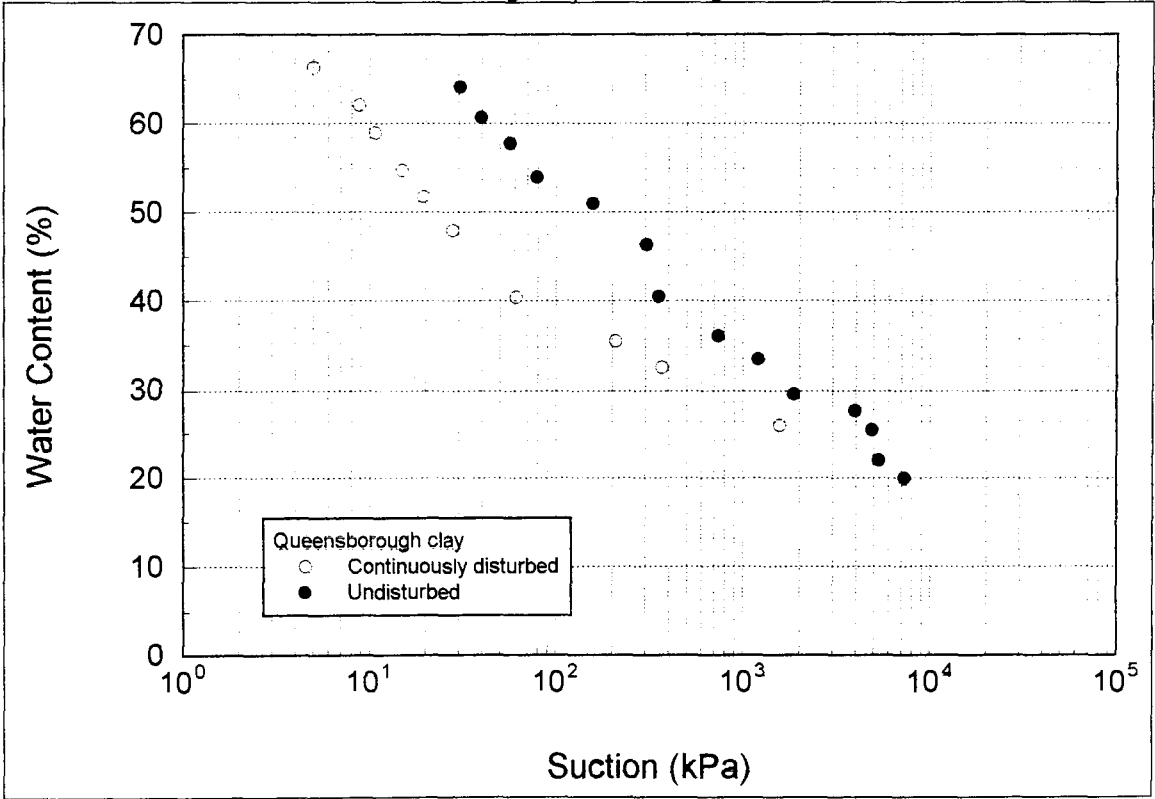


Figure 7.106 - Relationship between water content and suction for continuously disturbed and undisturbed Queensborough clay.

7.6 Global Analysis

7.6.1 Suction Capacity versus Liquid Limit

The relationship between suction capacity (C) and liquid limit for all the samples tested are shown in figure 7.107. Also included are results obtained from the literature.

Although some scatter is observed, the suction capacity for slurried samples agrees reasonably well with the results of Burland (1990) for one-dimensional consolidation. The results from undisturbed samples, most of them heavily overconsolidated, seem to suggest a lower boundary for the suction capacity/liquid limit relationship. Some undisturbed samples show a very high value for C, suggesting normally consolidated behaviour. One of the samples (sub-appenine blue clay) is above the upper limit of the slurried soils, showing the extreme compressibility of a collapsing bounded clay.

Statically compacted and dynamically compacted samples are located between these two limiting boundaries. The statically compacted samples present greater variability, probably due to the differences in stress history imposed by this type of compaction.

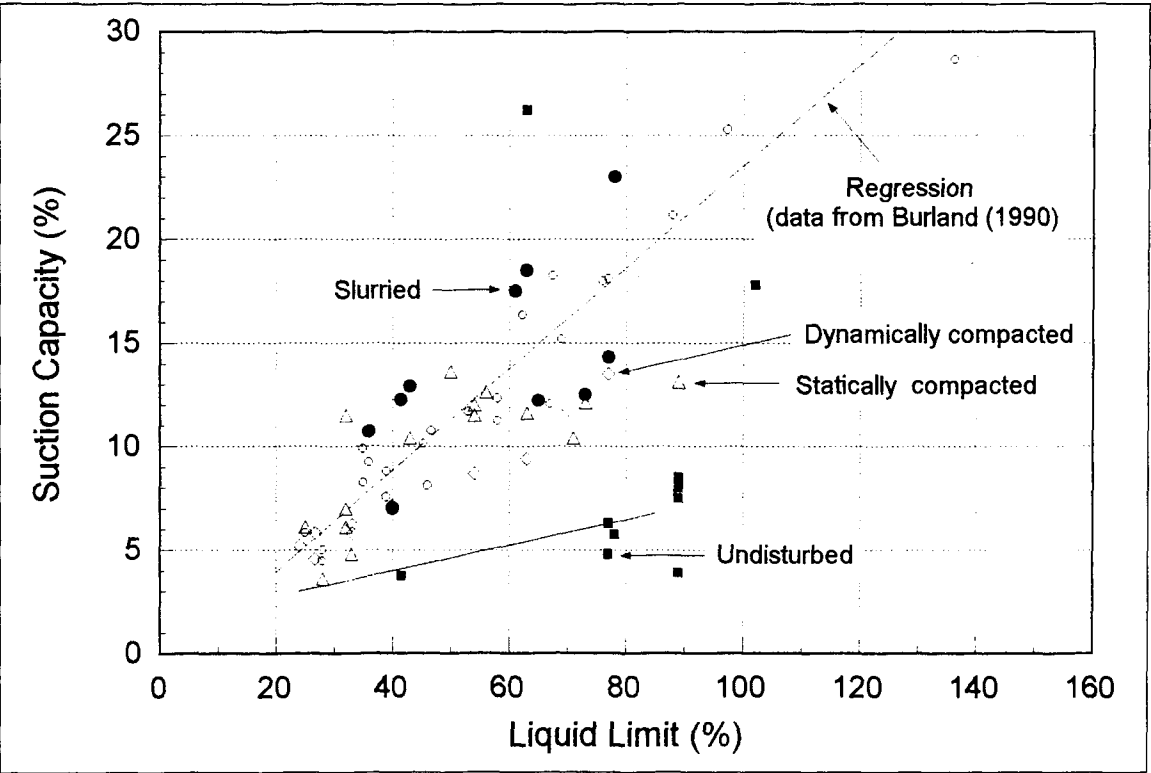


Figure 7.107 - Relationship between suction capacity and liquid limit for different types of samples.

7.6.2 - Compacted Samples

Vaughan (1977) suggested that the initial structure, and hence the behaviour, of compacted soils is controlled by the relative proportions of the saturated clay lumps. He said *"[in the field] the higher the proportion of saturated lumps, the more the compacted clay behaves like the same clay in an intact state, and the lower the proportion the more it behaves like remoulded clay"*.

Figure 7.108 presents a comparison of "one point" and drying tests suction measurements on undisturbed samples and statically compacted samples of London clay. The statically compacted samples were prepared in two ways, one by reconstituting soil passing through the n°40 sieve (sample LCST7) and the other by compacting "undisturbed lumps" of London clay (Cunningham, 1993). Two drying tests are plotted in the figure, one for an undisturbed sample (D51a1(1-1.45m)) and the other the statically compacted reconstituted sample (LCST7).

Figure 7.108 shows that the statically compacted reconstituted sample differs from the undisturbed samples, giving different suction capacities. It seems clear that the statically compacted samples, in which fragments of undisturbed soil were used, agreed well with the undisturbed samples. This confirms that the "undisturbed lumps" are an important component in the behaviour of compacted samples, and that they seem to control the suction.

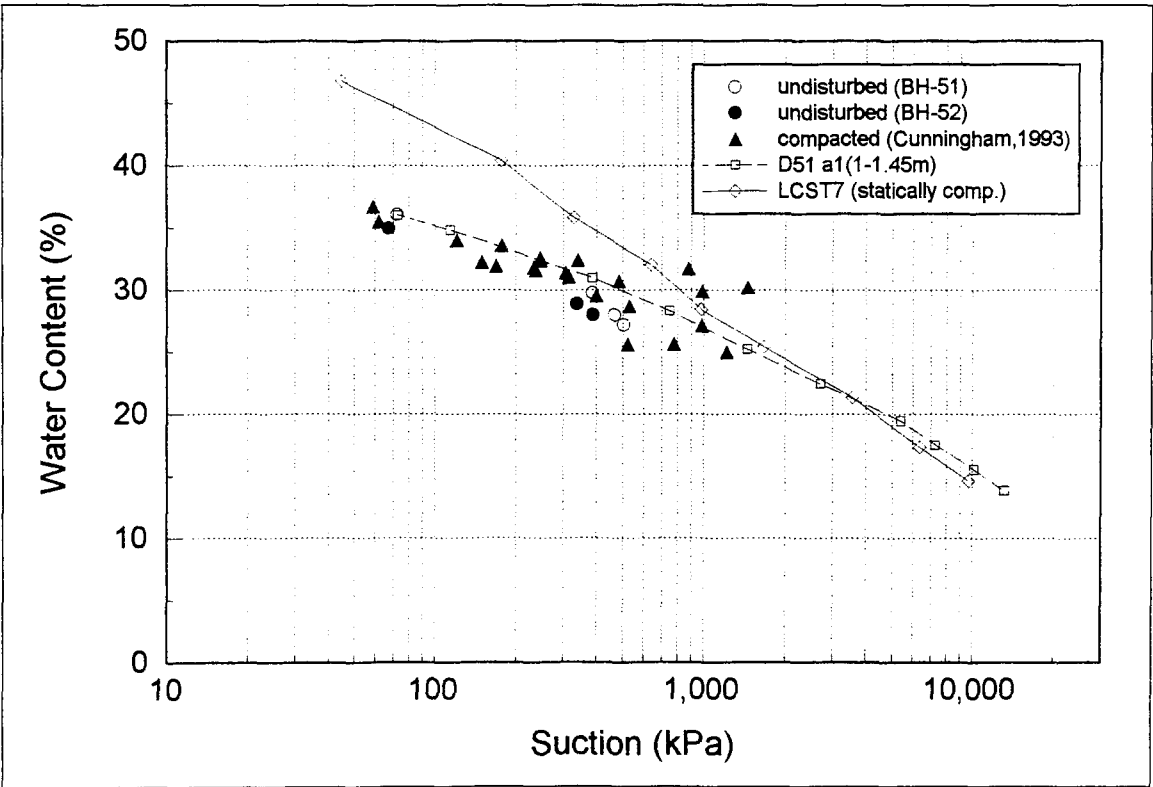


Figure 7.108 - Water content versus suction for different type of samples.

CHAPTER 8

Stiffness Measurement Using Bender Elements

8.1. Introduction

This chapter presents the result of a series of tests performed on statically compacted London clay. The soil stiffnesses were obtained using piezoceramic bender elements on unconfined unsaturated samples. The soil suctions were obtained using the filter paper technique. The results show that the suction is responsible for an increase in the shear modulus (G_{UBE}) up to a point where G_{UBE} decreases or remains constant until the soil is air-dry. The importance of taking the suction into account when measuring stiffness using wave propagation methods is confirmed.

The factors affecting the stiffness of soils are discussed by Tatsuoka and Shibuya (1992) and Lo Presti *et al.* (1993). The stiffness of saturated or dry soils is intrinsically linked with inhomogeneity and anisotropy of the material. Factors affecting the determination of the stiffness of saturated or dry samples include: sample disturbance, strain level or shear stress level where the stiffness is determined, stress path during consolidation and shearing and method of loading (cyclic or monotonic, drained or undrained).

Some saturated soils can sustain high suctions without desaturating. In such a situation the matrix suction can be directly related to the mean effective stress in the soil. For unsaturated soils, all the factors mentioned above which affect the soil stiffness are still valid. However, the stress state of the soil depends on the value of matrix suction and the mean effective stress in unsaturated soils is not equivalent to the soil suction.

Dynamic wave propagation methods can be used to obtain soil stiffness. Using a pair of bender elements, shear waves can be generated and detected (e.g. Dyvik and Olsen, 1989; Viggiani and Atkinson, 1994). This dynamic test is normally related to very small strains in soil and rocks (Tatsuoka and Shibuya, 1992). Dyvik and Olsen (1989) and Porovic and Jardine (1994) showed that the shear moduli at very low strain levels obtained using bender elements are equivalent to those obtained using resonant column tests and triaxial tests, for saturated or dry soils.

Barden *et al.* (1969) studied the volume change characteristics of unsaturated clays using a suction controlled oedometer cell. They observed that matrix suction increases the stiffness of the soil with a flocculated structure, compacted dry of the optimum water content. For soils compacted wet of the optimum, having a dispersed structure, the matrix suction has little effect

on the compressibility. An increase in the net normal stress ($\sigma - u_a$), increases the soil structure stiffness despite the type of soil structure.

Edil *et al.* (1981) showed that the initial tangent modulus (E_t), obtained in unconfined compression tests, is function of the initial matrix suction of the sample tested. The value of E_t generally increases with increasing matrix suction up to a critical value, beyond which it exhibits a decrease. Similar behaviour was observed concerning the dynamic shear modulus (resonant column test). Two samples (kaolinitic clay) with different structure (*i.e.* highly oriented fabric and highly random fabric) presented a critical suction in relation to the dynamic shear modulus, of approximately 400kPa. The unconfined strength increases rapidly with increasing matrix suction, without any noticeable change in behaviour at or above the critical suction.

Wu *et al.* (1984) and Qian *et al.* (1993) presented a study showing the effect of void ratio, confining pressure, grain shape and grain size distribution on the shear moduli of unsaturated sands. The shear moduli (G_{max}) were obtained using a resonant column test. In their experiments no suction measurements were performed. Instead, the degree of saturation (S) was used to infer the capillary effect on the shear modulus. Their results show that G_{max} increases as the degree of saturation reduces, up to a maximum value, and then decreases until the dry condition ($S=0\%$) is reached. The value of S at the maximum value of G_{max} was called the optimum degree of saturation ($S_{r(opt)}$). The optimum degree of saturation represents the point where the contribution of the suction reached its maximum. Qian *et al.* (1993) showed that the relation between the shear modulus of moist and dry soil (shear modulus ratio) increases with decreasing particle size. The soils they tested were uniform angular sands and subrounded sands with identical void ratios. It was observed that the optimum degree of saturation and the maximum shear modulus ratio is affected by the grain shape. The maximum shear modulus ratio was found to increase as the proportion of fine particles in the sand increased.

This chapter describes an attempt to relate soil suction to stiffness of unconfined unsaturated clay soil samples. A stiffness parameter called G_{UBE} is defined. The degree of saturation is correlated with the suction and G_{UBE} , in order to describe the behaviour of statically compacted London clay subjected to drying.

8.2. Test Method

The tests were performed at the Building Research Establishment (BRE) soil mechanics laboratory, using a conventional hydraulic triaxial cell in which a pair of bender elements have been installed. The soil used was London Clay from Chattenden. The samples were prepared by static compaction. Four samples were compacted at different initial water contents and void ratios. Four distinct values of suctions were obtained. The initial conditions of each sample are

presented in table 8.1. The samples had a diameter of 10cm and different heights. An undisturbed sample was also tested. The bender elements were installed into the top and bottom platens of the triaxial apparatus. The samples were fairly stiff and the bender element could not be pushed into the soil. Therefore, slots were required on the top and bottom of each sample, in order to accommodate the bender element. The bender elements were excited with a square pulse wave.

Sample	Water Content (%)	Void Ratio	Degree of Saturation (%)	Initial Suction (kPa)
1	21.7	0.716	83	1900
2	26.5	0.758	96	859
3	31.5	0.89	97	370
4	41.8	1.215	95	60
undisturbed	29.7	0.849	96	273

Table 8.1 - Initial characteristics of the samples.

The suction measurement were made using the filter paper technique, described in section 6.3.1. Five filter papers (Whatman N° 42) were placed in direct contact with each soil sample. The average of the five values thus obtained was assumed to be the suction of the sample for that stage. The samples were wrapped in two layers of "cling film" and left for 7 days to reach equilibrium. Following the removal of the filter papers on the seventh day, the samples were kept wrapped in "cling film". The slots in the samples were protected by the "cling film" and then filled with a soil slurry. This procedure were used to obtain a coupling between the bender element and the soil samples. Changes in the specimen's suction is avoided by isolating the slurry from the sample with the layer of "cling film". In this way, no change in soil suction is expected.

The samples were mounted on the base of the triaxial cell and the top cap placed on top of the sample. No confining stress was applied. A mass of 1.2Kg was placed on the top cap to keep the top bender element in place.

The small strain shear modulus (G_0) is related to the shear wave velocity (v) by

$$G_0 = \rho v^2 = \rho \frac{L^2}{T^2},$$

where ρ is the density of the soil, L is the effective travel length between the bender element that serves as a transmitter and that which functions as the receiver. The variable T is the travel time. The main source of error in bender element testing is the determination of the travel

length and time. The density can be obtained with reasonable accuracy (Viggiani and Atkinson, 1994).

In this investigation the travel lengths were assumed to be between the tips of bender elements. The arrival time of the shear wave was obtained as shown in figure 8.1. The shear modulus of the unsaturated specimen, thus obtained using the bender elements is termed by G_{UBE} .

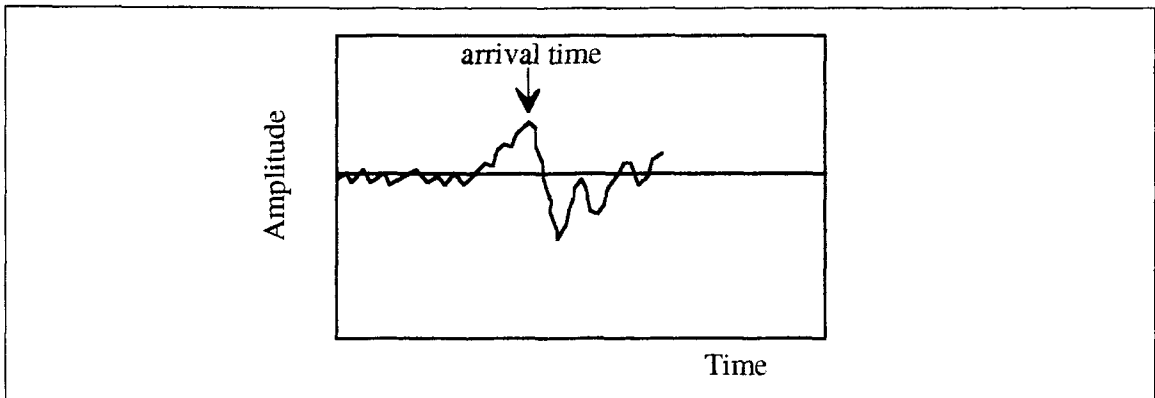


Figure 8.1 - Arrival of the shear wave (schematic).

8.3. Results and Discussion

Suction increase in a highly plastic soil is accompanied by a decrease in soil volume, and it is this volume change that results in a change in the shear modulus, if the soil is saturated. However, if the soil is unsaturated the direct relationship between suction and shear modulus may not exist. In this case the arrangement of the soil particles changes during each increment of suction, up to the shrinkage limit. Thereafter, the arrangement of soil particles remains unchanged. The interpretation of tests involving the measurement of soil stiffness in unsaturated soils is, therefore, more complex.

Figure 8.2 shows three interrelated plots which describe the behaviour of the tested samples. On figure 8.2a the initial states of the samples are indicated (arrows) and the optimum water content is shown (AAHSHO/BS Heavy Compaction Test). Figure 8.2b shows the results in terms of void ratio versus suction. The final points were obtained by air drying the samples in the laboratory at a relative humidity assumed to be 60%. This gives a equivalent suction of approximately 69MPa. The relation between G_{UBE} and suction is given in figure 8.2c. It can be seen that G_{UBE} initially increases with suction, until a maximum is reached and then the shear modulus either starts to decrease or remains constant. The point where the maximum G_{UBE} is obtained appears to coincide with the general air entry (GAE) point described by Marinho and Chandler (1993). Below this point samples with the same value of suction gave different shear moduli because they had different void ratios. It can be seen that the curves in figure 8.2b are converging and the differences in void ratio between samples reducing. In figure 8.2c, it can be seen that the G_{UBE} tends to a constant value, independent of the soil suction. Correlating figures 8.2b and 8.2c it can

be notice that G_{UBE} stops increasing at about 2MPa, but at this level of suction the void ratio is still decreasing. This behaviour suggest that the reduction in void ratio does not control the shear modulus.

There are two hypotheses to explain this behaviour. One is that, as a result of suction increase, the water in the soil loses continuity and hence the suction within it is no longer able to generate an increase in effective stress throughout the whole sample. The other hypothesis is that the reduction in stiffness is a results of the creation of micro cracks in the soil sample. These cracks increase the path length of the shear wave, reducing the shear modulus. The micro cracks counter balance the reduction in volume, keeping the G_{UBE} constant. From figures 2b and c it can be observed that even during the shrinkage process (*i.e.* while the void ratio is reducing) the shear modulus, G_{UBE} , can reduce. The results from the undisturbed sample showed a much greater value for the shear modulus which probably reflects its different structure and stress history. It can be seen (figure 2) that the initial void ratio and suction of the undisturbed sample are similar to sample 3, although the G_{UBE} are different.

In figure 3a the degree of saturation is plotted against G_{UBE} . The optimum degree of saturation ($S_{r(opt)}$) described by Wu *et al.* (1984) can be identified. Sample 2 and 3 have approximately the same $S_{r(opt)}$; samples 4 and 1 have greater $S_{r(opt)}$. Qian *et al.* (1993) pointed out that for non-plastic soils the optimum degree of saturation increases with the increase of void ratio, with the amount of fine material and with the shape of the grains. The optimum degree of saturation observed in the tests performed here occurs at the yielding point of the relationship between degree of saturation and suction (figure 3b). This yielding point is a result of the general air entry. This suggests that the pore size may be an important factor in defining $S_{r(opt)}$ in plastic soils.

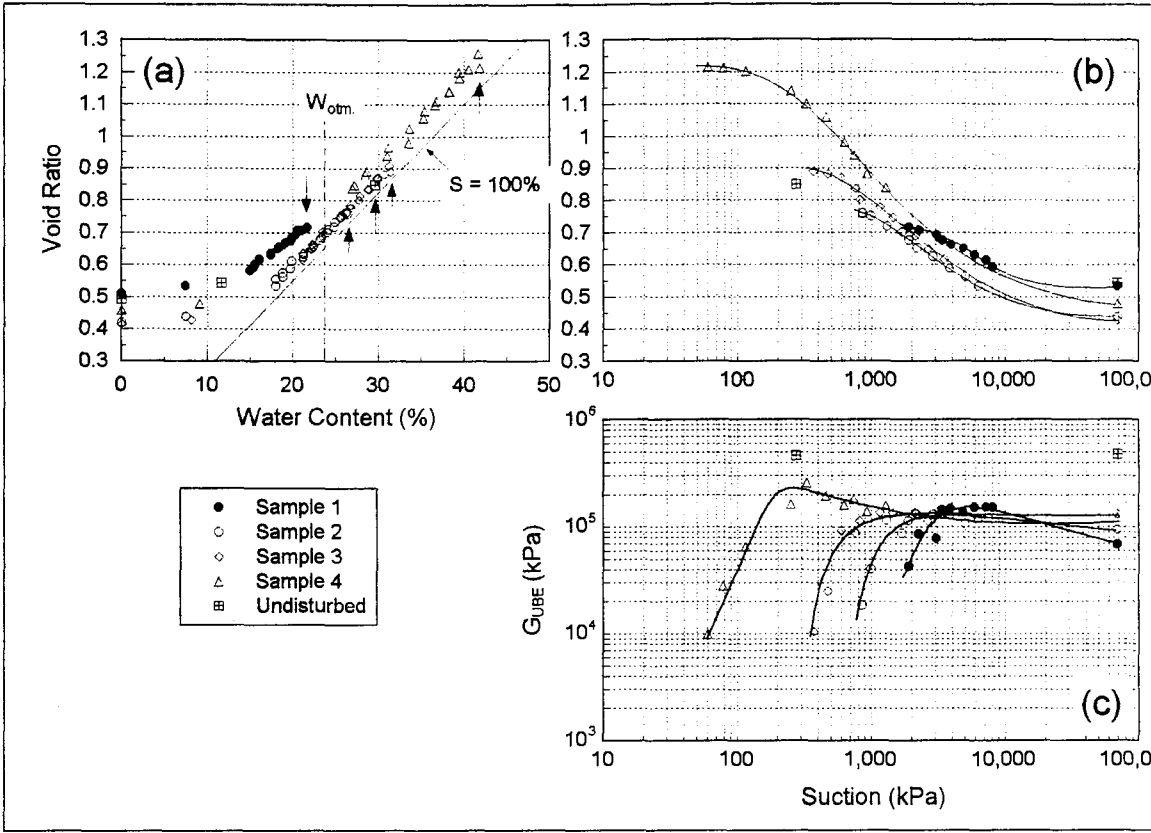


Figure 8.2 - Relationship between void ratio, water content, suction and G_{UBE} .

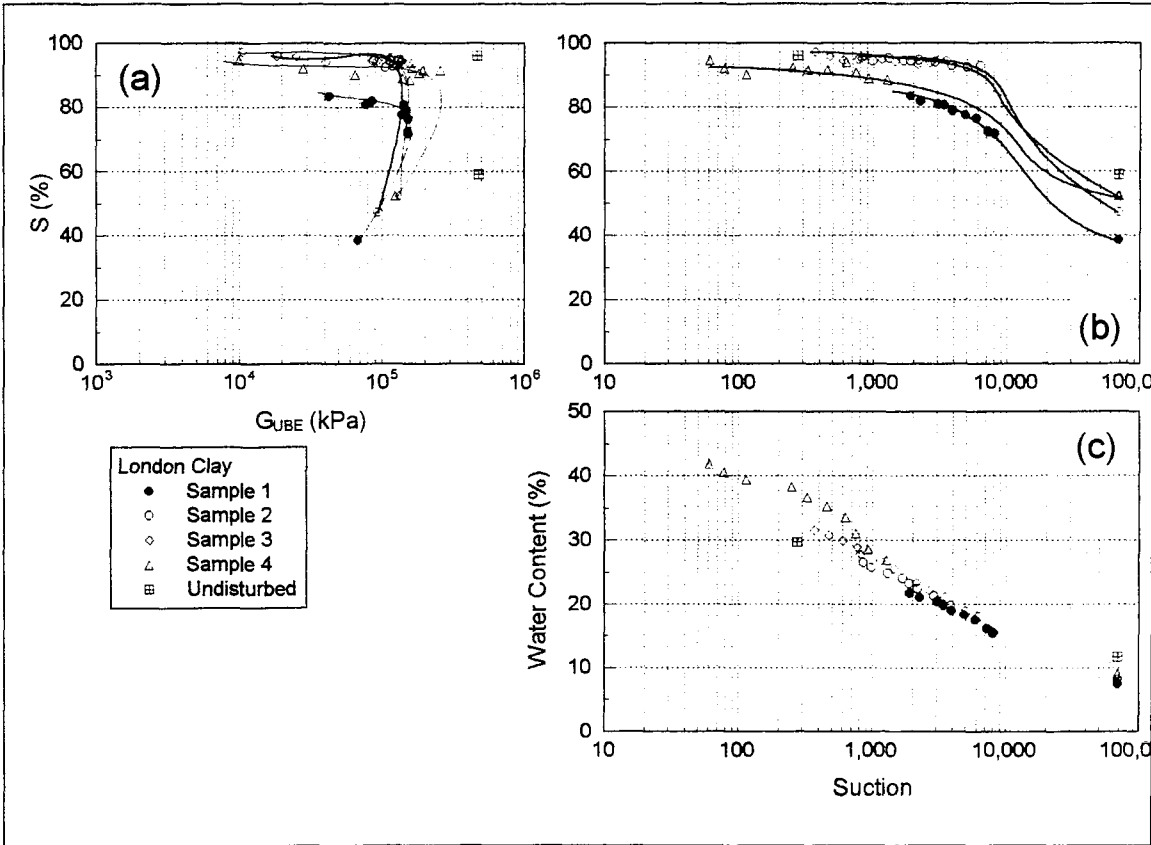


Figure 8.3 - Relationship between degree of saturation, water content, suction and G_{UBE} .

The relationship between water content and suction (figure 3c) does not show the yield point observed in figure 3b. This relationship is affected by the pore size distribution.

A three-dimensional representation of the variation of G_{UBE} with the void ratio and suction is shown in figure 8.4. The projections of the 3-D plot are also shown. The tendency of the shear modulus to converge to a unique value as the suction increases is shown. It can be seen that the decrease in void ratio is not followed by an increase in G_{UBE} for the whole of the drying process.

8.4. Conclusions

Suction can increase the stiffness of saturated and unsaturated soils and this should be taken into account when analysing soils with negative pore water pressure.

The increase in the shear modulus is due to the increase of suction and decrease of the void ratio. However, as a soil dries, a point is reached beyond which the void ratio is still reducing, and G_{UBE} decreases or remain constant. This observation suggests that the void ratio alone does not control the increase of the shear modulus of unsaturated soils. Up to the optimum degree of saturation, the increase in the shear modulus is mainly controlled by the increase in suction.

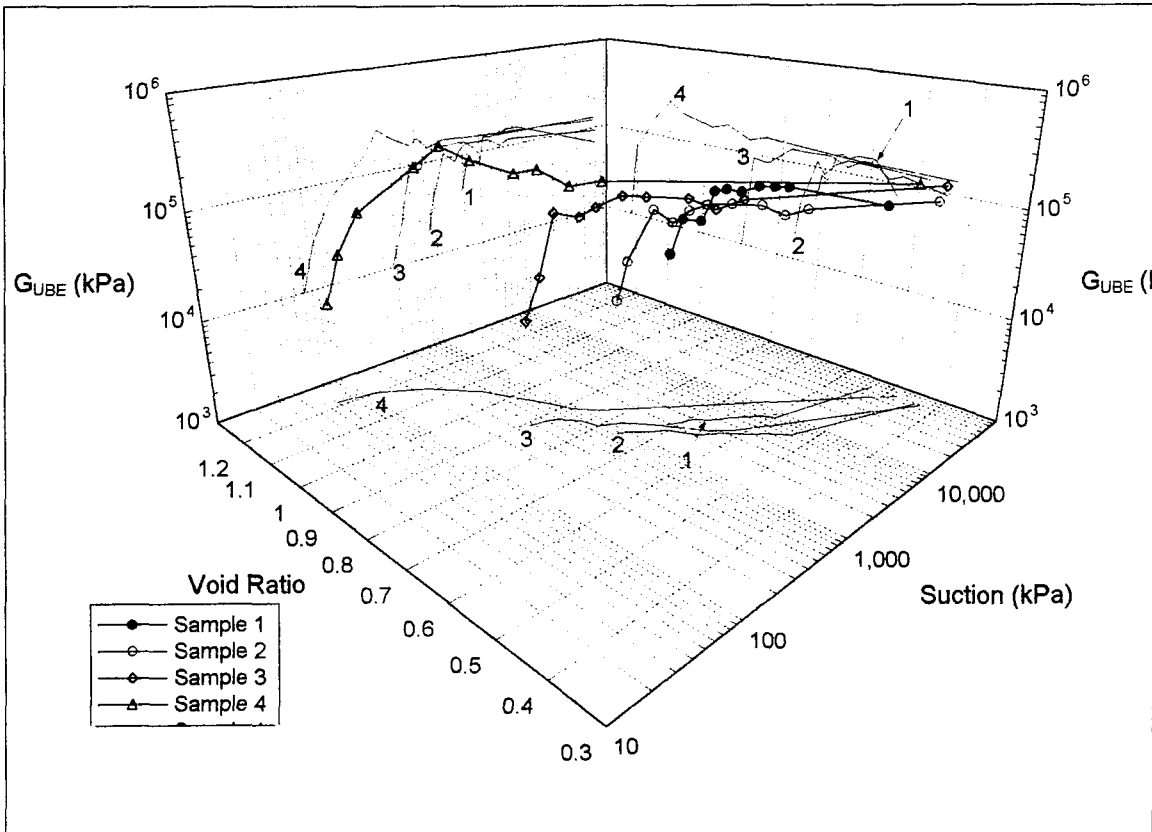


Figure 8.4 - Variation of G_{UBE} with suction and void ratio.

There exists a point, corresponding to the optimum degree of saturation, at which the shear modulus reaches a maximum. If drying proceeds beyond this point, the shear stiffness reduces or remains constant but the soil suction increases. The optimum degree of saturation therefore

marks the limit beyond which the measured suction is no longer effective. This can be inferred using the relationship between degree of saturation and suction. The results obtained in this study indicate that the optimum degree of saturation occurs at the general air entry point.

Although the increase in suction reduces the void ratio until the shrinkage limit, the shear modulus stops increasing well before this point. The effectiveness of the soil suction seems to be different for volume change and shear stiffness. Further research is required to confirm the observed behaviour.

CHAPTER 9

Conclusions

9.1 Literature review

A comprehensive literature review has been presented involving many topics related to unsaturated soils. The main conclusions from the literature are as follows.

9.1.1 Soil Suction

- a - The theory of soil suction may be described using thermodynamic concepts, and the definitions of the components of soil suction based on these concepts are valid.
- b - The total suction is the sum of matrix suction and osmotic suction. The total and matrix suctions can be measured independently of the determination of osmotic suction.
- c - The quantification of the osmotic suction of the soil is difficult. It seems likely that the osmotic suction can be obtained by subtracting matrix suction from total suction, provided the matrix and total suction are accurately measured.
- d - The concept of osmotic suction is simple to understand, but difficult to identify. The osmotic component of soil suction may be responsible for complexity in analysing soil suction measurements in general.
- e - Soil reacts to changes in osmotic suction, so that osmotic suction may be considered as an independent stress state variable. In most of the engineering problems osmotic suction is constant and does not control the mechanical behaviour of the soil.
- f - The concept of osmotic efficiency is very useful and is of considerable importance for many aspects of soil mechanics, including the use of clay for environmental barriers and at the interface between the suction measurement system and the soil.

9.1.2 Cavitation

- a - The phenomenon of static cavitation of water has been discussed, and it is concluded that the lack of information in the soil mechanics literature has delayed the understanding and development of soil suction measurement systems.
- b - It is well known in other sciences (*i.e.* physics, astronomy, medicine, *etc.*) that water can sustain a high tensile stress.
- c - The ability of water to sustain a high tension depends, *inter alia*, on the absence of air bubbles or on the stabilization of the air bubbles at the internal boundaries of the measurement system.

- d - In the case of a tensiometer the bubbles may be within the system itself, since the water flow mechanism do not allows air to came into the system.
- e - The suction at which cavitation occurs can be much increased if:
 - pure water is used,
 - the walls of the container are smooth
 - the water and its container are pre-pressurized to high pressures.
- f - The elimination of the cavitation nuclei is difficult, but they can be stabilized if the above recommendations are followed.
- g - The use of a small volume of water reduces the probability of cavitation occurring.

9.1.3 Filter Paper Technique

- a - The calibration curves presented in the literature are all very similar provided the same brand of filter paper (*e.g.* Whatman nº 42) is used, which reflects some accuracy of the method.
- b - The equilibration time for the water flow from the soil to the filter paper is a key factor for accurate suction measurement.
- c - The filter paper technique is a useful technique for suction measurement that can be used both in the laboratory and in the field.

9.1.4 Soil Shrinkage

- a - The phenomena of the drying of soil is not completely understood, and the amount of data available in the literature is small.
- b - The relationship between water content and suction is most useful, and can be used in the engineering practice.
- c - The model proposed by Brooks and Corey (1966) relating degree of saturation, suction and pore size distribution in non-expansive soils requires further studies and more data to be validated. The use of this model for expansive soils requires some new assumptions.

9.2 Experimental Work

9.2.1 Filter Paper Technique

- a - The filter paper technique is shown to be a simple and efficient tool for measuring soil suction, provided the test is performed with care.
- b - The interpretation of the suction measurement may require knowledge of the phenomena involved in the process of absorption by the filter paper of water from the soil.

- c - The filter paper is able to absorb water by capillary flow, even when a substantial area of the paper is not in direct contact with the soil sample. In this case flow occurs through the points where there is contact and equilibrium is reached with the water spreading uniformly throughout the paper.
- d - When there is lack of contact the equilibrium time may increase; this depends on the level of suction in the soil sample.
- e - The filter paper method can be used for measurement of total and matrix suction. However, for total suction measurements below 500kPa allowance must be made for increased the equilibration time.
- f - The osmotic suction can only be evaluated if accurate measurement is made of both matrix and total suction.
- g - As degree of saturation of the soil reduces during drying the reduction in contact between the filter paper and the soil water will result in the filter paper responding to a combination of matrix and total suction even though the filter paper is in physical contact with the soil. In this case the osmotic suction cannot be evaluated accurately.

9.2.2 Cavitation and Suction Measurement

- a - It is possible to generate and measure negative pressures in water well below -100kPa, independent of the volume of water in the system
- b - The ability to use a tensiometer to measure suction beyond 100kPa is more important than extending the range beyond 1MPa.
- c - The interface at the point of measurement used in tensiometers is an important part of the measurement system which may control the initial flow of water between the measurement system and the soil.
- d - When the interface between the tensiometer and the soil is a porous material with low permeability, osmotic effects can occur. These are the consequence of the osmotic efficiency of the interface material.

9.2.3 Soil Shrinkage

- a - The technique of drying samples is valuable for investigating many aspects of the unsaturated behaviour of soils.
- b - The study of the drying behaviour of plastic soils, under unconfined stress, confirms previous work on the development of suctions during drying.
- c - Plastic soils can sustain very high suctions without desaturation occurring. Prior to desaturation, where such soils do not crack the principle of effective stress can be applied.
- d - The effectiveness of the soil suction in inducing volume change is greatly reduced at suctions greater than the general air entry point.

- e - The differences between soils compacted in the field and in the laboratory is probably due to the presence of "undisturbed saturated lump" of soil in the former. These lumps, if substantial, control the volume change behaviour of the soil.
- f - For normally consolidated plastic soils, the relationship between water content and the logarithm of suction is usually linear. The slope of this relation is defined as the Suction Capacity (C).
- g - There is a relationship between suction capacity and liquid limit, which depends on the stress history of the sample.
- h - The sample water content (w) may be normalised by C to define a unique relation between w/C and the logarithm of suction that is of value for predictive purposes.
- i - Heavily overconsolidated soils have a low suction capacity and a small change in water content represents a large change in suction.
- j - The relation between the degree of saturation and suction depends on the initial condition of statically compacted samples, though the suction at the general air entry point seems to be largely independent of the initial degree of saturation, but depends on soil type.
- k - The final void ratio due to drying depends on the initial degree of saturation of the sample. This confirms the importance of the degree of saturation in the description of the drying behaviour of soils.

9.2.4 Stiffness Measurement using Bender Elements

Tests performed on statically compacted London clay lead to the following conclusions.

- a - The use of bender elements to obtain the shear modulus of drying soils proves to be a useful technique.
- b - The shear modulus of drying soils increases with increase in suction up to a critical value, above which the modulus either remains constant or decreases.
- c - This critical value is associated with the general air entry point of the sample.
- d - It is important to consider the suction when using shear waves to infer the shear modulus of soils *in situ* and in the laboratory.

CHAPTER 10

Recommendations for Future Research

This thesis has attempted to investigate the shrinkage behaviour of some plastic soils using simple experimental techniques. However, due to the multidisciplinary aspects of the mechanics of unsaturated soils there was need to consider information from many different sciences. The present work suggests a number of lines of research that could usefully be extended.

10.1 Filter Paper Method

Experiments at controlled constant temperatures should be performed to evaluate the influence of a change in temperature during equilibration for both matrix and total suction measurement. When performing these experiments care must be taken to consider the thermodynamic aspects of the phenomena involved.

It is important to evaluate the equilibration time for total suction measurements, particularly at suctions below 500kPa.

There is a necessity to determine the accuracy of the filter paper method.

10.2 Cavitation and Suction Measurement

- a - The ceramic porous interface used in tensiometers should be studied carefully. The understanding of the flow of water from the measurement system to the soil is very important for a reliable suction measurement system.
- b - An improved method is required for the calibration of tensiometers. The use of a differential transducer is suggested in order to evaluate the usual calibration procedures.
- c - Steps should be taken to improve the design of existing tensiometers to uplift their reliability.

10.3 Soil Shrinkage

- a - It is necessary to extend the investigation of the influence of the stress history of the soil on the drying behaviour, particularly on the suction capacity.

- b - Using initially a non-expansive soil, it is of interest to investigate the effect of the soil structure on the drying behaviour. The study should be followed by the use of expansive soils.
- c - Pore-size distribution determination of non-expansive and oven-dry expansive soils should be attempted.
- d - The development of a method to determine the pore-size distribution of expansive soils at any water content is required.
- e - The measurement of the volume of the sample can be improved by displacement techniques using a organic fluid such as toluene.
- f - Study of the behaviour of evaporation from drying soils is a area requiring study; comparison between isotropic and unidimensional evaporation is of particular interest, as also is the drying of soils under confined conditions. The use of expansive soils as protective barriers for waste disposal requires this latter information.
- g - Further extension of the data-base relating water content and suction is required.
- h - A comparative study of the influence of the stress history imposed by suction changes and by mechanical pressure changes requires more investigation.

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