# CRITICAL EVALUATION OF SOME SUCTION MEASUREMENT TECHNIQUES

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**DECLARATION**

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*My parents & wife*

*For dedicating their life for me and my wellbeing with endless love and support*

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# Abstract

Suction is an important stress-state variable of unsaturated soils. The magnitude of suction affects the shear strength, the hydraulic conductivity, and the volume change behaviour of unsaturated soils. The measurement of soil suction is a prerequisite for the characterisation of unsaturated soils.

Soil suction can be determined either by adopting direct or indirect measurement techniques. Despite several techniques available currently for measuring and controlling matric and total suctions of soils in the laboratory, several aspects related to various suction measurement techniques, such as the water phase continuity in null-type tests and compatibility of test results from various measuring techniques are yet to be explored in detail. Similarly, studies concerning determination of air-entry values (AEVs) and residual suctions of soils that exhibit volume change during the drying process are limited.

Suctions of two soils from Libya (a silty sand and an inorganic clay with intermediate plasticity) were experimentally measured using null-type axis-translation, filter paper, and chilled-mirror dew-point techniques. Axis-translation and vapour equilibrium techniques were used for establishing the drying and wetting suction-water content soil-water characteristic curves (SWCCs) of the soils. Compacted soil specimens were prepared by varying moulding water content, dry density, compaction type, and compaction effort in order to investigate the influence of initial compaction conditions on measured suctions and SWCCs of the soils. The water content-void ratio relationships (shrinkage curves) of the soils from Clod tests were used in conjunction with the drying suction-water content SWCCs to establish the suction-degree of saturation SWCCs that enabled determination of the air-entry values (AEVs) and residual suctions of the soils. Initially saturated slurried specimens of the soils were also considered for comparing with the test results of compacted soil specimens.

The test results from the investigation showed that the influence of compaction conditions on SWCCs of the soils was distinct only at a low suction range, whereas their impact was insignificant at higher suctions. The volume change of the soils during the drying process had significant impact on the AEVs and residual suctions. For initially saturated slurried specimens, the AEVs and the residual suctions of the soils determined form the suction-water content SWCCs were found to be distinctly lower than their counterparts determine from the suction-degree of saturation SWCCs. Suctions corresponding to the plastic limits of the soils agreed well with those determined from suction-degree of saturation SWCCs, whereas suctions corresponding the shrinkage limits overestimated the AEVs.

An increase in the chamber air pressure soon after the null-type tests were completed clearly indicated that the water phase continuity between the water in the soil specimens, the water in the ceramic disk, and the water in the compartment below the ceramic disk was lacking for all specimens tested. Soil specimens with higher water contents created better continuity in the water phase. At high suction range, the test results from the techniques based on vapour equilibrium (i.e., non contact filter paper, salt solution and chilled-mirror dew-point tests) showed very good compatibility, whereas differences were noted between the test results at low suction range from the techniques that are based on liquid phase equilibrium (i.e., pressure plate and null-type tests).

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Unsaturated soils are commonly found in many parts of the World, especially at shallow depths from the surface and in arid and semi-arid areas where the natural ground water table typically is at a greater depth (Fredlund & Rahardjo, 1993). In other cases, soils are usually compacted and used in many civil engineering works, such as roads, embankments, earth dams, backfills, and hydraulic barriers. Compacted soils are invariably unsaturated at the time of placement and possess negative pore-water pressure or suction. The presence of air and water within the pores spaces between the soil particles generates capillarity effects that create suction where the pore water pressure is negative, provided that pore air pressure is zero (Lu & Likos, 2004).

Suction is one of the important stress-state variables of unsaturated soils that affect the strength and volume change characteristics. The measurement of soil suction is therefore a prerequisite for understanding the behaviour of unsaturated soils and can be measured through direct and indirect methods. Tensiometer, suction probe, and null-type axis-translation device are the commonly used techniques for direct measurement of matric suctions (Olson & Langfelder, 1965; Ridley & Burland, 1993; Vanapalli et al., 1994; Tarantino & Mongiovi, 2002; Tripathy et al., 2005; Lourenço et al., 2006; Leong et al., 2009;

Tripathy et al., 2012). These devices employ the axis-translation technique (Hilf, 1956) and require a separation between water and air phases, usually by using a ceramic disk with high air-entry value. Indirect suction measurement methods measure the moisture equilibrium condition of the soil instead of suction (Bulut & Leong, 2008). Several of the available techniques can be used to measure soil suction indirectly; these include the use of psychrometers, chilled-mirror potentiometer, thermal and electrical conductivity sensors, and the filter paper technique.

For matric suction measurement using null-type axis-translation device it has been assumed that under constant water mass conditions and for any applied air pressure increase within the pores of unsaturated soil systems that possess sufficient continuity of the air phase, there will be a corresponding equal increase of the pore-water pressure (Hilf, 1956; Olson & Langfelder, 1965). However, no specific investigations have been carried out to support this hypothesis. Continuity of the air phase within the soil specimen is crucial in order to obtain reliable results. Similarly, continuity between the pore water in the soil specimen, the water in the pore of the ceramic disk, and the water in the compartment (i.e., dranse line) below the ceramic disk is necessary in order to correctly measure the matric suction. However, this aspect also has not been fully investigated.

The total suction can be determined by measuring the vapour pressure of the soil water or the relative humidity in the soil. The relative humidity can be measured directly by using relative humidity sensor or chilled-mirror device (e.g., Leong et al., 2003; Albrecht, 2003; Agus & Schanz, 2005). The filter paper can be used as a measuring tool to indirectly determine the soil suction (e.g., McKeen, 1980; Chandler et al., 1992; Houston et al., 1994; Leong et al., 2002). The filter paper method is highly dependent on the calibration curves that relate soil suction to water content of filter papers. There appears to be some inconsistency and disagreement in the previous studies with regard to the use and validity of published calibration curves. Different calibration curves for total and matric suction measurements are recommended by Houston et al. (1994), and Leong et al. (2002), whereas other studies suggested that only a single calibration curve is needed for total and matric suction measurements (Marinho & Oliveira, 2006; Walker et al., 2005). Several factors, such as method of calibration used, quality of filter paper, hysteresis and equilibration time, may be attributed for the different calibration curves found in the literature (Leong et al., 2002). This indicates that more studies are required to investigate the influence of these factors on filter paper calibration curves.

Suction is a function of soil structure and soil water content. The relationship between soil suction (matric suction or total suction) and water content (or degree of saturation or volumetric water content) is termed as soil-water characteristic curve (SWCC) and it is a crucial tool to predict and interpret the behaviour and response of unsaturated soils (Fredlund et al., 2012). Many studies have been conducted to study the factors that affect the SWCC, such as the initial compaction conditions, the stress history, and the soil type (e.g., Tinjum et al., 1997; Vanapalli et al., 1999; Fleureau et al., 2002).

A number of laboratory techniques available currently can be used for establishing the SWCCs of soils. These techniques are based on equilibrium through either the liquid or the vapour phase. However, the SWCC established by adopting different methodologies may not be unique even when the same principles of suction control or measurement are used (Ridley et al., 2003; Agus & Schanz, 2005; Sreedeep & Singh, 2011). A comparison of the suction values measured by employing different techniques need to be addressed in more details. Additionally, procedures used to establish the relationship between suction and water content, either by continuous drying suction measurements on the same soil specimen starting from high water content (SWCC) or by suction measurement of soil specimens prepared at different compaction conditions (water content-suction relation), have not been fully explored.

It can be found from a detailed review of the literature reported in Chapter 2, that most studies considered only the effects of water content change on suction and focused on soils that did not exhibit significant volume change. However, soils may undergo considerable volume change with changes in soil suction. Generally, shrinkage and swelling are responses of unsaturated soils subjected to drying (an increase in suction) and wetting (a decrease in suction), respectively. This can lead to erroneous estimations of suitable unsaturated soil property functions due to incorrect determination of air-entry values (AEVs) and the residual state of the soil (Romero & Vaunat, 2000; Tarantino & Tombolato, 2005; Salager et al., 2007; Miller et al., 2008; Fredlund et. al., 2011; Salager et al., 2013).

The AEVs are commonly less distinct in the drying suction-water content SWCCs, if the volume change of the soil during drying SWCC tests is large. The suction-degree of saturation SWCCs may be used for determination of AEVs (Fredlund & Rahardjo, 1993; Fredlund & Houston, 2013) which require determination of both the water content and the void ratio of soils at each applied suction. The shrinkage test provides a relationship between the water content and the void ratio of the soil and can be used in conjunction with the suction-water content SWCC to establish the relationship between void ratio and suction. Consequently, the suction-degree of saturation SWCCs can also be established and further the AEVs of soils can be determined. Through ignoring the volume change during suction change, errors in the determination of the true AEV of a soil can be several orders of magnitude (Fredlund & Houston, 2013). This highlights the importance of the shrinkage curve in interpreting the laboratory SWCC test results.

To eliminate possible errors owing to testing multiple specimens or volume determinations by measuring core dimensions of a soil specimen, Clod test on a single specimen can be used to trace the entire water content-void ratio shrinkage paths of soils (Krosley et al., 2003). Several studies have shown that the shrinkage paths of soils can be represented by smooth curves using several parametric models (McGarry & Malafant, 1987; Fredlund et al., 2002; Cornelis et al., 2006).

Some unsaturated soils may collapse upon wetting, but the level of collapse is influnce by the applied stress. Soils compacted at dry of optimum may produce a form of structure that leads the soil to collapse due to wetting. In other words, a majority of compacted soils are subjected to collapse due to inundation (Tadepalli & Fredlund, 1991; Lawton et al., 1992; Houston et al., 1993). Several factors influence the amount of collapse potential, such as water content, initial dry density, soil type, and applied pressure (e.g., Lawton et al., 1989; Nelson & Miller, 1992; Lim & Miller, 2004).

The volume change behaviour of soils can be due an external mechanical stress exerted on the soil (pressure-void ratio relationships) or due the process of decreasing or increasing in suction (suction-void ratio SWCC) (Fredlund, 1964; Flereau et al., 1993; Marcial et al., 2002; Tripathy et al., 2010). The effects of suction changes and total stress changes are usually similar on the volume change behaviour of soils up to the desaturation value (AEV) (Fredlund & Rahardjo, 1993). However, limited studies in the literature have compared the influences of an increase in vertical pressure and an increase in suction on the volume change of saturated soils.

The work reported in this thesis mainly dealt with experimental works on compacted unsaturated soils. However, it is recognised that this work relates strongly to parallel developments in constitutive modelling. Constitutive models for unsaturated soils can be divided into two categories; elastic models and elasto-plastic models. Elastic models relate strain increments (including water volume) to increments of stress (including suction) (e.g. Fredlund & Morgenstern, 1976; Lloret & Alonso, 1985). Wheeler & Karube (1996) presented a comprehensive review of this type of models. In the last two decades researchers have developed elasto-plastic models to link volume change and shear strength in an integrated way to describe stress-strain behaviour of unsaturated soils (Alonso et. al., 1990; Toll, 1990; Wheeler & Sivakumar, 1995; Cui and Delage, 1996; Wheeler, 1996; Rampino at al., 1999; Chiu and Ng, 2003; Wheeler et al., 2003). These models were developed under the framework of independent stress state variables and using the extended concept for unsaturated soils. It should be noted that the constitutive models for unsaturated soils are out of scope of this work. Comprehensive reviews of elasto-plastic model for unsaturated soils have been presented in the literature (e.g., Pham, 2005; Gens et al., 2006; and Wheeler, 2006).

## 1.2 Study objectives

Even though significant studies have been carried out on the behaviour of unsaturated soils in many parts of the World, the research in this area is still at premature state in Libya. This study therefore, constitutes one of the first attempts to investigate the behaviour of unsaturated Libyan soils. Two types of Libyan soils with different properties and mineralogical background were chosen and subjected to an extensive experimental programme in this research. The soils were collected from North-west (Tripoli area, Jaffara soil (JF)) and from North-east (Benghazi area, Terrarosa soil (TR)) of Libya. The study includes; matric and total suction measurements, drying and wetting SWCC tests using various currently available laboratory methods, volume measurements, investigation of several factors affecting suction, and assessing the applicability and methodology of some of the currently available methods for suction measurements.

The primary objectives of this research were as follows: (*i*) to acquire a general understanding of the behaviour of unsaturated Libyan soils and enhance the existing Libyan soil database, (*ii*) to establish the drying and wetting suction-water content SWCCs from initially saturated slurry and compacted conditions at zero external stress, (*iii*) to establish the suction-void ratio SWCCs and the suction-degree of saturation SWCCs of the soils and further determine the air-entry values, (*iv*) to measure matric and total suction at different compaction conditions using various available techniques, (*v*) to study factors which influence the SWCCs and measured initial suctions (the initial water content, the compaction energy, the compaction type, and the soil types), (*vi*) to explore and verify the continuity in the water phase between the soil water, the water in the ceramic disk, and the water in the compartment below the ceramic disk in the fabricated null-type axis translation device, and (*vii*) to compare the suction values determined by different techniques.

## 1.3 Thesis outline

The thesis is divided into ten consecutive chapters.

**CHAPTER 1** presents the background of the research, the main objectives of this research and outline of the thesis.

**CHAPTER 2** presents a review of literature pertaining to the studies undertaken. A brief review of the concept of soil suction followed by a summary of the common suction measurement and suction control techniques that have been reported, are presented. The effects of compaction conditions and soil type on suction in unsaturated soils are discussed.

The chapter also presents general information about the volume change behaviour of unsaturated soils and the significance of the suction-void ratio SWCCs, various volume measurement techniques, modelling of the shrinkage paths and determination of the air-entry value (AEV).

**CHAPTER 3** describes the properties of the soils and experimental procedures used. The physical properties determined include Atterberg limits, grain size distribution, and minerals composition using X-ray diffraction (XRD) technique are first presented followed by the specimen preparation and compaction methods adopted. The collapse behaviour of compacted specimens of soils determined from double oedometer test are also presented. Further, the methods used for establishing the drying and wetting suction-water content SWCCs and volume measurement using Clod method are presented. Subsequently, the devices and testing methods used for soil suction measurements (null-type pressure plate, filter paper, and chilled-mirror) are presented.

**CHAPTER 4** presents the drying and wetting suction-water content SWCCs results obtained for both soils used. The SWCCs tests are carried out on initially slurried and compacted specimens using axis-translation and vapour equilibrium techniques. The effects of initial compaction conditions on the suction-water content SWCCs are also presented.

**CHAPTER 5** presents the shrinkage behaviour of the soils from saturated slurried and compacted conditions. The water content-void ratio relationships (shrinkage curves) of the soils using Clod method are presented. Two parametric models were used to best-fit the experimental water content-void ratio shrinkage paths of the soils. The results of drying suction-water content SWCCs are combined with the shrinkage curve results and are subsequently used to establish the suction-void ratio SWCCs and the suction-degree of saturation SWCCs. Comparisons of the AEVs determined (*i*) based on the suction-water content SWCCs from pressure plate and desiccator test results and (*ii*) based the on suction–degree of saturation SWCCs, are presented. Comparisons of suction-void ratio SWCC results with pressure-void ratio results (one-dimensional consolidation test) for initially compacted saturated soils are also presented.

**CHAPTER 6** presents the matric suction measured by using null-type axis-translation technique. Soil specimens used for suction measurements were prepared at various compaction conditions in which the initial compaction water content, dry density, compaction type, and compaction effort were varied. The effects of initial compaction conditions on matric suction of the soils are presented in detail.

**CHAPTER 7** presents a detailed study concerning the continuity in the water phase between soil specimens, the water in the ceramic disk, and the water in the compartment during null-type axis-translation tests. Continuity in the water phase was verified soon after the measurements of matric suction were completed by increasing the chamber air pressure and monitoring the corresponding water pressure increase below the ceramic disk. The influence of using of various interface materials (viz., a wet filter paper, slurries prepared from the tested soil, and a kaolinite) on the water phase continuity and the measured suction values are discussed.

**CHAPTER 8** presents matric and total suction results performed using filter paper method. Aspects that influence contact and non contact filter paper calibration curves, such as suction sources, equilibrium time, and hysteresis, are evaluated. Measurements of total suction were also carried out using chilled-mirror dew-point device and the results are presented. The influence of initial compaction conditions on matric and total suctions using filter paper and chilled-mirror dew-point techniques are also discussed.

**CHAPTER 9** presents comparisons of the following: (*i*) SWCCs established by pressure plate and salt solution tests and the measured matric and total suctions determined by null-type axis-translation tests, filter paper, and chilled mirror tests, (*ii*) the test results obtained by controlled and measured suctions in pressure plate and null-type axis-translation tests, and (*iii*) total suction of the soils determined by two different testing procedures using chilled-mirror dew point potentiometer.

**CHAPTER 10** presents the main conclusions drawn based on the findings of this study.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

A brief review of the literature concerning the fundamentals of unsaturated soil mechanics is presented in this chapter. This chapter starts with a review of the concept of soil suction followed by a summary of the commonly used suction measurement and suction control techniques. Important aspects associated with the soil-water characteristic curve (SWCC) are presented. Significance of the suction-void ratio SWCC, various volume measurement techniques, modelling of the shrinkage paths, and determination of the air-entry value (AEV) of soils are also presented.

## 2.2 Occurrence and applications of unsaturated soil mechanics

Unsaturated soils are commonly found in most parts of the World, especially at shallow depths from the surface and in arid and semi-arid areas where the ground water table typically is often many metres deep (Fredlund & Rahardjo, 1993; Murray & Sivakumar, 2010).

Irrespective of the nature of climate, several engineering structures for geotechnical applications are constructed using compacted soils (i.e., earth dams, road embankment, pavements, and waste containment structure such as covers and liners) that are typically in a state of unsaturated condition at the time of placement. Compacted soils have two level of pore distribution: macro voids and micro voids. Macro void are large and are between aggregates or particles. The compaction is a process that expells the air from macro voids, complete removal of air voids is impossible and therefore, the end-product will be in the state of unsaturation. The structure of the end-product depends on the level of compaction and the compaction water content. Collapsible soils, residual soils, and expansive soils are typical examples of natural unsaturated soils. Common to all these soils is the negative pore water pressure, which plays an important role in their hydro-mechanical behaviour.

For many conventional geotechnical applications, soils are assumed to be saturated. A saturated soil is considered to have two phases, namely solid (i.e., soil) and liquid phases (i.e., water) and all the pores in a saturated soil are occupied by water. The engineering behaviour of saturated soils can be described in terms of a single stress state variable, (i.e., $\sigma` = \sigma - u_w$) (Terzaghi, 1943). A soil that is in a state of unsaturated condition consists of four different phases. Two phases that flow under the influence of stress gradient (i.e., air and water) and two phases that come to equilibrium under the influence of stress gradient (i.e., soil particles forming a structural arrangement and the contractile skin forming a partition between the fluid phases) ( Fredlund & Morgenstern, 1977; Fredlund & Rahardjo, 1993).

In recent years, the mechanics of unsaturated soils has become a rapidly expanding field, which is applied both in geotechnical and geo-environmental engineering practice including shear strength behaviour of unsaturated soils (Vanapalli et al., 1996), efficiency of covers with capillary barrier effects (Bussiere et al., 2003), bearing capacity of foundation materials (Oloo, 1997; Rassam & Williams, 1999), seepage through dams (Papagiannakis & Fredlund, 1984), compressibility and swelling soil response (Sivakumar, 1993; Rampino et al., 2000), and land subsidence (Thu & Fredlund, 2000).

Unsaturated soils are encountered in many engineering problems. Some of the engineering problems associated with unsaturated soils include (Fredlund, 2000): (*i*) the shrinking and swelling of the soil due to drying and wetting, (*ii*) consolidation due to an increase in vertical pressures, (*iii*) shear strength reduction and instability of the excavation, (*iv*) assessment of slope stability under changing climatic conditions, (*v*) the shear strength and volume change of the compacted soils used for engineering practice, (*vi*) the design of shallow foundations for light structures under moisture loading, and (*vii*) the design of a cover system for underground waste storage and containment.

## 2.3 Compaction behaviour of soils

Soil compaction is widely used in the construction of earth structures, such as roads, embankments, dams, landfills, foundations, and for engineered barriers. The main purpose of compaction is to maximise the dry density of soils by expelling air and therefore, to achieve the desired strength, compressibility, and hydraulic conductivity of the soils used.

Compaction of soil can be defined as the process by which the soil particles are rearranged and packed together into a closer state of contact by mechanical means, resulting in a decrease in the porosity of the soil and increase its dry density (Head, 1980). In practice, the compacted soil behaviour is characterized by the dry density ($\rho_d$) and the water content ($w$). The compaction characteristics of soils are determined in the laboratory by various compaction tests (i.e., dynamic or impact, kneading, static, and vibration).

Several studies have reported the relevant effect of the compaction water content on the soil structure (Lambe, 1969; Barden & Sides, 1970; Delage et al, 1996; Simms & Yanful, 2001). Soil compacted dry of optimum and wet of optimum, at same dry density, produce different soil fabrics (orientation of the soil particles) and hence cause the same soil to behave differently in terms of their strength parameters, volume change, and permeability. Soils compacted dry of optimum have an open structure with larger interconnected pores and tend to exhibit higher stiffness and lower shrinkage during drying than compacted samples on the wet side, at the same dry density (Sivakumar & Wheeler, 2000) due to a more aggregated structure. Also, the permeability of soil compacted on the dry side of optimum is higher than soil compacted wet of optimum due the larger voids between the aggregated soil (Mitchell et al., 1965). A soil compacted wet of optimum loses the interconnected air phase (Vanapalli, 1994). The air may remain in the pores is in occluded form. In addition, compaction on the wet side of optimum water content involves lower collapse.

The optimum water content is found to be the water content that separates the occluded and open structures (Marshall, 1979). The soils compacted at optimum conditions exhibit structures and resulting engineering behaviour intermediate between the structure and engineering behaviour of materials compacted dry and wet of optimum. The different behaviour of a soil due to compaction conditions are attributed to the distribution of the pore space between micro pores and macro pores (Delage et al., 1996). However, it is not easy to distinguish between the effect of the structure and the effect of initial conditions established during compaction (Alonso & Pinyol, 2008).

## 2.4 Suction and water potential

The theory of suction was developed in soil physics in the early 1900's based on energy consideration (e.g., Buckingham, 1907; Gardner & Widtsoe, 1921). In soil physics, soil suction is generally referred to as the potential energy state of water in soil (Jury et al., 1991). The potential energy state of water in soil is defined as the difference in energy per unit quantity of water compared to a reference state. The components of soil-water potential ($\Psi$) can be represented by the sum of matric potential ($\Psi_m$), gravitational potential ($\Psi_g$), osmotic potential ($\Psi_\pi$), and pressure potential ($\Psi_p$) (Yong & Warkentin 1975; Campbell, 1988; Or & Wraith, 1999) (Eq. 2.1).

$$\Psi = \Psi_m + \Psi_g + \Psi_\pi + \Psi_p \qquad \text{(Eq. 2.1)}$$

where $\Psi_m$ is the matric potential, pertaining to sorption forces between soil fractions and soil-water, $\Psi_\pi$ is the osmotic potential, equal to $\Psi_s$ (the solute potential), referring to interaction forces between solutes and water molecules, $\Psi_g$ is the gravitational potential, referring to position in the gravitational field, and $\Psi_p$ is the pressure potential, primarily due to externally applied pressure transmitted through the fluid phase of the soil–water system.

The gravitational and pressure potentials are typically neglected in unsaturated soil because soil water does not change elevation at a certain point under consideration, and the external pressure assumed zero (Or & Wraith, 1999; Toker, 2002). Thus, the total soil-water potential quantifies the thermodynamic potential of soil pore water relative to a reference potential of free water, which is equal to the sum of matric and osmotic potential components.

$$\Psi = \Psi_m + \Psi_\pi \qquad \text{(Eq. 2.2)}$$

Generally in geotechnical engineering, the soil water potential is referred to as soil suction. It is also called total suction or negative pore pressure. This approach provides a more mechanistic view of the state of soil water in relation to the strength, compressibility, stress-strain response and hydraulic conductivity of unsaturated soils (Wan et al., 1995).

### 2.4.1 Total suction

The use of suction in explaining the mechanical behaviour of unsaturated soils in relation to engineering problems was introduced by Croney & Coleman (1948) and Croney et al. (1950). In general, soil suction refers to the measure of the ability of a soil to hold and attract water. Aitchison (1965) defined the soil suction and its components from a thermodynamic context which become accepted concept in geotechnical engineering (Krahn & Fredlund, 1972; Fredlund & Rahardjo, 1993). Suction or total suction is defined as the total free energy of the soil water determined as the ratio of the partial pressure of the water vapour in equilibrium with a solution identical in composition to the soil water, to the partial pressure of the water vapour in equilibrium with a pool of free pure water. The thermodynamic relationship between total suction and its partial vapour pressure of the soil pore water is described by Kelvin's equation:

$$\psi = \frac{RT}{v_{w0}\omega_r} \ln\left[\frac{u_v}{u_{v0}}\right] = -\frac{RT}{v_{w0}\omega_r}\ln\left(\frac{RH}{100}\right) \qquad \text{(Eq. 2.3)}$$

where $R$ = universal gas constant (8.31432 J/(mol K)), $T$ = absolute temperature (°K), $v_{0\omega}$ = specific volume of water (m$^3$/kg), which is the inverse of the density of water, $\omega_v$ = molecular mass of water vapor (18.016 g/mol), $u_v$ = partial pressure of pore-water vapor (kPa), and $u_{v0}$ = saturation pressure of water vapor (kPa). The ratio $u_v/u_{v0}$ is equal to the relative humidity ($RH$).

### 2.4.2 Matric suction

In unsaturated soils, matric suction is controlled by a capillary effect and adsorption of water (Richards, 1974). The contribution of each mechanism to matric suction as a whole depends on soil composition and geometrical configuration of the soil structure. In engineering practice, matric suction is considered to be the pressure difference between the pore air pressure ($u_a$) and the pore-water pressure ($u_w$), i.e., ($u_a$ - $u_w$).

For granular soils, matric suction component is mainly associated with the capillary phenomenon. The pores between soil particles can each be represented as individual capillaries each with an equivalent radius and a meniscus will form at air-water interface between adjacent soil particles in a manner similar to water in a capillary tube. Therefore, matric suction can be considered as the pore water tension present due to surface tension effects within the soil mass. Matric suction is strongly related to geometrical factors such as pore size, shape, and distribution (Fredlund & Rahardjo, 1993; Houston et al., 1994).

Capillarity can be related to the matric suction based on the pore size distribution of materials (Fredlund & Rahardjo, 1993) (Eq. 2.4)

$$u_a - u_w = \frac{2 \quad T_s cos\theta}{r} \qquad \text{(Eq. 2.4)}$$

where $T_s$ is the surface tension of the air-water interface, $r$ is the radius of curvature of the meniscus, and $\theta$ is the contact angle between the solid and liquid phases.

### 2.4.3 Osmotic suction

The osmotic suction represents the suction that originates from dissolved salt in the pore water. It is equivalent to suction derived from the measurement of partial pressure of water vapour in equilibrium with a solution, which has identical composition of the soil water, relative to the partial pressure of vapour in equilibrium with free pure water (Aitchison, 1965).

It can be stated that the osmotic suction arises from the chemical imbalance between the pore water in the soil volume under consideration and an external source of water (Murray & Sivakumar, 2010). For example, when a pool of pure water is placed in contact with a salt solution through a membrane, which allows only the water to flow through, an osmotic suction will develop due to the difference in the concentration of salt solution and water will flow through membrane.

Osmotic solution can be altered by either changing the mass of water or the amount and type of salt in solution. However, in most practical problems encountered in geotechnical engineering, osmotic suction changes are generally less significant than matric suction changes (Nelson & Miller, 1992, Fredlund & Rahardjo, 1993; Murray & Sivakumar, 2010).

## 2.5 Suction measurements

Suction measurement techniques can be categorised as either a direct or indirect measurements. The direct measurement of soil suction relies on the direct observation of the pore water pressure, whereas indirect methods involve the measurement of soil properties which are directly related to suction through a calibration with a known value of suction (i.e. relative humidity, resistivity, and water content) (Ridley & Wray, 1995). Table 2.1 presents a summary of the conventional methods for suction measurements along with ranges of measurement, advantages, and limitations. Null-type axis-translation, filter paper, and chilled-mirror techniques were employed in this study.

### 2.5.1 Measurement of matric suction using null-type axis-translation technique

Tensiometers, high suction probes and null-type axis-translation are the most commonly used devices to directly measure the matric suction of soils. These devices require a separation between water and air phase, usually by using a ceramic disk with high air-entry value.

The principle of suction measurement using a tensiometer is that once pressure equilibrium between the soil and the tensiometer is achieved, water in the tensiometer will be in tension of the same magnitude as the negative pore-water pressure in the soil. Due to the cavitation problem, the technique can only measure matric suction up to about 100 kPa. Improvements have been made to the tensiometer technique to measure matric suction up to 1500 kPa (Ridley & Burland, 1993; Guan & Fredlund, 1997; Marinho & Pinto, 1997; Toker, 2002, Tarantino & Mongiovi, 2002; Lourenço

***Table 2.1 Suction measurements methods***

| Suction measurement method | Suction component | Suction range (kPa) | Equilibrium time | Comments | References |
|---|---|---|---|---|---|
| Null-type axis-translation | Matric | 0 - 1500 | 1 - 16 hrs | Direct, limit to the air-entry value of ceramic disk | Hilf, (1956); Bishop & Donald, (1961); Olson & Langfelder, (1965); Pufahl, (1970); Krahn & Fredlund, (1972); Fredlund & Morgenstern, (1977); Mou & Chu, (1981); Fredlund, (1989); Tripathy et al., (2005); Vanapalli et al., (2008); Leong et al., (2009) |
| Tensiometers | Matric | 0 – 90 | Several minutes | Direct, difficulties with cavitation required daily maintenance | Sweeney, (1982); Cassel & Klute, (1986); Tadepalli, (1990) |
| High suction tensiometers | Matric | 0 – 1500 | Several minutes | Direct, cavitation at high suction air diffusion through ceramic cup | Ridley & Burland, (1993); Guan & Fredlund, (1997); Marinho & Pinto, (1997); Toker, (2002); Tarantino & Mongiovi, (2002); Lourenço et al., (2006) |
| Time domain reflectometry | Matric | 0 - 500 | Instantaneous | Indirect, required soil water characteristic curve, expansive, sophisticated electronic device | Topp et al., (1980); Benson & Bosscher, (1999); Yu & Drnevich, (2004) |

| | | | | | |
|---|---|---|---|---|---|
| Thermal conductivity sensors | Matric | 10 - 1500 | Several hours to days | Indirect, measurement using variable-pore-size ceramic sensor, temperature change influence the accuracy | Shaw & Baver, (1939); Lee & Fredlund, (1984); Feng et al., (2003); Leong et al., (2011) |
| Electrical conductivity sensors | Matric | 10 - 1500 | Several hours to week | Indirect, affected by salinity and temperature of soil water | Aitchison &Richards ,(1985); Skinner et al., (1997); He, (1999) |
| Filter paper method | Matric | 0 - 1000 | 2 - 5 days | Indirect, depends on calibration curve and equilibrium time, low cost | Gardner, (1937); Houston etal., (1994); Bulut et al., (2000, 2001); Likos & Lu, (2002); Leong, (2002); ASTM D5298-10 |
| | Total | above 1000 | 3 - 14 days | | |
| Relative humidity probes | Total | above 1000 | Several minutes to hours | Indirect, constant temperature required, accuracy vary by manufacturer | Benson & Bosscher, (1999); Albrecht et al., (2003); Agus & Schanz, (2005) |
| Chilled-mirror hygrometer | Total | 100 - 300000 | 3 - 20 mins | Indirect, error at low suction levels | Gee et al., (1992); Leong et al., (2003); Agus & Schanz, (2005) |
| Psychrometers | Total | 100 - 8000 | 5 - 10 hrs | Indirect, affected by temperature fluctuation sensitivity deteriorate with time | Richards, (1965); Krahn and Fredlund, (1972); Harrison & Blight, (2000); Tang et al., (2002); Sivakumar, (2005) |

et al., 2006). These types of tensiometers avoid cavitation in which the volume of water reservoir beneath the ceramic tip is minimised and water in the water reservoir is pre-pressurised. These types of tensiometers are called high capacity tensiometers (HCT) or high suction probes and can be used to measure matric suctions up to 1500 kPa. Marinho et al. (2008) discussed the similarities (saturation procedures, the need for intimate contact between soil specimen and ceramic disk, air diffusion, air entry, etc) and differences (absolute positive and negative pressures, cavitation, etc.) which give the necessary basis to use and interpret the results obtained from tensiometer and null-type axis-translation techniques.

Null-type axis-translation apparatus (Tripathy et al., 2012) (Fig.2.1*a*) is conventionally used to measure the matric suction of unsaturated soil specimens applying the axis-translation technique (Hilf, 1956; Olson & Langfelder, 1965; Pufahl, 1970; Krahn & Fredlund, 1972; Mou & Chu, 1981; Vanapalli et al., 1994; Tripathy et al., 2005; Leong et al., 2009; Kurucuk & Fredlund 2011, to name a few). The measurement of matric suction using this technique is limited by the air-entry value of the ceramic disk used.

This technique is called as null-type-axis-translation because water pressure in the water compartment is maintained as close as possible at a zero value, and it translates the origin of reference for pore water pressure from standard atmospheric condition to the final air pressure in the chamber. Hilf (1956) and Olson & Langfelder (1965) have demonstrated that under constant water mass condition and for any applied air pressure increase within the pores of unsaturated soil systems that possess sufficient continuity of the air phase, there will be a corresponding equal increase of the pore-water pressure. Therefore, the difference between the applied air pressure and the pore-water pressure (i.e., matric suction) remains constant regardless of the translation of both the pore-air and pore-water pressures.

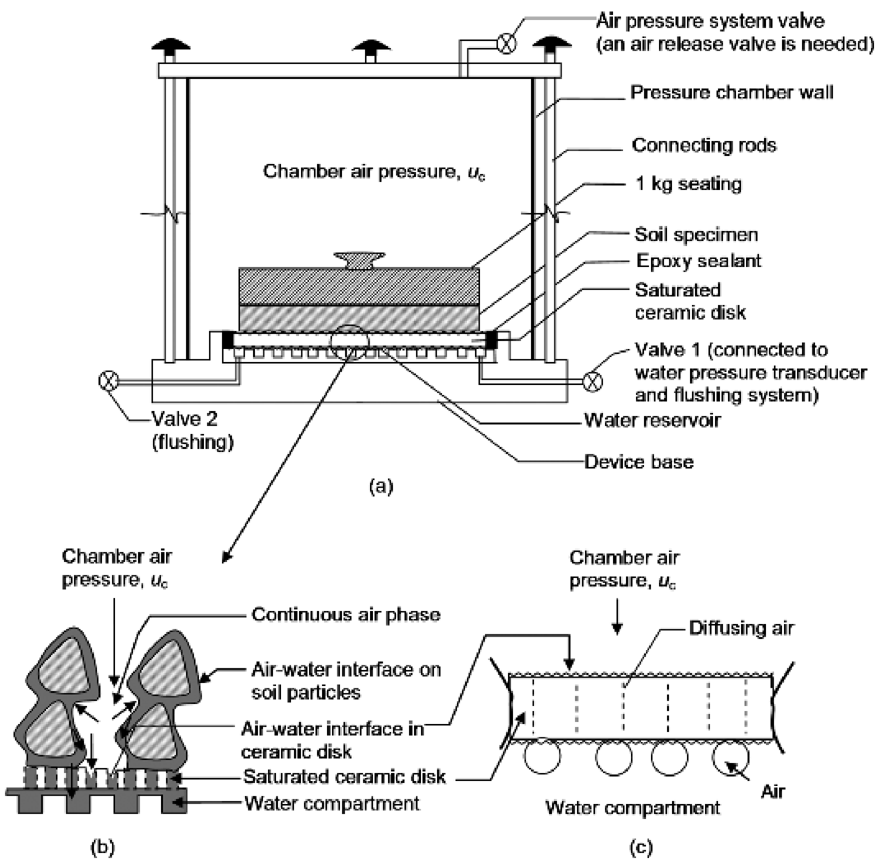



***Fig. 2.1—(a) Schematic of null-type axis-translation device, (b) water phase continuity requirement, and (c) air diffusion through saturated ceramic disk, (from Tripathy et al., 2012)***

Several researchers have reported measurements of matric suction of compacted soils using the null-type axis-translation technique. The studies have emphasized two distinct aspects associated with measurement of matric suctions, such as (*i*) the factors associated with the compaction conditions of soils and (*ii*) the factors that are responsible for the flexibility of the measuring system. Studies on the former have of the opinion that: (*i*) continuity of the air phase within the soil specimen is required to obtain reliable test results; in this context, the degree of saturation of soil specimens less than about 80% may be considered as the upper limit for the compaction conditions to exclude the influence of the compressibility of occluded air bubbles on the measured suctions and (*ii*) some influence of soil structure and fabric may be expected on the measured suctions depending upon the type of compaction adopted (viz., static, dynamic, kneading).

#### *2.5.1.1 Flexibility of the measuring system*

A number of factors are believed to be responsible for the flexibility of the measuring system (Fredlund & Rahardjo 1993), such as (*i*) the thickness and the air-entry value of the ceramic disk, (*ii*) defects in the ceramic disk and method of mounting the disk, (*iii*) deflection of the membrane of the pore water pressure transducer used, (*iv*) air diffusion through ceramic disk, (*v*) contact between soil specimen and the saturated ceramic disk, (*vi*) expansion of the water compartment below the ceramic disk, and (*vii*) compressibility of the air-water mixture in the water compartment. All of these factors influence the measured equilibration time and reliability of test results. The combined influence of the presence of the diffused air in the water compartment, the expansion of the water compartment, and the compressibility of the air-water mixture can be studied by monitoring the pore-water pressure change due to an increase in the chamber air pressure at the end of suction measurement.

#### *2.5.1.2 Contact between soil specimen and ceramic disk*

The measured suction will not be representative of that found in the soil if the contact between the soil pore water and the water in the ceramic disk is not established. Figure 2.1*b* shows schematically the water phase continuity between soil specimen and the saturated ceramic disk. Discontinuity between the water in the soil and the water in the ceramic disk may significantly increase the time required for equilibrium.

To deal with this issue, Olson & Langfelder (1965) recommended that 1 kg mass be placed on top of the soil specimen to ensure a good contact between the saturated ceramic disk and the soil specimen. In contrast, Topp et al. (1993) recommended that soil specimens may be embedded in a thin layer of kaolinite clay to ensure proper contact. Marinho et al. (2008) also suggested placing a small amount of slurry of the same soil to be tested prepared at water content near the liquid limit.

However, there have been no independent comparative studies reported exploring measurements of matric suction using null-type axis-translation technique by adopting various interfaces between soils specimens and the ceramic disk.

### *2.5.1.3 Air diffusion*

Air diffusion through saturated ceramic disks is known to be one of the main problems associated with testing unsaturated soils (Fredlund, 1975; Bocking & Fredlund, 1980). The diffused air comes out of the solution below the ceramic disk and prevents the water phase continuity between the water in the ceramic disk and the water in the compartment below the ceramic disk (Fig. 2.1*c*). Air diffusion tends to underestimate the actual matric suction of the soil (Fredlund, 1975).

Fredlund & Rahardjo (1993) stated that tests lasting more than one day (without equilibrium attained) will experience air diffusion. Vanapalli et al. (2008) suggested that the system should be flushed periodically to remove the dissolved air under the ceramic disk. However, flushing the system too often will extend the testing durations. Padilla et al. (2006) measured the diffusion rate at different pressures for 1, 3, 5, and 15 bar high air-entry ceramic disk. They concluded that 1 and 3 bar ceramic disks did not generate measurable amount of diffused air. The amount of diffused air generated using 5 bar ceramic disks was relatively small as compared to 15 bar disks.

### *2.5.1.4 Compressibility of the air-water mixture in the water compartment*

An increase in the air pressure on soils that contain occluded air bubbles will result in a compression of the air-water mixture that in turn tends to decrease the volume of the pore fluid and the soil. A decrease in the volume of soil in turn causes a decrease in the size of the air-water interface and hence the actual suction is overestimated (Bocking & Fredlund, 1980). On the other hand, air diffusing through the high air entry disk causes an increase in the volume of air in the water compartment. In a closed system, the air replaces the water below the ceramic disk and pushes the water through the ceramic disk into the soil specimen (see Fig. 2.1*c*) (Fredlund, 1975). An increase in the water content causes a decrease in matric suction of the soil and hence, the actual matric suction of the soil is underestimated. Fredlund & Morgenstern (1973) stated that compression of the air-water mixture in the water compartment increases due to a greater applied chamber air pressure, whereas the water compartment tends to expand due to an increase in the water pressure thus creating discontinuity of the water phase between the ceramic disk and the water in the compartment.

#### *2.5.1.5 Suction equilibration time*

Bocking & Fredlund (1980) stated that the time response curves for null-type axis-translation tests show an apparent equilibrium state and may not be a true representative of actual suction of the soil. Depending upon the rate of application of the chamber air pressure to the soil specimen and the compressibility of the soil, it is possible to temporarily overshoot the actual suction value.

The time required to reach equilibrium suctions when using the axis-translation technique for the measurement of matric suction is dependent on the type of soil, size of specimen, and the permeability characteristic of the high air-entry disk. Marinho et al. (2008) and Delage et al. (2008) pointed out that a difference in the relative humidity of soil sample for which matric suction measurement is carried out and that of the compressed air in the pressure chamber may cause some instability of the system. This may in turn influence the suction equilibration time. The equilibration time was also found to increase with an increase in the suction level (Oliveira & Marinho, 2008). In many cases, the equilibration time of about 3–6 hrs has been observed for compacted specimens of various soils (Fredlund & Vanapalli, 2002; Pufahl, 1970; Fredlund & Rahardjo, 1993; and Tripathy et al., 2005). In some cases, a quicker response was also possible depending on the initial compaction conditions (Rahardjo & Leong, 2006; and Leong et al., 2009). In general, drier specimens would take longer time to equilibrate in null-type tests.

### 2.5.2 Indirect suction measurement

Indirect suction measurement methods measure the moisture equilibrium condition of the soil instead of suction (Bulut & Leong, 2008). These methods use measurements or indicators of water content or a physical property that is sensitive to a change in water content (e.g. relative humidity, electrical resistance and rate of heat dissipation) (Ridley & Wray, 1995).

A number of techniques have been used to measure soil suction indirectly (Table 2.1). These include the use of psychrometers, chilled-mirror hygrometer, thermal and electrical conductivity sensors, and the filter paper technique. The total suction can be determined by measuring the vapour pressures of the soil water or relative humidity in the soil. The relative humidity can be measured directly by using relative humidity sensor or chilled-mirror device. The filter paper can be used as a measuring sensor to indirectly determine the relative humidity.

Since comprehensive reviews of suction measurement techniques exist elsewhere, (e.g., Ridley & Wray, 1995; Rahardjo & Leong, 2006), only filter paper and chilled-mirror methods will be briefly discussed here.

#### *2.5.2.1 Filter paper*

The filter paper method was developed by soil scientists and agronomists for measuring soil suction (e.g., Gardner, 1937; Fawcett & Collis-George, 1967; Al-Khafaf & Hanks, 1974). In geotechnical engineering fields, many researchers have also used the technique as a routine method for suction measurement (e.g., McKeen, 1980; Chandler & Gutierez, 1986; Chandler et al., 1992; Houston et al., 1994; Ridley, 1995; Leong et al., 2002). The advantages of filter paper method are the ability to measure matric and total suctions, and are considered to be an inexpensive, reasonably accurate, and technically simple method that can measure a wide range of soil suction.

The principle of the filter paper method is to measure suction indirectly by relating the water absorbed by specified filter papers with suction by means of calibration curves. If soil specimen and filter paper are sealed in a closed container, moisture exchange will take place until equilibrium is reached (Al-Khafaf & Hanks, 1974). When the soil specimen and the filter paper is separated from each other, moisture transfer take place via vapour transfer, and hence total suction can be measured. Matric suction is measured if the soil specimen is in direct contact with the filter paper. In this case, the filter paper absorbs water through liquid flow, the salts present in the soil water will also move with the water into the filter paper and there will not be a salt solution gradient between any two points in the soil mass.

Schleicher & Schuell No. 589 and Whatman No. 42 are the most commonly used types of filter paper. Leong et al. (2002) stated that the consistency between the calibration curves obtained using different techniques and by different authors are greater by using Whatman No. 42 than Schleicher and Schuell No 589.

The filter paper method is highly dependent on the performance (and speed) of the operator and calibration curves used. McQueen & Miller (1968) suggested that the adopted conditions and testing procedures for calibrating the filter paper should be similar to the actual soil suction measurements.

### *2.5.2.2 Calibration curve of filter paper*

Different calibration curves relating soil suction to water content of filter papers can be found in the literature (Table 2.2). Some studies claimed that the calibration curves are different for total or matric suction measurements (Houston, et al., 1994; Bulut, et al., 2001; Leong, et al., 2002). However, other studies (Marinho & Oliveira, 2006; Walker et al., 2005) stated that only one calibration curve for total and matric suction can be obtained if longer equilibration time is allowed especially at lower imposed levels of suction. Ridley & Wray (1995) indicated that the non contact filter paper is insensitive when used for measuring low total suctions due to possible vapour and temperature non-equilibrium during suction measurement.

It is clear that there is a disagreement over the use and validity of published calibration curves. Verification is always recommended when using the published suction calibration curves since such curves are expected to be valid for specific equalisation time used during the calibration process. Several factors, such as suction source used in calibration, quality of filter paper, hysteresis, and equilibration time, may be attributed for the different calibration curves found in the literature (Leong et al., 2002).

#### *2.5.2.2.1 Suction source used during calibration of filter paper*

It can be seen from Table 2.2 that several methods have been used by various researchers to apply suction during filter paper calibration. A method used for generating suction depends upon the level of suction required.

***Table 2.2 Published filter paper calibration equations***

| Reference | FP type* | FP method | Suction range (KPa) | $w_{fp}^{+}$ range | Suction Eq. | Suction source | Equilibrium time |
|---|---|---|---|---|---|---|---|
| Fawcett & Collis (1967) | WM 42 | contact | $100\text{-}10^6$ | <45.3 | $\Psi_{pF} = 6.601 - 0.0839w_{fp}$ | vacuum desiccator | 6 -7 days |
| | | | 1-100 | >45.3 | $\Psi_{pF} = 3.642 - 0.0151w_{fp}$ | a pressure membrane, pressure plate | |
| McQueen & Miller (1968) | SS 589 | contact & non contact | | <54 | $\log \Psi = 5.238 - 0.0723w_{fb}$ | combination of suction plate, pressure plate, and slat solution | 7 days |
| | | | | >54 | $\log \Psi = 1.8966 - 0.01025w_{fp}$ | | |
| Al-Khafaf & Hanks (1974) | SS 589 | contact & non contact | | <85 | $\log \Psi = 4.136 - 0.0337w_{fp}$ | slat solution, Thrmocouple psychrometer, pressure plates, and soil column | 2 days |
| | | | | >85 | $\log \Psi = 2.0021 - 0.009w_{fp}$ | | |
| McKeen (1980) | SS 589 | | | < 66 | $\log \Psi = 4.9 - 1.0624w_{fp}$ | suction plate, pressure membrane, pressure plate | |
| | | | | ≥ 66 | $\log \Psi = 1.25 - 0.0069w_{fp}$ | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hamblin (1981) | WM 42 | contact | 1-3000 | | $\ln \Psi = 2.397 - 3.683 \ln(w_{fp})$ | up to 70 kPa- suction plate, up to 0.7 MPa -direct pressure plate, up to 1.5 MPa-pressure membrane, and up to 5.5 MPa-saturated vapour pressure at 20°C | mintues-36 days |
| Mckeen (1985) | SS 589 | contact & non contact | 6- 2 pF<br>2 -1.5 pF | | $\Psi = 5.90 - 6.2407\ w_{fp}$<br>$\Psi = 2.25 - 0.6853\ w_{fp}$ | combination of suction plate, pressure plate, and slat solution filed soil sample | |
| Chandler & Gutierrez (1986) | WM 42 | contact | 80-6000 | < 47 | $\Psi_{pf} = 4.84 - 0.0622\ w_{fp}$ | oedometer samples and salt solution | 5 days |
| ASTM | WM 42 | contact & non contact | | <45.3<br>>45.3 | $\log \Psi = 5.327 - 0.0779 w_{fp}$<br>$\log \Psi = 2.412 - 0.0135 w_{fp}$ | combination of suction plate, pressure plate, and slat solution | 7 days |
| ASTM | SS 589 | contact & non contact | | <54<br>>54 | $\log \Psi = 5.058 - 0.0688 w_{fp}$<br>$\log \Psi = 1.882 - 0.0102 w_{fp}$ | combination of suction plate, pressure plate, and slat solution | 7 days |
| Miller & Nelson (1992) | TS 4705 -F10 | contact | | <43 | $\log \Psi = 4.883 - 0.0599 w_{fp}$ | suction plate, pressure membrane, pressure plate | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Chandler et al. (1992) | WM 42 | contact | ≥ 80 | ≤ 47 | $\log \Psi = 4.84 - 0.0622w_{fp}$ | oedometer and triaxial samples, pressure plate | |
| | | | ≤80 | > 47 | $\log \Psi = 6.05 - 2.48 \log (w_{fp})$ | | |
| Houston et al. (1994 | FQC | contact | 1.9-4.4 pF | | $\text{Log } w = 2.852 - 0.332\Psi_{pF}$ | pressure plate, and tensiometers | 7 days |
| | | Non contact | $4.5 < \Psi_{pF} < 6.0$ | | $\text{Log } w = 3.63 - 0.483\Psi_{pF}$ | slat solution | 7 days |
| Deka et al (1995) | WM 42 | contact | >47.9 | < 55.6 | $\log \Psi = 5.297 - 6.507\ w_{fp}$ | 1.0 - 65kPa-suction plate | 6 days |
| | | | <47.9 | >55.6 | $\log \Psi = 2.38 - 1.259\ w_{fp}$ | 0.25-100 MPa- thermocouple psychrometer | 7 days |
| Deka et al. (1995) | WM 42 | contact | >48.9 | >51.3 | $\log \Psi = 5.32 - 7.083\ w_{fp}$ | 1.0 - 65kPa-suction plate | 6 days |
| | | | <48.9 | <51.3 | $\log \Psi = 2.338 - 1.226w_{fp}$ | 0.25-100 MPa- thermocouple psychrometer | 7 days |
| Leong et al. (2002) | WM 42 | contact | <1000 | <47 | $\log \Psi = 4.945 - 0.0673w_{fp}$ | pressure plate | 2 -5 days |
| | | contact | <1000 | ≥47 | $\log \Psi = 2.909 - 0.0229w_{fp}$ | pressure plate | 2 -5 days |
| | | non contact | >1000 | <26 | $\log \Psi = 5.31 - 0.0879w_{fp}$ | slat solution | 7-14 days |
| | WM 42 | non contact | >1000 | ≥26 | $\log \Psi = 8.779 - 0.222w_{fp}$ | slat solution | 7-14 days |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Leong et al. (2002) | SS 589 | contact | | ≥54 | $\log \Psi = 2.659 - 0.018w_{fp}$ | pressure plate | 2 -5 days |
| | | contact | | <54 | $\log \Psi = 5.438 - 0.069w_{fp}$ | pressure plate | 2 -5 days |
| | SS 589 | non contact | | ≥32 | $\log \Psi = 8.778 - 0.191w_{fp}$ | slat solution | 7-14 days |
| | | non contact | | <32 | $\log \Psi = 5.26 - 0.0705w_{fp}$ | slat solution | 7-14 days |
| Likos & Lu (2003) | WM 42 | non contact | 4.5-2.75 log (kPa) | | $\log \Psi = 5.48 - 0.138\ w_{fp}$ | slat solution | |
| Oliveira & Marinho (2006) | WM 42 | contact & non contact | | <33 | $\log \Psi = 2.57 - 0.0154\ w_{fp}$ | 10-30, suction plate,70-40, pressure plate | 7 days |
| | | | | < 33 | $\log \Psi = 4.83 - 0.0839\ w_{fp}$ | 500-5000, NaCl solution | 7-15 days |
| Power et al. (2008) | WM 42 | contact | 300 | ≤38 | $\log \Psi = 151.13 - 94.343 \log(w_{fp})$ | pressure plate apparatus | 12 days |
| | | | 20-300 | >38 | $\log \Psi = 6.712 - 2.933 \log(w_{fp})$ | | |

* *Filter paper type , WM 42- Whatman No. 42, SS 509 - Schleicher and Schuell No 589, FQC - Fisher quantitative coarse (9.54 A), TS 4705-F10 - Thomas Scientific 4705-F10*

+ $w_{fp}$ *- Filter paper water content*

$\Psi$ *- Suction*

For filter paper calibration test, matric suctions are normally imposed using a pressure membrane extractor or pressure plate apparatus, or even a suction plate apparatus in which axis-translation technique is employed (e.g., Al-Khafaf & Hanks, 1974; Hamblin, 1981; Greacen et al., 1987; Deka et al., 1995; Leong et al., 2002).

The calibration curve for the filter paper total suction measurement is commonly achieved by placing it in a closed container above a slat solution of known vapour pressure (total suction) (Fawcett & Collis-George, 1967; McQueen & Miller, 1968; Al-Khafaf & Hanks, 1974; Hamblin, 1981; Chandler & Gutierrez, 1986; Sibley et al., 1990; Houston et al., 1994; Harrison & Blight, 1998; Leong et al., 2002; Likos & Lu, 2003). The main problem when using the vapour equilibrium technique is due to the difficulty in maintaining a thermal equilibrium between the salt solution used and the vapour space above the salt solution. Agus & Schanz (2005) suggested that suction measurement should be limited to values higher than 200 kPa, at 0.1°C temperature fluctuation when using the vapour equilibrium technique, in order to limit the error in suction measurement to 30%. On the other hand, Marinho & Oliveira (2006) stated that temperature fluctuation does not interfere with the relative humidity but affects the speed that the water molecule escapes from the liquid state and this may interfere with the equilibrium time.

*2.5.2.2.2 Equilibrium time in filter paper calibration tests*

Table 2.2 shows that various researchers have adopted different equilibration time for calibrating filter papers. The equilibration time depends upon the suction source, measured suction type, number of pieces of filter paper used, and suction level. Swarbrick (1995) reported that that the contact and non contact calibration curves are time dependent and are incompatible. The proper equilibrium time is a key component in either calibrating or testing with filter papers (Hamblin, 1981). Insufficient equilibration time will lead to higher suction values, while longer equilibration time may cause the filter paper to degrade.

Leong et al. (2002) pointed out that the water vapour pressure in the air space above salt solution will take some time to reach equilibrium then the filter paper will come to equilibrium with the water vapour in the air space. On the other hand, when placing a filter paper in a pressure plate apparatus, the equilibration time is the time the filter paper takes to achieve equilibrium with the applied matric suction. Generally, the equilibrium time for non contact filter paper method is longer than for contact filter paper method. For contact filter paper method liquid phase equilibration is fairly rapid and generally requires only a few days, provided that a good contact was established comparing to vapour equilibration in non contact filter paper method.

ASTM D5294-10 recommended a minimum equilibration time of seven days for contact and non contact filter paper tests. McQueen & Miller (1968) suggested that the equilibrium is about seven days. Al-Khafaf & Hanks (1974) used an equilibrium time of two days. Hamblin (1981) examined the equilibrium time for contact filter paper and reported that the equilibrium varied from a few minutes to approximately 36 hours. Greacen et al. (1987) reported that the water content of the filter paper increases at low suction and the water content increase will continue up to a seven days. Houston et al. (1994) suggested that true equilibrium may never be reached for non contact filter paper measurements at low suction values. Marinho (1994) studied the time required for equilibration of Whatman No. 42 (non contact method) and suggested that the equilibrium time increases as the suction level decrease (Table2.3).

***Table 2.3 Suggested equilibrating time for measuring total suction (non contact) using NaCl solution (Marinho, 1994)***

| Total suction (kPa) | Equilibration time |
|---|---|
| 0 - 100 | more than 30 days |
| 100 - 250 | 30 days |
| 250 - 1000 | 15 days |
| 1000 - 30000 | 7 days |

Ridley (1995) reported that a great reduction in the total suction sensitivity for a narrow filter paper water content range occurs if a 14 day equilibration time is selected instead of a 7 day equilibration time. Harrison & Blight (1998) used an equilibrium time of 7 to 10 days for initially dry filter paper (contact and non contact). For initially wet filter paper in contact method the equilibration times was 21 days, while in non contact method the equilibration times were between 25 to 30 days. Leong et al. (2002) observed that the equilibration times for initially wet filter paper were longer than those needed for initially dry filter paper. The equilibration times of Whatman No. 42 and S&S 589 filter papers (initially dry) in a pressure plate and over salt solutions were found to be between two and five days, respectively.

*2.5.2.2.3 Hysteresis in filter paper calibration curves*

Filter paper is expect to exhibit hysteretic behaviour during the drying and wetting processes due to the fibrous porous nature of the material. Thus the calibration curve for an initially dry filter paper may be anticipated to be different from that of an initially wet filter paper.

Al-Khafaf & Hanks (1974) noted that the filter papers should always be wetted up (initially dry) to avoid problems with the hysteresis. Fawcett & Collis-George (1967), Hamblin (1981), Chandler & Gutierrez (1986) and Deka et al. (1995) indicated that initially air dried filter paper should be used. However, Ridley (1995) stated that air drying of the filter paper before calibrating or testing may not be sufficient. In order to ensure the same wetting path is followed and to avoid the hysteresis effect, Swarbrick (1995) suggested that the filter paper should be oven dried. ASTM D 5928 recommended using an oven dried filter paper before calibrating or testing.

Chander & Gutierrez (1986) showed that the rate of change in the drying process was higher than in wetting process, indicating hysteresis of the filter paper. Ridley (1995) showed matric suction calibration data on Whatman No. 42 filter paper where hysteresis was observed. Deka et al. (1995) investigated calibration curves on both the drying and wetting curves and noted that calibration suctions based on drying curve underestimated the actual suction values. Harrison & Blight (1998) showed calibration data of Whatman No. 42 and Schleicher and Schuell No. 589 filter papers during drying and wetting processes which exhibited hysteresis. They also used a pressure plate for calibrating the filter papers and found the equilibrium time for initially dry filter papers to be 10 days, whereas for initially wet filter papers the equilibrium time was 25 to 30 days. Houston et al. (1994) and Leong et al. (2002) indicated that insufficient equilibration time can produce a remarkable hysteresis and concluded that hysteresis appears to be minor when equilibrium time is sufficient.

*2.5.2.2.4 Calibration tests of different batches of filter papers*

The different calibration curves obtained for the same filter paper, found in the literature, may be attributed due to the difference in characteristic of filter papers among different batches of filter paper. Hamblin (1981) and McKeen (1980) reported no significant difference between calibration curves developed from different batches produced two years apart. Sibley & Williams (1990) also observed that the calibration curves for batches procured from the same production batch, at the same time, and from the same supplier were almost identical. Similar results were found by Fawcett & Collis-George (1967), Chandler & Gutierrez (1986), and Swarbrick (1995). However, several researchers recommended establishing the calibration curve for each batch of filter papers before further application. Greacen et al. (1989), Likos & Lu (2002) and Marinho & Oliveira (2006) found high variability in calibration curves obtained for different batches of filter papers.

Another concern regarding using filter paper technique is the deterioration of filter paper with time, primarily due to bacterial and algal growth. Fawcett & Collis- George (1967), McQueen & Miller (1968), Al-Khafaf & Hanks (1974) and Hamblin (1981) used a pretreat filter paper with different solutions. Hamblin (1981) and Chandler and Gutierrez (1986) reported that there was no need to pretreat the filter paper prior to use. Leong et al. (2002) found no reports in the literature of serious problems with bacterial or algal growth on filter papers when they were used for measurements of suction. They stated that a short seven days equilibrium time does not offer enough time for bacterial growth.

#### *2.5.2.3 Total suction measurement using the chilled-mirror dew-point technique*

The chilled-mirror dew-point technique has been used in soil science to quantify water potential of soil. In geotechnical engineering, the technique has been used for measuring total suction of soils (Leong et al., 2003; Agus & Schanz, 2005). The working principle of the chilled-mirror potentiameter device is based on the thermodynamic relationship between relative humidity, temperature and total suction according to Kelvin's equation. The device computes the total suction based on the equilibrium of the liquid phase of the water in a soil specimen with the vapour phase of the water in the air space above the sample in a sealed chamber. The primary advantages of chilled-mirror potentiometer for soil suction measurement are its simplicity and speed.

### 2.5.3 Indirect measurement of osmotic suction

Osmotic suction may be present in both saturated and unsaturated soils. Osmotic suction depends upon the concentration of ions dissolved in the pore water. Osmotic suction can be indirectly determined by measuring the electrical conductivity of the pore water (Fredlund & Rahardjo, 1993). The soil pore-water can be extracted using a pore-fluid squeezer. The electrical conductivity of the soil water is converted to suction using an osmotic suction-electrical conductivity calibration curve, such as that provided by USDA (1950). The squeezing technique was used by a number of researchers for measuring osmotic suction of soils (e.g., Krahn & Fredlund, 1972; Iyer, 1990; Leong et al., 2003). The determination of osmotic suction by measuring the electrical conductivity is generally applicable for the entire range of osmotic suction; however, the results may be influenced by the magnitude of the extraction pressure used and the type of soil.

### 2.5.4 Effect of compaction conditions on soil suction

Several studies have been performed to investigate the effect of compaction conditions (water content, dry density, degree of saturation, compaction effort, and compaction method) on the suction of compacted soils. Most of the studies demonstrated that the matric and total suctions are primarily influenced by the compaction water content. The pores between the soil particles are nearly filled with water at high water content, and causing the air-water interface to be relatively flat. In contrast, decreasing the water content implicates the reduction of the radius of the meniscus, and causing the suction in the soil to increase.

Croney & Coleman (1954) and Khrahn & Fredlund (1972) reported that the initial suction decreases with the increasing water content and the relationship between matric suction and water content appear to be unique. Olson & Langfelder (1965) carried out a series of tests using five different soils and reported the similar findings (Fig. 2.2). Vanapalli et al. (1999) used axis-translation technique to measure the matric suction of compacted glacial till and demonstrated that a unique relationship appears to exist between matric suction and the as-compacted water content. Sreedeep & Singh (2005) showed that soil suction decreases with an increase in water content for the same dry density. Malaya & Sreedeep (2010) used a tensiometer to measure the matric suction on specimens with same water content but compacted at different dry densities and found that the water content is the predominant parameter that determines suction in the soil.

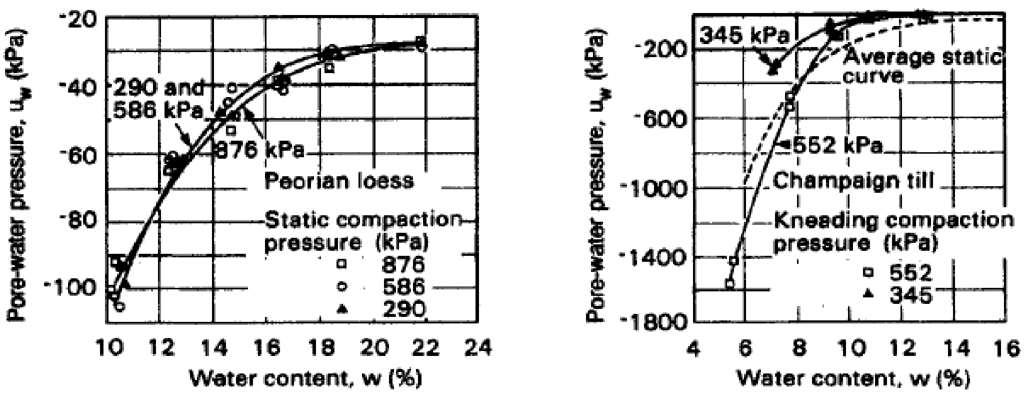



***Fig.2.2 Negative pore-water pressure measurements on compacted specimens using the axis-translation technique (from Olson & Langfelder, 1965)***

There are some contradictions, however, reported in the literature regarding the effect of compaction dry density (or compaction effort) on the soil suction at constant water content. Olson & Langfelder (1965) and Krahn & Fredlund (1972) tested compacted soils prepared by static and impact compaction method and concluded that the effect of dry density on matric suction was insignificant. Similar findings were reported by other researchers (e.g., Vanapalli, 1994; Wan et al., 1995; Agus & Schanz, 2006; Malaya & Sreedeep, 2010; among others). On the other hand, Croney & Coleman (1954) reported that matric suction is influenced by the soil dry density in incompressible or undisturbed soils. Mou & Chu (1981) also measured higher suction values in more dense specimens at the same water content in two soils prepared by static and kneading compaction methods. Tripathy et al. (2003) also found that at a given compaction water content the soil suction decreased with an increase in compaction effort (increase in density). Gibbs (1965) reported that the effect of dry density on suction is dependent upon the water content level based on test results that related suction to both the water content and dry density in a form of iso-lines of equal suctions. Gonzalez & Colmenares (2006) concluded that suction is influenced by the water content with some influence of the dry density. Yang et al. (2012) concluded that the soil suction increases with increasing the compaction effort, provided that the effect of the change in void ratio on soil suction is larger than the effect of the change in degree of saturation on soil suction. On the other hand, if the effect of the change in void ratio on soil suction is smaller than the effect of the change in degree of saturation on soil suction, the soil suction decreases with a reduction in compaction effort.

Shackel (1973) studied the effect of degree of saturation on suction and found the matric suction depends primarily upon the degree of saturation and was slightly influenced by the dry density. Gonzalez & Colmenares (2006) found that at a constant dry density, an increase in the as-compacted degree of saturation cause a markedly reduction in the matric suction and at a constant degree of saturation, the matric suction increased as the compaction dry density increased. Similar finding was reported by Sudhakar & Revanasiddappa (2000). At a given degree of saturation, the smaller pores of denser specimens produce higher matric suction.

From the data reported by Olson & Langfelder (1965), Marinho & Stuermer (2000) and Gonzalez & Colmenares (2006), it can be noted that the type of mechanical compaction (e.g., dynamic or static or kneading compaction) may result in a different relationship between water content and matric suction. Mou & Chu (1981) indicated that the different soil structures resulting from the different compaction methods causing the water content versus matric suction relationships to be different.

## 2.6 Suction control methods

The most commonly used techniques for controlling suction of soils are: (*i*) axis-translation, (*ii*) relative humidity or vapour equilibrium, and (*iii*) osmotic technique. These techniques have been used in several experimental research works on unsaturated soils. The principles and the main characteristics of these techniques are briefly described below.

### 2.6.1 Axis-translation technique

The axis-translation technique (Hilf, 1956) was mainly developed in order to overcome the problem of cavitation at sufficiently low negative water pressures. The axis-translation technique simply translates the origin of the reference for the pore-water pressure ($u_w$) from current value to a higher value equal to the air pressure applied to the soil specimen ($u_a$). In this manner, and under undarin condition, matric suction ($u_a$ - $u_w$) of the soil specimen remains constant regardless of the translation of the pore-air and pore-water pressure.

For imposing matric suction, the axis-translation technique requires the control of the pore-air pressure and the pore-water pressure is kept at atmospheric. Axis-translation is accomplished by separating air and water phases in a soil through a saturated high air-entry porous material, usually a ceramic disk. The saturated high air-entry ceramic disk allows water passage, but prevents flow of free air when the applied matric suction does not exceed air-entry value of the ceramic disk. Pressure plate, pressure membrane, and suction plate devices are developed based on the axis-translation technique.

The axis-translation technique is commonly used in the laboratory testing of unsaturated soils because it is relatively easy to convert existing equipment for saturated soil testing by simply adding a high air entry filter and an air pressure source. It has been successfully applied to the volume change and shear strength testing of an unsaturated soil, with equipment including oedometers (Alonso et al., 1995), direct shear apparatus (Gan, & Fredlund, 1988) and triaxial apparatus (Matyas & Radhakrishna, 1968; Wheeler & Sivakumar, 1995).

#### *2.6.1.1 Limitations of axis-translation technique*

Axis-translation technique requires the air and water phases to be continuous in order to characterize actual suction within the soil sample. Good contact between the soil specimen and the saturated ceramic disk should be established throughout the experiment to ensure the continuity between water phase in the soil specimen tested and that in the pores of the ceramic disk used (Murray & Sivakumar, 2010). Another limitation of the axis-translation technique is related to the air diffusion through the high air-entry ceramic disk. Unsaturated soil testing using axis-translation technique often requires an extended period of time. As the test progresses, pore-air diffuses through the water in the high-air entry disk and appears as air bubbles beneath the disk, which may introduce inaccuracy to the measurement of water volume or pore-water pressure (Fredlund & Rahardjo, 1993). Romero (2001) reported that the air diffusion rate varied fairly with applied matric suction. The higher is the applied water pressure; the lower will be the rate of air diffusion. Periodic flushing of air bubbles beneath the ceramic disk is necessary to ensure continuity between the pore-water in the soil and the water in the measuring system. Controlling of matric suction using this technique is limited by the air entry value of the ceramic disk used.

### 2.6.2 Vapour equilibrium technique

The vapour equilibrium technique is based on the observation that the relative humidity in the airspace above a salt solution is unique to the concentration and chemical composition of that solution (e.g., Young, 1967; Greenspan, 1976). Knowing the equilibrium relative humidity of the airspace enables the calculation of total suction using Kelvin's equation (Fredlund & Rahardjo, 1993). Therefore, by controlling the relative humidity of the atmosphere surrounding the soil specimen, total suction can be applied on an unsaturated soil specimen.

In this technique, a soil specimen is placed in sealed system where an aqueous solution results in a controlled partial vapour pressure generated by the known concentration salt solution. Under isothermal equilibrium conditions, the soil specimen undergoes water exchange with the vapour until the suction in the specimen is in equilibrium with the partial vapour pressure. Applied total suction can be altered by using different saturated salt solutions or varying the concentration of same salt solution leading to different relative humidity values (Tang & Cui, 2005).

Delage et al. (1998) stated that the sensitivity of relative humidity is depends both upon the absolute temperature and the physical properties of the chemical components. They showed that the uncertainty in this technique may be acceptable for suction values higher than 8 MPa. Romero et al. (2001) pointed out the difficulty of controlling the humidity at low values of relative humidity, since the technique is extremely sensitive to temperature gradient that exists between the salt solution, the vapour space, and the soil specimen. They suggested 3 MPa as a lower limit in using vapour equilibrium technique. The upper limit of the imposed suction depends on the minimum relative humidity that could be achieved.

The limitation of this method is that equilibration of suction within the soil is very slow due to the very low vapour transfer and can take up to several weeks to several months depending on soil type. However, testing times can be significantly reduced by forcing the vapour to flow through the soil specimens by means of a vacuum pump (Delage et al., 1998; ;Agus, 2005; Blatz et al., 2008; ).

Vapour equilibrium technique was used by a number of researchers for applying total suction in soils. It has been used for controlling total suction during unsaturated oedometer tests (e.g., Lloret et al., 2003), triaxial tests (e.g., Blatz & Graham, 2000), and for the determination of soil-water characteristic curve (e.g., Croney et al., 1952).

### 2.6.3 Osmotic technique

Osmotic technique is applied in testing unsaturated soil to control matric suction. In the osmotic technique, water drainage of the soil specimen tested is generated by osmosis process due to a difference in concentration between the pore-water and the solution (normally polyethylene glycol, PEG) used. A semi-permeable membrane which is permeable to water but not to the PEG molecules is required to separate the pore-water and the PEG solution. The soil water will flow across the semi permeable membrane, until the suction in the soil and the osmotic suction of the PEG solution are in equilibrium. By varying the concentration of PEG solution, various osmotic gradients can be created (Zur, 1966).

Osmotic technique has been used to study the water retention behaviour of soils (Fleureau et al., 1993; Marcial et al., 2002; Tripathy et al., 2011). Similarly, several researchers have used this technique to control suction in oedometers, the shear box and the triaxial tests (e.g., Delage et al., 1992; Cuisinier & Masrouri, 2004; Cui & Delage, 1996).

The main limitation of the osmotic technique are associated with (*i*) intrusion of PEG into soil specimens during testing (Williams & Shaykewich, 1969; Tarantino & Mongiovi, 2000; Delage & Cui, 2008; Tripathy et al., 2011) and (*ii*) the nonlinearity of the calibration curves (Money, 1989; Delage et al., 2008). These problems are more relevant at higher applied suctions.

## 2.7 Soil-water characteristic curve (SWCC)

Behaviour of unsaturated soil is highly dependent on the magnitude of soil suction, which in turn is influenced by soil water content for a given soil. The soil-water characteristic curve (SWCC) represents the ability of a soil to retain water at over a range of suctions (Fredlund, 2002). The SWCC defines the relationship between the amount of water in the soil pores, which is generally quantified in terms of gravimetric water content ($w$) or volumetric water content ($\theta$) or degree of saturation, ($S_r$) and soil suction. All three parameters provide similar information if the initial volume of the soil specimen remains constant. The SWCC can be established by equilibrating a soil specimen to a series of different applied suctions or by using multiple specimens equilibrated at different applied suctions (Fredlund et al., 2001). Matric suction and total suction at higher suction region are routinely plotted together to generate the entire SWCC. SWCCs are commonly developed in the laboratory using pressure plate extractors and salt solution tests.

The relationship encompasses both desorption or drying and absorption or wetting process. The drying curve differs from the wetting curve as a result of hysteresis, which can be explained by the complex nature of soil pore structure. This phenomenon is caused by several factors, such as geometric nonuniformity of individual pores, changes in the contact angle during drying and wetting, trapped air in the voids, and the air-water interface development during the wetting or drying process (Hillel, 1982; Fredlund & Rahardjo, 1993).

The use of the soil-water characteristic curve has been identified as important relationship for quantifying unsaturated soil behaviour. Methods have been proposed to predict volume change, shear strength, coefficient of permeability, diffusion, adsorption, vapour diffusion, thermal conductivity, and a variety of other properties for unsaturated soil based in part on the information provided in the SWCC (Fredlund & Rahardjo, 1993; Barbour, 1998; Fredlund, 2000).

### 2.7.1 Features of SWCC (SWCC identifiable zones)

The key parameters used to define the SWCC include; the air-entry suction (AEV) and the residual water content ($\theta_r$). The AEV of the soil can be defined as the value of suction at which the air starts to enter the largest pores in the soil. The residual water content can be defined as the water content where a large suction change is required to remove the additional water from the soil (Fredlund & Xing, 1994). In other words, it is the water content at which an increase in suction does not produce a significant change in water content.

A typical SWCC exhibits different zones along the drying curve. White et al. (1970), Vanapalli (1994), and Lu & Likos (2004) defined three zones of desaturation (Fig. 2.3): (*i*) the boundary effect zone (saturation zone) where almost all the soil pores are filled with water and the soil remains saturated, (*ii*) the transition zone (desaturation zone) where the soil starts to desaturate and the water content or degree of saturation reduces significantly with increase in suction, and (*iii*) the residual zone where a large increase in suction lead to relatively small changes in soil water content or degree of saturation and characterised by a discontinuous water phase. The water content in soil at the commencement of this stage is generally referred to as residual water content. It is believed that similar ones apply to the wetting curve (Fredlund, 2000).

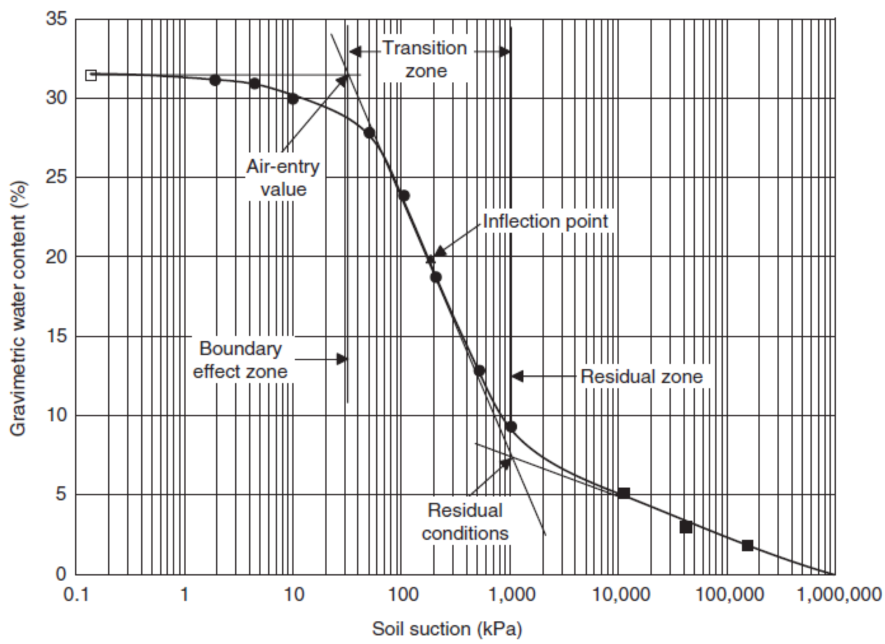



***Fig.2.3 Identifiable stages of a typical SWCC (from Vanapalli et al. 1999)***

### 2.7.2 Factors influencing the SWCC

The shape of the SWCC depends upon the pore size distribution and volume change of the soil. These two characteristics are affected by the initial water content, soil structure, soil type, compaction effort, and the stress history (e.g., Tinjum et al., 1997; Vanapalli et al., 1999; Simms & Yanful, 2001; Fredlund et al., 2002).

#### *2.7.2.1 Influence of initial compaction water content*

Soil compacted with an initial compaction water content representing the dry and wet of optimum will produce specimens that have differences in soil structure and pore-size distribution (Gens et al., 1995; and Vanapalli et al., 1999). Orientation of soil particles determines the size of the pores and their distribution, which affects the order of the SWCCs for the same soil type and compaction effort. The particle orientation at dry of optimum leads to soil fabric that has more interconnected pores compared to wet of optimum (Mitchell et al., 1965). The resistance to de-saturation is relatively low in the dry of optimum specimens in comparison to wet of optimum specimens, in which case the pore channels are generally disconnected and offer resistance to the de-saturation process (Cui & Delage, 1996). The boundary between pore conditions of dry and wet of optimum is approximately occurs at water content equal to the optimum water content (Tarantino & Tombolato, 2005).

Vanapalli et al. (1999), Tinjum et al. (1997), and Miller et al. (2002) showed that the shape of the SWCC is a function of the initial water content. Tests results presented by these researches showed that the SWCC representing dry of optimum plots below the wet of optimum and it is relatively steeper, because the soil would retain less water in the case of dry of optimum in comparison to the wet of optimum compaction water content. In other words, at the same suction, specimens prepared wet of optimum have higher water content than specimens prepared dry of optimum. Additionally, the AEV increased as the initial water content increased (Yang et al., 2004). Soils compacted dry of optimum exhibited lower AEVs than soil compacted wet of optimum. The influence of the initial compaction water content is more obvious for the near saturation portion of the SWCC in which capillary forces are present. At high suction, SWCCs with different initial water contents tend to converge (Vanapalli et al., 1999; Baker & Frydman, 2009).

#### 2.7.2.2 Influence of compaction effort

Typically, there will be a reduction in the size and the number of pores in the soil with an increase in the compaction effort. An increase in compaction effort implies an increase in dry density and a decrease in void ratio, thus, some differences in the SWCC of the same soil compacted with different efforts are expected.

Croney & Coleman (1954) reported that a specimen with a high initial compacted density had a higher air-entry value than that of a specimen with a low initial compacted density. Tinjum et al. (1997) reported that the changes in shape of the SWCC are consistent with changes in pore structure that occur when compaction water content and compaction effort are varied. Leong & Rahardjo (2002) studied the influence of compaction effort (three different efforts were used) on the SWCC of a mudstone residual soil. They observed an increase in the AEV and narrow band of the SWCC as the compaction effort increases. Similar finding were reported by Miller et al. (2002) and Sun et al. (2006). In another study, Sugii et al. (2002) showed that the SWCC is unique for the different compaction efforts beyond the transition zone for the tested sandy soil. Marinho et al. (2000) stated that the compaction energy seems to affect the level of suction that is controlled by capillary phenomena. At higher suction values, the effect of compaction effort (or dry density) tends to diminish.

A review of literature indicates that the influence of compaction effort on the SWCC is more predominant in fine grained soils than that for coarse grained soils. Bowels (1979) indicated that the compaction method and the compaction effort have higher influence on the final dry density of fine grained soils than in coarse grained soils.

#### 2.7.2.3 Influence of soil type and fine fractions

Soils with smaller particles such as a silt and clay usually have smaller pore space and greater relative surface area, and present a tendency to desaturate at a slower rate (Vanapalli et al., 1999). On the other hand, coarse grained soils, such as the sand, possesses lower AEV and show a distinct point at which they begin to rapidly desaturate with increasing suction. The rate of desaturation depends upon the distribution of the pores in the soil. Study conducted by Cote & Konrad (2002) showed that the maximum pore size is controlled by the percentage of fines rather than the coarse fraction of the material, which in turn influence the SWCC. Indrawan et al. (2006) studied the effects of the addition of coarse grained soils to a residual soil on the drying SWCC and found the AEV and the residual suction decreases with an increase in the gravelly sand and medium sand contents. They also reported that the slopes of the drying SWCCs for the soil mixtures tend to increase with an increase in the coarse-grained fractions. Yang et al. (2004) observed that the drying SWCC of the soil is closely related to the grain size distribution of the soil. The AEV and residual suction values of different soils can vary depending upon the percentage of fines within the soil and the orientation of the particles. (Miller et al., 2002; Yang et al., 2004; Nam et al., 2010).

### 2.7.3 Modelling of SWCC

Several empirical, analytical and statistical models are developed to fit the experimental data and to describe the SWCC. Most of the SWCC equations are empirical in nature and based on the shape of the SWCC. Leong & Rahardjo (1997) and Sillers et al. (2001) presented a comprehensive summary and evaluation of these models. The most commonly used SWCC models are those proposed by van Genuchten (1980) and Fredlund & Xing (1994).

#### *2.7.3.1 van Genuchten model*

van Genuchten (1980) proposed a closed form, three parameter model for the SWCC (Eq. 2.5).

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{\frac{1}{\left[1 + \left(\frac{\Psi}{a}\right)^n\right]}\right\}^m \qquad \text{(Eq. 2.5)}$$

where Θ is the normalised volumetric water content or the effective degree of saturation ($S_e$), $\theta_w$ is the volumetric water content, $\theta_{res}$ is the residual volumetric water content, $\theta_s$ is the saturated volumetric water content , $\Psi$ is the soil suction (kPa), and *a*, *n*, and *m* are fitting parameters.

The model is widely used and fits the SWCC over the entire range of soil suction using three fitting parameters (*a, n* and *m)*. Parameters $a$ , $n$ and $m$ are related to the inverse of the AEV, the pore size distribution of the soil (rate of change slope of curve), and asymmetric shape of the curve, respectively. The advantages of the van Genuchten (1980) model are (Sillers et al., 2001): (*i*) it provides a wide range of flexibility, allowing it to better fit data from a variety of soil types, (*ii*) the model parameters have physical meaning, (*iii*) the effect of one soil parameter can be distinguished from the effect of the others.

### *2.7.3.2 Fredlund & Xing model*

Fredlund & Xing (1994) proposed a model based on the shape of the SWCC being a function of the material's pore size distribution. They introduced a correction function, C($\psi$), in the equation to force the SWCC to pass through a soil suction of $10^6$ kPa at zero water content. This model is in a form similar to the van Genutchen (1980)'s model, however, it has been observed that Fredlund & Xing, (1994)'s equation gave the best fit to the experimental data and requires fewer iterations to determine the parameter values in order to fit experimental data (Leong & Rahardjo, 1997; and Sillers, 2001). The model is expressed as:

$$w(\psi) = C(\psi)\frac{w_s}{\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m} \qquad \text{(Eq. 2.6)}$$

$$C(\psi) = 1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left[1+\left(\frac{10^6}{\psi_r}\right)\right]} \qquad \text{(Eq. 2.7)}$$

where $w_s$ is the saturated water content, $\psi$ is the soil suction (kPa), $e$ is the natural number ($e$ = 2.71828), $C(\psi)$ is the correction factor, $\psi_r$ is the soil suction (kPa) corresponding to the residual water content, and $a$, $n$, and $m$ are fitting parameters.

The model parameters (a, n, and m) in Eqs. 2.6 and 2.7 have the same meaning as mentioned in van Genutchen (1980). The advantages of the Fredlund and Xing (1994)'s model are as follows (Sillers et al., 2001): (*i*) it is continuous over the entire soil suction range, (*ii*) there is great flexibility for the model to fit a wide variety of datasets, (*iii*) the soil parameters are meaningful, and (*iv*) the effect of one parameter can be distinguished from the effect of the other two parameters.

## 2.8 Comparison of suction measurements by different methods

Suction is the fundamental property for the characterisation of unsaturated soil, hence its reliable measurement is vital for the study of unsaturated soils. Several methods have been developed in the past for suction measurements. A brief review of the literature concerning a comparison of measured suctions determined by using different techniques are presented in this section.

Guan & Fredlund (1997) conducted laboratory tests for measuring matric suction of Regina clay and fine silt using filter paper, null-pressure plate, high suction probe, and thermal conductivity sensor. They reported that the results obtained using the filter-paper method and the thermal conductivity sensor tests were in reasonable agreement with the measured suction using the suction probe at relatively high degree of saturation. However, at low degree of saturation scatter in the results obtained by the filter-paper method were observed. On the other hand, agreements were noted between the results obtained from null-pressure device and suction probe at degree of saturation less than 60%. For higher degree of saturation, the matric suctions determined by null-pressure plate were higher than that measured by high suction probe.

Petry & Bryant (2002) showed that total suction values obtained from WP4 chilled-mirror device are generally somewhat higher than filter paper method values. They attributed these differences due the difference in equilibration time in both methods. Bulut et al. (2002) compared the accuracy of the chilled-mirror device with the filter paper method for total suction measurements of undisturbed soil samples. They reported that the at high suction levels the results obtained from the two methods agreed well; however, differences were found at low suction levels. Similarly, Lu & Likos (2004) showed close agreement between total suctions measured with filter paper and chilled-mirror methods on kaolinite over total suction ranging from 0.2 to 6 MPa.

Leong et al. (2003) used a chilled-mirror dew-point technique to measure the relative humidity of kaolin and two residual soils. The tests results showed that total suctions obtained using the device were always higher than the sum of the matric and osmotic suctions measured independently. They reported that the technique could be used to quantify total suction as low as about 150 kPa. Leong et al. (2007) extended the work reported in Leong et al. (2003) and stated that the accuracy of measured suction dependent upon the method used.

Navaneethan et al. (2005) performed suction measurements on four different clays using pressure plate, triaxial cell (measurement of positive pore water pressure after undrained loading), and filter paper techniques. They concluded that the most reliable and consistent results  can be obtained from pressure plate method, whereas the measured suction by undrained loading in a triaxial cell are generally overestimated and the results obtained from filter paper method are highly dependent on the calibration curve used.

Agus & Schanz (2005) assessed four methods for measuring total suction of bentonite–sand mixture; the non contact filter paper method, the psychrometer technique, the relative humidity (RH) sensor, and the chilled-mirror hygrometer technique. The filter paper method results were comparable to the chilled-mirror provided that both techniques are used on soil samples of the same age. The measured total suctions by psychrometer technique were smaller than the chilled-mirror technique, whereas the RH sensor measured larger total suctions than the chilled-mirror. They concluded that the chilled-mirror technique was the most accurate among the four methods.

Cardoso et al. (2007) compared the suction values measured by SMI transistor psychrometer and the WP4 chilled-mirror dew-point psychrometer. The test results showed a good agreement in the total suction range 0.5 to 7 MPa. On the contrary, in the high-suction range (7 to 70 MPa) differences between the results of both devices were observed. Cardoso et al. (2007) attributed the differences in terms of the hydraulic paths undergone by the soils during the measurement period.

Patrick et al. (2007) showed differences and scatter between the total suction results from filter paper and chilled-mirror device. They reported that the possible sources of these discrepancies are: (*i*) errors in chilled-mirror total suction measurements due to incomplete equilibration in the sealed test chamber of the chilled-mirror device and (*ii*) errors in estimated filter paper total suction values due to natural variations of the zero-water content intercept in the log total suction versus water content relationship.

Lourenço et al. (2008) found the suction values of kaolin specimens measured by the high suction tensiometer were smaller than that imposed by the axis translation technique (pressure plate tests). They attributed that to the lack of equilibrium in terms of soil water content in pressure plate tests. Leong et al. (2009) reported that the measured matric suction values using high suction tensiometer and modified null-type device were close with the discrepancy being within ±10%.

Sreedeep & Singh (2011) reported differences in the suctions of fine-grained soils determined by using tensiometer, pressure membrane extractor, and a dew point potentiameter (WP4). They attributed that to insufficient equilibrium time when using of tensiometer and the accuracy of WP4 measurments at low suction values (<1000 kPa).

Zielinski et al (2011) found that the test results obtained by contact filter paper, chilled-mirror dew-point, tensiometer, and time-domain reflectometry, are in good agreements. Noguchi (2009) reported different suction results of sandy clay soil determined by contact filter paper, high capacity suction probe, and pressure plate tests. They suggested that the high capacity suction probes provide the most accurate measurements and the filter paper method underestimated the suction value, whereas the pressure plate overestimated the soil water content. Similar differences were observed between the pressure plate and the tensiometer by Tarantino et al. (2011).

## 2.9 Volume change behaviour

Volume changes are largely due to rearrangement of the grains and changes in the volume of the voids in response to a change in stress state (Fredlund & Morgenstern, 1976). The mechanically induced compression energy is distributed into the soil structure, whereas the energy induced by capillary forces (suction) is distributed into the water phase contained in the soil pores.

Total volume changes of fully saturated soil is equal to the water volume changes since for the stress ranges relevant to engineering practice both water and solid phases are nearly incompressible and the volume changes are caused by inflow or outflow of water. On the other hand, volumetric changes in an unsaturated soil include changes of total volume and water volume due to the presence of the air phase in the soil. In order to fully understand the behaviour of unsaturated soils both the overall and the water volume changes due to changes of stress and suction need to be defined (Fredlund & Rahardjo, 1993). Volume changes associated with the soil structure and the water phase are often written in terms of void ratio change and water content change in geotechnical engineering practice.

Unsaturated soil may either swell or collapse due to wetting, as a function of the applied stress. Alonso et al. (1987) stated that an unsaturated soil may either swell or collapse upon wetting if the confining stress is sufficiently low (swell) or high (collapse), and that a soil might experience a reversal in the volumetric behaviour during wetting (initial swelling followed by collapse). Matyas & Radharkrishna (1968) and Sivakumar et al. (2006) amongst others reported that wetting the soil at a low value of net stress results in an increase of volume (swell), while a decrease in volume (collapse) occurs at high values of net stress. Matyas & Radharkrishna (1968) also indicated that a reduction in suction has two effects on soil structure: a reduction in interparticle stress and a reduction in the rigidity of the soil structure. The volumetric behaviour of the unsaturated soil varies for different soils and different initial conditions.

### 2.9.1 Collapse potential of soil

One-dimensional wetting-induced compression behaviour of compacted soils is usually studied in the laboratory using the single- or double-oedometer method (Lawton et al., 1989). In the method of single oedometer test (ASTM D5333-92), a dry soil specimen is loaded incrementally to a preset stress level (usually 200 kPa). Then, the specimen is wetted and settlement is measured. The single oedometer test is fast, simple and inexpensive to conduct. However, researchers have shown that single oedometer test tends to underestimate actual settlement in the field (Lim & Miller, 2004).

The double-oedometer method proposed by Jennings & Knight (1957) requires testing two identical specimens. One specimen is initially inundated with water under a small seating load and allowed to swell then loaded in standard incremental fashion. The other specimen is tested at the as-compacted water content using standard incremental loading procedures with the exception that loading increments were maintained for 1 h. The vertical strain difference between the as-compacted and inundated test results at a given stress level is assumed to be the collapse or swell potential. The deformation caused due to wetting is not influenced by the loading-wetting sequence (Jennings & Knight, 1957). Although the sequence of loading and wetting is different between the single- and double-oedometer methods, many researchers (Lawton et al., 1989; Miller et al., 1997) found that the two methods generally agree in the collapse region.

Generally, soils with low clay content, compacted at low densities can exhibit collapse behaviour upon wetting (Houston et al., 1993). Collapse of compacted clay soils occurs (Barden et al., 1973; Mitchell, 1976; Pereira & Fredlund, 2000) when (*i*) the compacted soil has an open, potentially unstable and unsaturated structure, (*ii*) a high enough value of external stress is applied to cause the structure to be metastable, and (*iii*) a high enough value of matric suction is available to stabilize the intergranular contacts and whose reduction on wetting leads to collapse.

Several studies have been performed to study the factors that influence the collapse potential of soils. Mishu (1963) reported that under similar conditions, the more plastic soil exhibited larger collapse. Lawton et al. (1989, 1991) suggested that given the proper conditions (compaction conditions, clay content) all soils are susceptible to collapse. Lawton et al. (1992) observed that the collapse potential increases with decreasing degree of saturation, decreasing dry density, and increasing total stress level. Alwail et al., (1994) also concluded that an increase in collapse potential with increasing clay-size fraction and clay-to-silt ratio based on double-oedometer tests. Fredlund & Gan (1995) found that the collapse potential decreases linearly with increasing initial water content for a constant initial dry density, and increasing initial dry density for constant initial water content. Similar behaviour was observed by Rao & Revanasiddappa (2002) and Lim & Miller (2004). Miller & Cleomene (2007) studied the influence of soil fabric on wetting-induced compression behaviour of compacted soils. They concluded that the difference in compression behaviour between soils compacted in field and tested in laboratory due to different soil fabrics may have a significant influence on the volume change behaviour during wetting.

The collapse potential was found to be directly related to the matric suction of compacted soil. Tadepalli & Fredlund (1991) studied collapse behaviour of a compacted soil, and found the soil consolidation coefficient vary linearly with the matric suction during saturation. Rao & Revanasiddappa (2000, 2002) found compacted specimens dry of optimum have higher matric suction and collapse potential values than specimens compacted wet of optimum for degrees of relative compaction less than 100%. Their results also showed the collapse potential increases with increasing matric suction, and it generally increased with decreasing relative compaction.

### 2.9.2 Shrinkage behaviour

Shrinkage is the reduction in total volume as the response to the evaporation of water from the soil. Drying a soil sample induces tensile internal stresses (pore water tensions) caused by capillary menisci, which forces particles to reorient and attract to each other, hence leading to shrinkage (Baumgartl & Kock, 2004). Shrinkage behaviour is typically caused by evaporation (a change in the temperature), transpiration, and lowering the groundwater table in arid and semi-arid regions. The definition considers a relationship between void ratio and gravimetric water content, commonly called the soil shrinkage characteristic curve (Tripathy et al., 2002). Two different shrinkage paths of soils are shown in Fig. 2.5, such as that for saturated slurried soils and compacted soils (Haines, 1923; and Tripathy et al., 2002).

The shrinkage behaviour of an initially saturated soil upon drying can be characterized by the following four phases stages (Fig. 2.5) (Haines, 1923; Bronswijk, 1991): (*i*) structural shrinkage: water filled the larger and relatively voids drain without any accompanying shrinkage, thus, some air will enter into the large pores, (*ii*) normal shrinkage: in this stage the decrease in the volume of water in saturated soil equals the volume decrease of the soil and the soil remains saturated, thereby leading to a 45° line parallel to the 100% saturation line, (*iii*) residual shrinkage: in this stage air enters the pores and water loss during drying process is greater than the soil volume decrease, and (*iv*) zero shrinkage: the soil has reached its maximum density under the drying process, and water loss is not accompanied by any further change in volume. However, all of these four shrinkage phases are not always present. In some cases the shrinkage curve does not present the phase of structural shrinkage (Cornelis et al., 2006). The relative extent of the different shrinkage ranges varies for different soils (Parker et al., 1977).

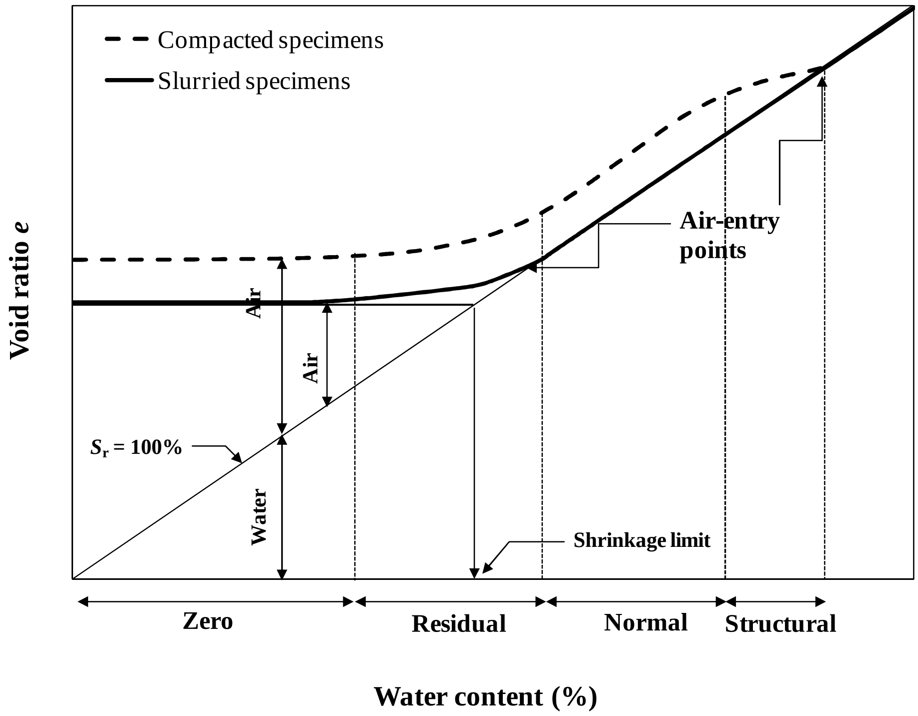



***Fig. 2.5 Typical shrinkage curve (based on Haines, 1923)***

Several parameters can be obtained from the shrinkage curve. The point when immediately the soil begins the desaturation (the shrinkage curve gets detached from the saturation line) is considered as the plastic limit. This point is associated with the Air Entry Value (AEV) (Fredlund, et al., 2011; Fredlund & Rahardjo, 1993; Cornelis et al., 2006). The shrinkage limit is defined as the water content corresponding to the minimum volume that a soil can attain upon drying to zero water content. The shrinkage limit water content can be determined by extending the zero shrinkage line to the theoretical degree of saturation line ($S_r$ = 100%) (Keźdi, 1980).

### 2.9.3 Suction-void ratio SWCCs

Soils undergo volume increase (swell) when their water-content is increased as a consequence of suction reduction. On the other hand, an increase in suction results in reduction in volume of the soil and induces shrinkage due to reduction in the water content.

The volume change of a soil specimen is commonly not measured when performing a laboratory test for the SWCC. The volume change during drying of a soil can be significant and is relevant to the interpretation of SWCC data (Fredlund & Rahardjo, 1993; Fleureau et al., 1993). The shrinkage curve can be used to estimate the volume changes. Thus, the relationship between void ratio and suction can be deduced from the combination of shrinkage curve and suction-water content SWCC (Fredlund et al., 2011). Consequently, the degree of saturation versus soil suction can also be established by using basic volume-mass relationship.

### 2.9.4 Volume measurement techniques

There are several methods currently available for measuring the shrinkage characteristic of soil specimens, such as dimension measurements using callipers or laser retractometer, methods based on the determination of the soil bulk density by measuring the weight and volume of the specimen while being dried. Volume determinations by measuring core dimensions have potential errors due to physical measurement errors especially if the soil is very wet and the regularity of the sample is often lost during drying (Tariq & Durnford, 1993). The use of fluid displacement method was found to give the better results. Although several researches employed this technique either by submerging the soil specimen in fluids such as kerosene, petroleum, toluene, mercury, and kerdane oil, or by first coating the specimen (encasement methods) with water repellent solutions (viz. Molten wax, Dow Saran resin dissolved in Methyl Ethyl Ketone (MEK saran), waterproof Polyvinyl Acetate (PVAc) based adhesives); however, they followed the same general procedure (Brasher, 1966; McKeen, 1985; Nelson & Miller, 1992; Tariq & Durnford, 1993; Bradeau et al., 1999; Albrecht & Benson, 2001; Fleureau et al., 2002; Krosley et al., 2003; Peron et al., 2007; Tadza, 2011).

Encasement method using molten wax requires duplicate soil specimens to be tested to establish the entire shrinkage path (Ward et al., 1965; ASTM D4943-08). On the other hand, Clod test using Methyl ethyl ketone (MEK) saran or PVAc as encasement eliminates the need of multiple specimens and only a single specimen is required to establish the entire shrinkage path (Brasher, 1966; McKeen, 1985; Nelson and Miller, 1992; Krosley et al., 2003).

In the Clod tests, encased soils are allowed to dry under a free unconfined condition. The volume of the Clod is measured by utilising Archimedes' principle (by weighing the Clod first in air and then under liquid of known density) (Nelson & Miller, 1992). Krosley et al. (2003) proposed the use of alternative encasement material, a water based glue (PVAc), which improved the testing time as compared to MEK saran due to improved vapour permeability of the glue. The glue is easily available and is non-hazardous.

### 2.9.5 Modelling of the shrinkage curves

Several models have been proposed in the past to describe the shrinkage characteristic of soils, which include polynomial models (Giráldez & Sposito, 1983; Fredlund et al., 2002), linear models consisting of different straight lines for the different shrinkage phases (McGarry & Malafant, 1987), logistic models (McGarry & Malafant, 1987), and sigmoid models (Groenevelt & Grant, 2002; Cornelis et al., 2006). Kim et al. (1992), Tariq & Durnford (1993), and Braudeau et al. (1999) suggested combining exponential or polynomial function with linear ones. Although most of the models are empirically developed, some of these models utilize the basic properties of soils to replicate the shrinkage paths.

Fredlund et al. (1997,2002) proposed an equation based on the hyperbolic nature of shrinkage curve to best-fit data for the shrinkage curve. The equation has parameters with physical meaning (Eq. 2.8).

$$e(w) = a_{sh} \left[\frac{w^{c_{sh}}}{{b_{sh}}^{c_{sh}}} + 1\right]^{\left[\frac{1}{c_{sh}}\right]} \qquad \text{(Eq. 2.8)}$$

where $a_{sh}$ = the minimum void ratio, ($e_{min}$), $b_{sh}$ = slope of the line of tangency, (e.g., drying from saturated conditions), $c_{sh}$ = curvature of the shrinkage curve, and $w$ = water content.

$a_{sh}/b_{sh} = G_s/S_r$ = constant for a specific soil ($G_s$ is the specific gravity and $S_r$ is the degree of saturation).

It is possible to estimate the remaining parameters required for the designation of the shrinkage curve once the minimum void ratio of the soil is known. The minimum void ratio the soil can attain is defined by the variable, $a_{sh}$. The $c_{sh}$ parameter provides the remaining shape of the shrinkage curve. The curvature of the shrinkage curve is controlled by varying the $c_{sh}$ parameter (Fredlund et al., 2011).

McGarry & Malafant (1987) proposed a generalized logistic model with four parameters to describe the S shape of the shrinkage characteristic (Eq. 2.9).

$$e = e_0 + \frac{e_v}{1 + exp\,[-\beta(wG_s - \, wG_{si})]} \qquad \text{(Eq. 2.9)}$$

where $e_v$ is the maximum void ratio range, equal to the void ratio at the saturation $e_D$ minus the $e_0$, $\beta$ is a slope parameter depending on the air entry value and $w$ is the water content at the inflection point.

## 2.10 Determination of air-entry value (AEV) and residual suction

During the drying process, the transition from saturated to unsaturated state of soils is indicated by the air-entry value, AEV (Fredlund & Rahardjo, 1993). The AEV is the suction at which the degree of saturation drops below 100%. If a soil undergoes insignificant volume change during establishing the drying SWCC, suction- gravimetric water content, suction-volumetric water content, and suction-degree of saturation SWCCs will lead to similar values of AEV and residual suction. However, if the volume change of the soil is large, the AEVs are usually less distinct on the SWCCs. In this case, suction-degree of saturation SWCC can be used for determination of AEV and residual suction (Croney & Coleman, 1954; Fredlund & Rahardjo, 1993; Vanapalli et al., 1999; and Fredlund, 2011).

Vanapalli et al. (1999) presented a graphical procedure to quantify the air entry value and the residual state when the entire suction range is used. The procedure involves first drawing a line tangent to the curve through the inflection point on the straight line potion of the SWCC. The air entry value of the soil is obtained by extending the constant slope portion of the SWCC to intersect to the line represent the SWCC in the low suction range (at saturated water content or 100% saturation). The residual degree of saturation can be defined at the intersection of the tangent line and the extended line represents the SWCC in the high suction range (1,000,000 kPa).

The shrinkage curve of a soil may be referred to for determining the water content at the air-entry and the residual water content. Further, the suctions corresponding to these water contents can be obtained from the suction-water content SWCC. During the drying process an initially saturated slurried soil specimen follows the 100% saturation line until air begins to enter the largest voids at which the shrinkage curve starts to deviate from the 100% saturation line. The soil continues to dry until the volume of voids remains constant indicated by the shrinkage limit of the soil.

The suction corresponding to the shrinkage limit of clays has been considered as the AEV by several researchers (Fleureau et al. 1993; Fredlund and Rahardjo, 1993, P´eron et al. 2006). However, soil may well desaturate prior to the shrinkage limit, hence the shrinkage limit may well differ from the air entry water content. The desaturation point may remain close to the plastic limit in some cases. Hence, the suction corresponding to the plastic limit may be considered as the AEV (Fredlund et al., 2011). Fredlund et al. (2012) suggested that the residual conditions may correspond to the shrinkage limit of the soil. These studies clearly suggest that determination of the AEV and the residual suction based on the shrinkage paths and the suction-water content SWCC of the soil is yet conjectural. It may be noted that these approaches of determining the AEVs and the residual suctions may strictly apply for initially saturated slurried soil specimens. Tripathy et al. (2002) stated that the plastic limit and the shrinkage limit have specific meaning for initially saturated slurried soils and such references may not be applicable in case of shrinkage paths of compacted soils.

## 2.11 Concluding remarks

In this chapter, a brief review of the concept of suction as well as the methods for measuring and controlling soil suction has been presented. A review of the influence of compaction conditions on soil suction was included. General information on the soil-water characteristic curve (SWCC) and its features and factors affecting the SWCC were covered. Soil volume change due to suction along with the soil shrinkage behaviour were also discussed.

A review of literature highlighted some specific aspects related to SWCCs and suction of soils. These include:

- Suction is a function of soil structure and soil water content.
- The influence of the initial compaction conditions is more obvious for the near saturation portion of the SWCC. At high suction, SWCCs with different compaction conditions tend to converge.
- Several methods are currently available for suction measurements, however each method has its own limitations and advantages.
- The water phase continuity in null-type axis-translation has not been fully investigated.
- Filter paper method is highly depends upon the calibration curve which in turn depends upon several factors (suction source, equilibrium time, and hysteresis).
- The importance of using the suction-water content SWCCs and shrinkage paths for determination of AEVs of soils.

# CHAPTER 3

# MATERIALS USED AND EXPERIMENTAL PROCEDURE

## 3.1 Introduction

Several regions of the earth constitute of semi-arid or arid regions (Nelson & Miller, 1992). These regions have climates in which the annual evaporation potential exceeds the annual rainfall. Subsequently, the soils in these areas are very dry nearer to the ground surface. Typically the soils in these regions are in a state of unsaturated conditions.

Libya is located in an arid to semi-arid environment. Very limited research studies have been reported in the literature concerning the behaviour of unsaturated Libyan soils. For this reason, an extensive experimental program was undertaken in order to investigative the unsaturated characteristics of two Libyan soils.

A detailed experimental programme was planned and several laboratory tests were carried out. The drying suction-water content SWCCs were established using the axis-translation technique (pressure plate tests) and the vapour equilibrium technique (desiccator tests). The wetting suction-water content SWCCs were established using a volumetric pressure plate extractor and the vapour equilibrium technique (desiccator tests).

The void ratios of soil specimens during the drying process were measured using Clod method in order to establish the water content-void ratio shrinkage paths. The Clod tests results were combined with suction-water content SWCCs to establish the suction-void ratio SWCCs and suction-degree of saturation SWCCs of the soils.

Matric suction measurements were carried out using a null-type axis-translation device and contact filter paper method. Additionally, a chilled-mirror device and non-contact filter paper method were used for total suction measurements.

In this chapter, the properties of the soils used and the experimental procedures adopted are described. The experimental methods adopted to determine the index properties of the soils, such as the Atterberg limits, the grain size distribution, and the mineralogy are first briefly presented followed by the specimen preparation and compaction methods. Further, the methods used for determination of the drying and wetting suction-water content SWCCs and volume measurement using Clod method are presented. Subsequently, the devices and testing methods used for soil suction measurements (null-type pressure plate, filter paper, and chilled-mirror) are presented. The concluding remarks are presented towards the end of the chapter.

## 3.2 Soils used

Two types of Libyan soils with different textures were used. The soils were collected from North-west (Tripoli area) and from North-east (Benghazi area) of Libya. The soils were subjected to an extensive laboratory testing to generate the experimental database that could be used to evaluate special features of the unsaturated Libyan soils.

### 3.2.1 General country background

Libya occupies a part of northern Africa from 20 to 34° N and 10 to 25° E (Fig. 3.1). It is bounded in the east by Egypt, in the west by Tunisia, and Algeria, Mediterranean Sea in the north, and by Sudan, Chad, and Niger, in the south.

Libya's total population was at 5.3 million in 2001, almost 90% of the population lives in the coastal region in the north, and the rest in widely scattered oases in mid- and southern Libya. According to the population distribution in Libya based on 2001 estimation, people concentrate on two locations: the first, in the northwest (Jifara Plain) where about 60% of all Libyans live, including Tripoli city - the capital of Libya - where more than one million people live, and the second location in north-eastern Libya (Benghazi Plain).

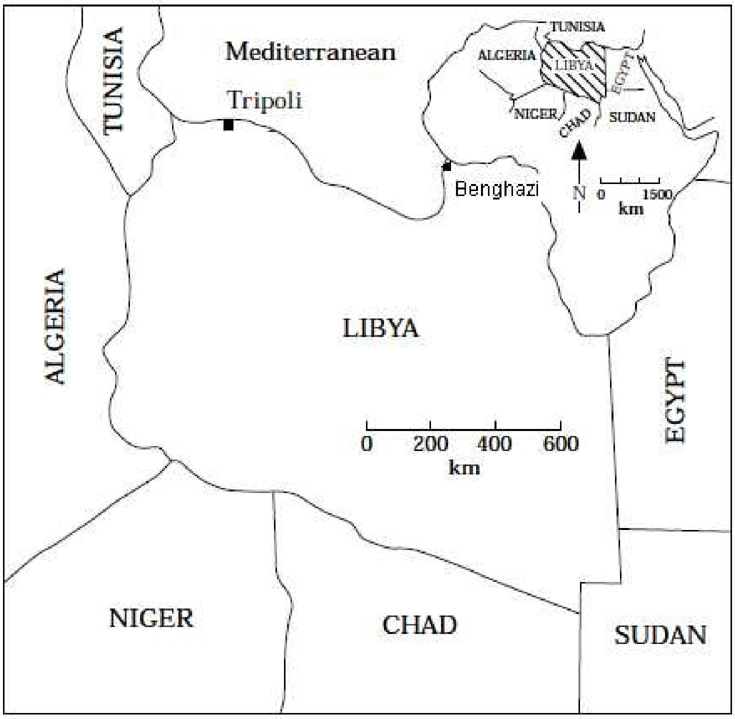



***Fig. 3.1 location map of Libya***

Libya has Mediterranean climate with a greater variety of seasonal changes. The dominant climatic influences are the Sea and the Sahara Desert. In coastal lowlands, where

90 percent of the population live, the climate is Mediterranean, with warm summers and mild winters. The climate in the desert interior is characterised by very hot summers and extreme diurnal temperature ranges.

Rainfall is the main feature of precipitation in Libya. The average annual rainfall in Libya is 380 mm, but only 7% of the land surface of the country has a rainfall of more than 100 mm/year. The highest rainfalls occur in the Northern Tripoli region (Jabal Nafusah and Jifarah Plain) and in the Northern Binghazi region (Jabal Al Akhdar): these two areas are the only ones where the average yearly rainfall exceeds 250 to 300 mm (Pallas, 1980).

### 3.2.2 Sampling location

The first soil was taken from Tripoli area located in the north-western Libya (Fig. 3.1). Tripoli city is located at the western side of Libya on the sea edge of about 80 km of the wide flat coastal Jeffara plain. This plain is gradually slopes from the coastline to about 130 m above the mean sea level. The coastal plain terminated in a steep fault escarpment that rise to from the Jebel Nefusa plateau, about 400 to 600 m above sea level and roughly parallel to the coastline. Jefarah Formation consists mainly of fine materials, mostly silt and sand, occasionally with gravel caliche bands and gypsum; it covers extensive parts of the Jefarah Plain. The soil used in this study was collected from the near surface layer of coastal strip of Jeffara plain. The near surface layer is recent windblown silty sand of variable thickness ranging from 1.0 to more than 10.0 m. This layer has varying silt content of 5 to 40% and may have nodules of cemented carbonate. The soil is predominantly consists of quartz and traces of other clay minerals such as kaolinite can be found. The soil will be referred to as JF soil throughout in this study.

The second soil was taken from Benghazi area located in the north-eastern Libya (Fig 3.1). The Benghazi plain area is bounded on the west by the Mediterranean Sea and on the east by the escarpment of Jabal Akhdar (Green Mountain). There are three important geomorphic units in the plain and its catchment area. These are: the plain along the sea coast, the Benghazi platform, and the terrace of Jebal AL Akhdar (Khan et al., 1978). The sediments in this region can be classified according to their origin into aeolian, littoral marine, lagoonal (Sabkha) and alluvial deposits (Khan & Hasnain, 1981). The aeolian deposits are composed of fine-grained, equigranular sand which is mostly made up of shell fragments and limestone grains. The littoral marine unit mostly consists of calcareous sandstones or calcarenites. A series of periodically dried coastal lagoonal sediments called Sabkhas are developed along the coast line. The lagoonal sediments are red silty or sandy clay with accumulated minute gypsum and salt crystals. Alluvial deposits consist of beds of loam clay and gravel. These deposits are intercalated, especially at their base, with limestone gravel. The significant part of the region, along the Mediterranean Sea shore, is covered by specific soils called Terra-Rossa soils. These soils are mainly found in areas where the underlying bedrock consists of limestone, and is created when limestone weathers and erodes, producing a mix of clay and sand that contains iron oxide, giving the soil its red colour. Its thickness in the basin is not more than 10 m. These soils consist of kaolinite and traces of illite and chlorite as its clay minerals, also including quartz and feldspar. The soil will be referred to as TR soil in this study.

## 3.3 Physical properties of soils used

Standard laboratory tests were performed in this study to obtain the index properties of the soils. These included determination of practical size distribution, Atterberg limits (i.e., liquid limit, plastic limit, and shrinkage limit), and specific gravity.

### 3.3.1 Specific Gravity

Specific gravity ($G_s$) of a soil is the ratio of density or specific weight of the soil particles to the density or unit weight of water. The specific gravity of the soil was determined by using density bottle (pycnometer) according to BS 1377-2 (1990). Three different tests were conducted on three different samples from both soils. The specific gravity values were found to be 2.66 and 2.73 for JF soil and TR soil, respectively.

### 3.3.2 Atterberg Limits

Atterberg limit tests were conducted to study the plasticity property of the soils. The liquid limit and plastic limit are the water contents at which the soils exhibit both liquid and plastic property, respectively. The liquid and plastic limits tests were conducted according to BS 1377-2 (1990). The liquid limits of the soils were determined based on that portion of soils which passed through a 425 µm sieve and using the fall-cone method. The plastic limit of each soil was determined by using soil passing through a 425 µm sieve and rolling 3 mm diameter threads of the soils until they began to crumble. The difference between these liquid limit and plastic limit is known as the plasticity index, which is generally used to characterize the plastic nature of soils. Table 3.1 shows the Atterberg limits of the soils. It can be seen in Table 3.1 that the TR soil exhibited higher plasticity (LL = 39% and PL = 16%) than JF soil (LL = 23% and PL = 16%). This is attributed due to a higher amount of clay fraction found in TR soil.

The shrinkage limit is defined as the water content at which the soil does not undergo further volume change during the drying process. The shrinkage limits of both soils were determined according to the method described in ASTM D4943-08. Soil specimens were prepared at 1.2 times their respective liquid limit values and placed within a greased shrinkage dish. Mass measurements were frequently monitored until no further reductions in mass were observed. Subsequently, the water contents and volume measurements using the wax method were carried out. The shrinkage limits of the soil were calculated using Eq. 3.1.

$$SL\ (\%) = \frac{\left((V - V_d)\rho_w\right)}{m_s} \times 100 \qquad \text{Eq. (3.1)}$$

The *SL* is the shrinkage limit, *V* is the volume of wet specimen (i.e. volume of the shrinkage dish in $cm^3$), $V_d$ is the volume of dry soil, $\rho_w$ is the density of water, and $m_s$ is the mass of dry soil.

The shrinkage limit for JF soil was found to be 13.4%, whereas the shrinkage limits for TR soil was found to be 10.5%. These values indicated that both soils may exhibit some volume change during saturation.

***Table 3.1 Properties of the soils used***

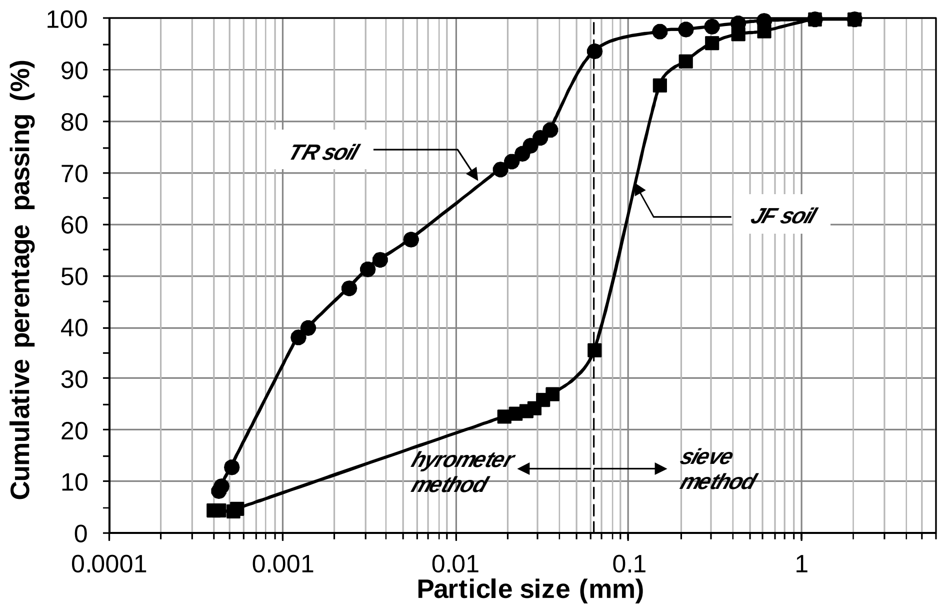
| Properties | JF Soil | TR soil |
|---|---|---|
| Specific gravity of soil solids, $G_s$ | 2.66 | 2.73 |
| Atterberg Limits | | |
| Liquid limit, LL (%) | 23.0 | 38.6 |
| Plastic limit, PL (%) | 16.0 | 15.8 |
| Plasticity index, PI | 7.0 | 22.8 |
| Shrinkage limit, SL (%) | 14.4 | 11.5 |
| Particle size distribution | | |
| Sand (%) | 64.6 | 4.7 |
| Silt (%) | 24.4 | 47.7 |
| Clay (%) | 11 | 47.6 |
| BS light compaction characteristics | | |
| Optimum water content (%) | 11.2 | 20.1 |
| Maximum dry density ($Mg/m^3$) | 1.99 | 1.69 |
| BS heavy compaction characteristics | | |
| Optimum water content (%) | 9.2 | 15.4 |
| Maximum dry density ($Mg/m^3$) | 2.09 | 1.87 |

### 3.3.3 Particle size distribution

Particle size distribution tests were performed on JF and TR soils in accordance with BS 1377-2 (1990). Both dry and wet sieve methods were used. In addition, particle size of fine fractions of the soils and clay–size fraction (i.e. < 2.0 $\mu m$ in diameter) were determined using sedimentation technique (hydrometer method).

Figure 3.2 shows the grading curves of the soils. The measured particle size percentages of each soil are presented in Table 3.1. The particle size distribution curves of the soils (Fig. 3.2) indicated that JF soil contained about 64.6% sand, 24.4% silt, and 11% clay-size fractions. TR soil contained about 5% sand, 47.7% silt, and 47.6% clay-size fractions.

According to British standard (BS) classification system BS 1377-2 (BSI 1990), JF soil was classified as silty sand of low plasticity (SML) and TR soil as inorganic clay of intermediate plasticity (CI).




| CLAY | SILT | | | SAND | | | GRAVEL |
|---|---|---|---|---|---|---|---|
| | Fine | Medium | Coarse | Fine | Medium | Coarse | Fine |

***Fig. 3.2 Particle size distribution of soils used***

### 3.3.4 Mineral compositions

The mineral compositions of the soils were determined by X-ray diffraction method (Grim, 1968; Mitchell, 1993). According to Bragg's law, the XRD identifies the minerals based on the relationship between the angle of incidence of the X-rays, $\theta$, to the *c*-axis spacing, *d*. A Philips automated powder diffractometer PW 1710, was used for XRD analysis in this study. The diffractometer consists of a Goniometer (specimen holder), a copper X-ray generator and a controller. The soil particles were ground to minimize the orientation preference and to maximize sample representativeness. Soil powders with hygroscopic water contents were tested. The X-ray diffraction analysis of both soils is shown in Fig. 3.3. X-ray diffraction analysis showed that JF soil contains quartz, carbonate, and feldspar as its non-

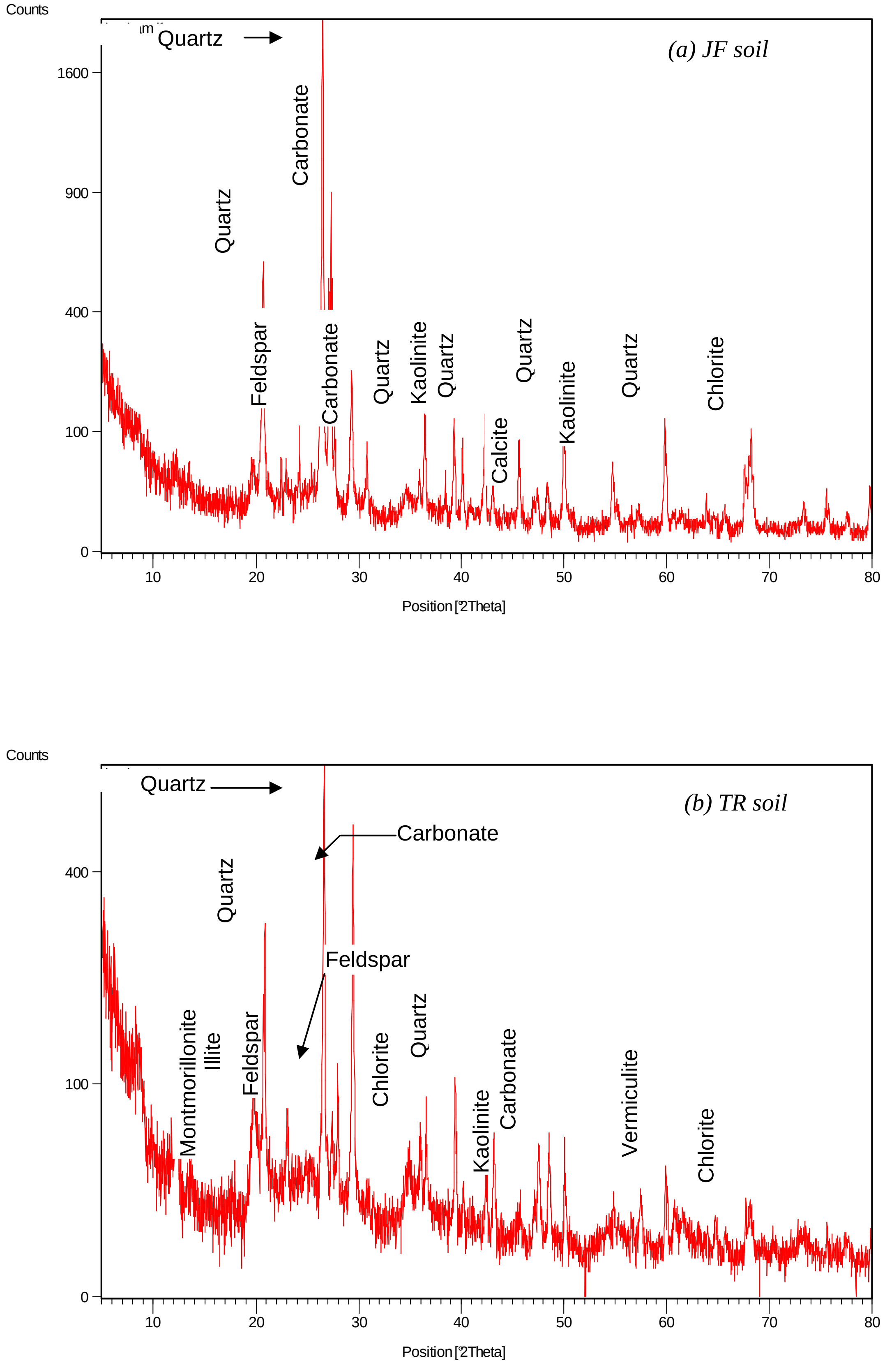



***Fig. 3.3: X-ray diffraction chart for (a) JF soil and (b) TR soil***

clay minerals, including other clays minerals such as kaolinite and chlorite. The XRD test results for TR soil showed that it contains illite, kaolinite, chlorite and traces of quartz, feldspar and carbonate were also found. However, based on X-ray diffraction results it was difficult to specify the proportions of each mineral in both soils as the peak intensities are strongly influenced by the orientation of the particles in the specimen (Jasmund & Mering, 1978).

## 3.4 Compaction tests

Compaction tests for both soils were carried out by following the procedure laid out in BS 1377-4 (1990). The tests were carried for heavy and light compaction efforts. For heavy compaction, the soil were compacted in five layers in a mould having a volume of 1000 cm, using 27 blows per layer with a 4.5 kg rammer falling though a height of 450 mm. The light compaction tests were conducted in three layers using 2.5 kg rammer falling though a height 300 mm.

The compaction curves of the JF soil and TR soil (full lines in Figs. 3.4 and 3.5) and the corresponding optimum water content (i.e., the optimum moisture content or the OMC) and the maximum dry density ($\rho_{dmax}$) for BS-light and BS-heavy compaction efforts are shown in Figs. 3.4 and 3.5. The optimum water content for JF soil remained close to the degree of saturation ($S_r$) of 85% for BS-light compaction effort (OMC = 11.2%) and 90% for BS-heavy compaction effort (OMC = 9.3%). For TR soil, the optimum water content remained close to the degree of saturation ($S_r$) of 90% for both BS-light and BS-heavy compaction efforts (OMC = 20.1% and 15.4%, for light and heavy compaction efforts).

For both JF and TR soils (Figs. 3.4 and 3.5), the limbs of the compaction curves on the wet-side of the optimum conditions for both BS-light and BS-heavy compaction merged with an increasing in the water content and remained close to $S_r$ = 85% and 90%. This indicates that air remained within the soil systems (percentage air void of about 15%) in occluded form at very high water contents for both the compaction efforts and for both soils.

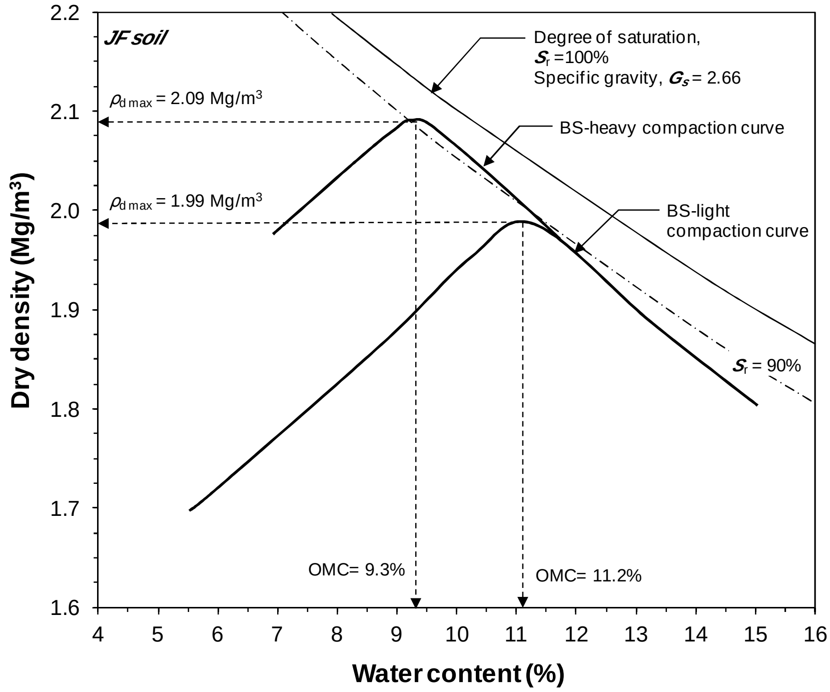



***Fig. 3.4 Compaction characteristics of the JF soil (BS-light and BS-heavy)***

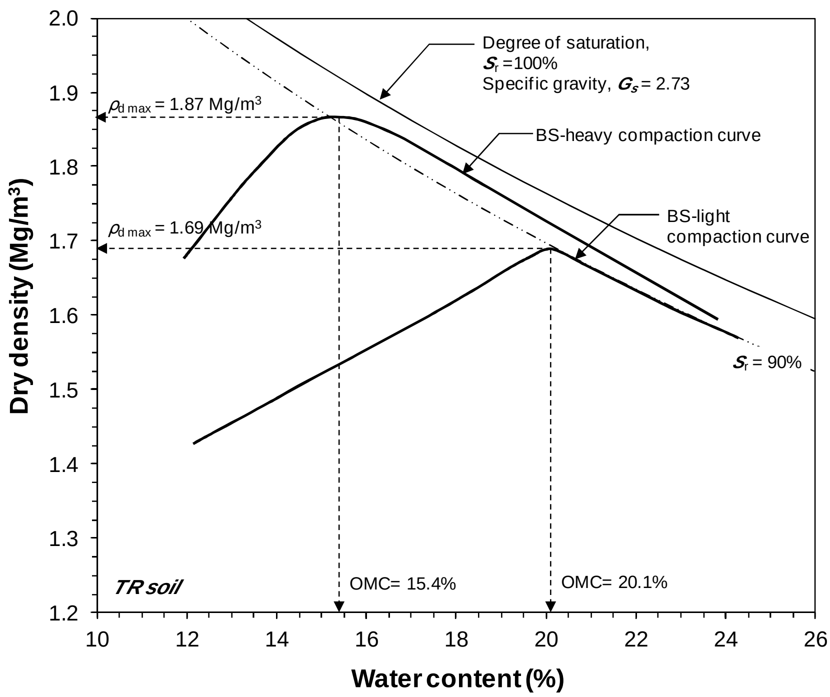



***Fig. 3.5 Compaction characteristics of the TR soil (BS-light and BS-heavy)***

## 3.5 Compressibility and collapse behaviour

Two methods are currently used to evaluate and determine the collapse potential of soils, namely the single and the double oedometer tests. The tests have been shown to be reliable in investigating the collapsibility properties of soils. According to Lawton et al. (1989) and Basma & Tuncer (1992), these methods lead to similar results. In this study, the experimental procedures for double oedometer test proposed by Jennings & Knight (1957) were adopted. One specimen was tested in its as-compacted conditions while the other soil specimen was initially saturated prior to loading. The vertical strain difference between the saturated and as-compacted specimens was considered for determining the collapse potential at various vertical pressures. The following sections presents the test procedure adopted for determining the collapse potential along with specimen preparation method and the test results.

### 3.5.1 Specimen preparation for double oedometer test

The double oedometer test (Jennings & Knight, 1957) was used to study the collapse behaviour of compacted specimens of JF and TR soils. Two identical soil specimens were prepared for each soil at the predetermined compaction conditions. Several compaction conditions of the soils were chosen for the double oedometer tests. Statically compacted specimens corresponding to BS light compaction effort were prepared at various initial compacted water contents and dry densities.

The water content and dry density for JF soil varied between 4.7% to 22% and 1.53 $Mg/m^3$ to 1.90 $Mg/m^3$ (Table 3.2). The specimens of TR soil were prepared at dry densities varying between 1.53 $Mg/m^3$ to 1.90 $Mg/m^3$ and initial water contents varying between 4.7% to 22% (Table 3.2).

***Table 3.2 Initial compaction conditions of JF and TR soil for double oedometer test***

| Soil type | Specimen condition | Initial compaction conditions | | | | |
|---|---|---|---|---|---|---|
| | | Specimens notation | Water content (%) | Dry density ($Mg/m^3$) | Void ratio | Degree of saturation (%) |
| JF soil | Saturated | JF-SL6.8 | 6.8 | 1.78 | 0.494 | 36.6 |
| | | JF-SL8.1 | 8.1 | 1.84 | 0.445 | 48.3 |
| | | JF-SL9.0 | 9.0 | 1.92 | 0.385 | 62.1 |
| | | JF-SL11.2 | 11.2 | 2.01 | 0.323 | 92.1 |
| | As-compacted | JF-SL6.8 | 6.6 | 1.78 | 0.494 | 35.5 |
| | | JF-SL8.1 | 8.1 | 1.84 | 0.445 | 48.3 |
| | | JF-SL9.0 | 8.9 | 1.92 | 0.385 | 61.4 |
| | | JF-SL11.2 | 11.1 | 2.00 | 0.330 | 89.5 |
| TR soil | Saturated | TR-SL15.2* | 15.4 | 1.55 | 0.761 | 55.2 |
| | | TR-SL16.3 | 16.3 | 1.58 | 0.728 | 61.1 |
| | | TR-SL18.4 | 18.4 | 1.66 | 0.645 | 77.9 |
| | | TR-SL20.5 | 20.6 | 1.68 | 0.625 | 89.9 |
| | As-compacted | TR-SL16.3 | 16.2 | 1.58 | 0.728 | 60.8 |
| | | TR-SL18.4 | 18.3 | 1.65 | 0.654 | 76.4 |
| | | TR-SL20.5 | 20.4 | 1.68 | 0.625 | 89.1 |

** soil specimen used for only 1D oedometer test*

### 3.5.2 Testing Procedure

The soil specimens were compacted directly in standard oedometer rings (76 mm dia. and 15 mm high). The oedometer rings were lubricated with silicon grease to minimize the side friction effect. The as-compacted specimens were then transferred to standard consolidation loading devices. For testing unsaturated soil specimens, the porous stones at the bottom and top of the soil specimens were wrapped in plastic sheets prior to placing in contact with the as-compacted specimens in order to prevent capillary affects from occurring between the as-compacted specimens and the porous stones. Additionally, the entire oedometer cell was covered with several layers of cling film to maintain the water content of the as-compacted specimen constant throughout the tests. After assembling the loading devices, the soil specimens were immediately loaded according to standard incremental loading procedure. In this study, loading pressure of 5, 50, 100, 200, 400, and 800 kPa were selected. Each loading increment was allowed to remain for a period of one hour and dial gauge readings were monitored at the following time intervals: 0, 0.25, 0.5, 1, 2, 4, 5, 10, 20, 30, 40, 50, and 60 minutes. For testing the specimens of saturated condition, the soil specimens were initially saturated with deionised water under a small seating pressure (5 kPa). After a 24-hour equilibrium period, the specimens were consolidated using the same loading sequence (5, 50, 100, 200, 400, and 800 kPa) used for the as-compacted ones with each increment held constant for 24 hours. The specimens were unloaded to the token load in a stepwise process.

The test method allows determining the difference in the void ratio between saturated and as-compacted specimens under any stress level. The collapse potentials of the soil specimens were determined according to the equation (Eq. 3.2) (Jennings & Knight, 1975, ASTM D 5333-03):

$$\text{Collapse potential (\%)} = \frac{e_i - e_f}{1 + e_0} \times 100 \qquad (Eq. 3.2)$$

where, $e_0$ is the initial void ratio of identical specimens and $e_i$ and $e_f$ are the values of the void ratio of the specimens at as-compacted water content and at saturation conditions respectively, under the same applied vertical stress.

### 3.5.3 Experimental results of double oedometer tests

Figures 3.6*a* and *b* show the results of double oedometer tests for specimens of JF and TR soils with varying initial water content. The test results are presented in terms of void ratio of the specimens versus vertical pressure on a logarithmic scale. Due to some slight variations in the initial void ratios of the specimens for any given test, the results for specimens with similar dry densities are shown to start at an average void ratio.

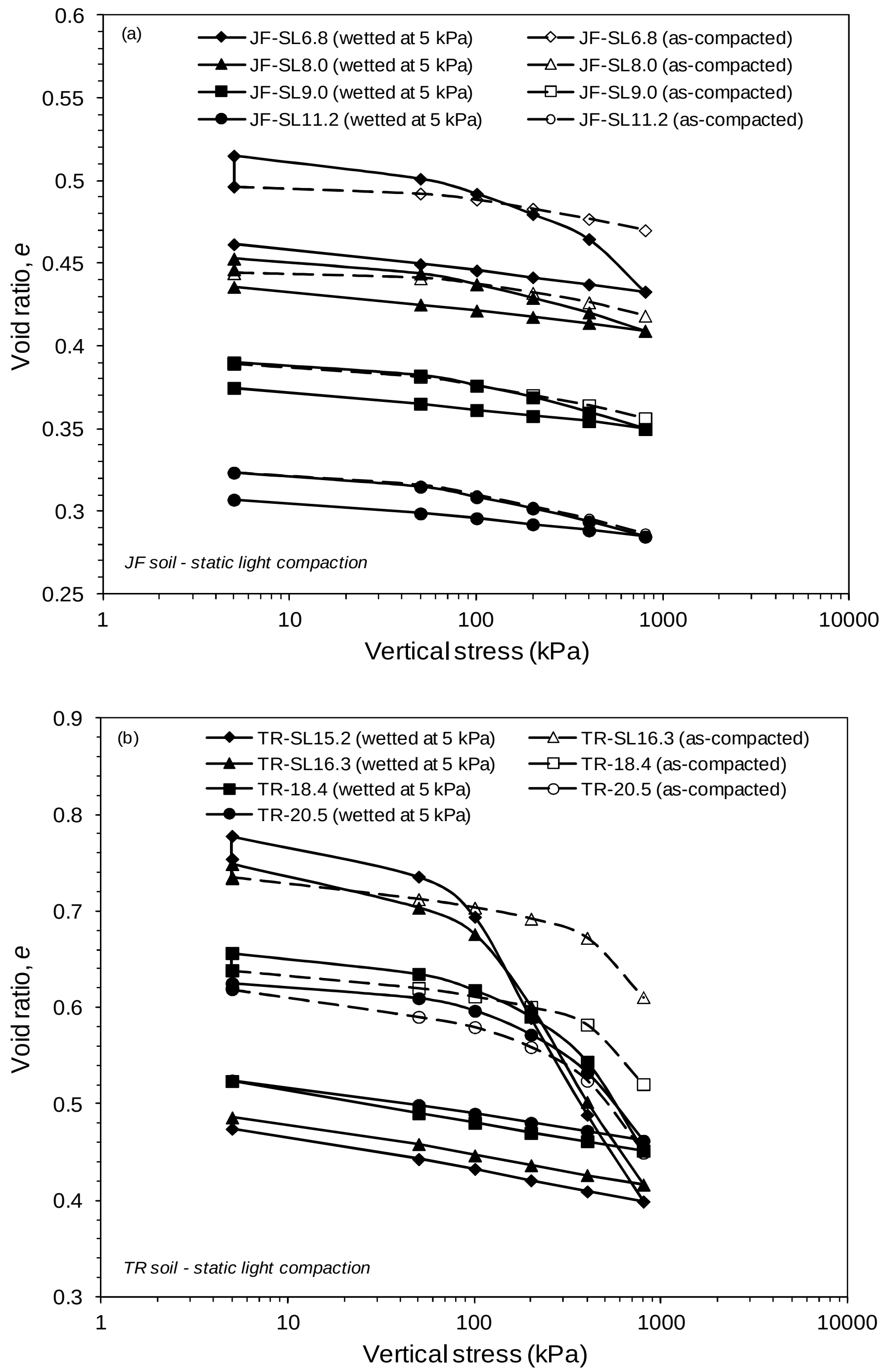



***Fig. 3.6 Compression curves (void ratio vs. vertical stress) for***

***(a) JF soil and (b) TR soil***

Figures 3.6*a* and *b* show that, the void ratio versus vertical pressure curves of saturated specimens remained above the corresponding as-compacted compression curves. This occurred for the specimens those had exhibited slight swelling. The percent swell was less than 1.3% for JF soil and 1.0% for TR soil. However, as the applied stress increased, a collapse may be expected as the as-compacted compression curves remained above the saturated comparession curves. The specimens compacted at dry of optimum water content (JF-SL6.8 and TR-SL15.2) show higher increase in volume (swell) at seating load than the specimens compacted at optimum water content (JF-SL11.2 and TR-SL20.5). The specimen notation follows, soil name, compaction type (SL – static light), and the water content.

The test results presented in Figs. 3.6*a* and *b* showed that the saturated compression curves intersect the corresponding as-compacted compression curves at specific values of the vertical stress. This value represents the vertical stress at which there will be no volume change for the saturated specimens. The tests results also showed insignificant difference in compression curves between the saturated and as-compacted specimens compacted at high water contents for both soils (e.g. JF-SL11.2 and TR-SL20.5).

Figures 3.7*a* and *b* show the collapse potential versus applied vertical stress for both soils. It can be observed from the test results in Figs. 3.7*a* and *b* that the collapse potential of the soil specimens increases with an increasing in the applied vertical stress and decreases with the compaction water content. An insignificant collapse potential can be noted for the both JF and TR soil specimens compacted at optimum water content.

It can be seen from Figs. 3.7*a* and *b* that specimens compacted at low water content (dry of optimum) show a higher values of collapse potential than the specimens compacted at high water content (optimum or wet of optimum). Barden et al. (1979) reported that the structural stability of compacted specimens at dry of optimum depends on the matric suction rather than the dense of particle arrangement. Dense particle arrangement affects more the structural stability of the wetter compacted specimens and the matric suction has less effect.

The test results are found to be in good agreements with the findings of other researches (Lawton et al., 1992; Medero et al., 2009; Villar & Rodrigues, 2011).

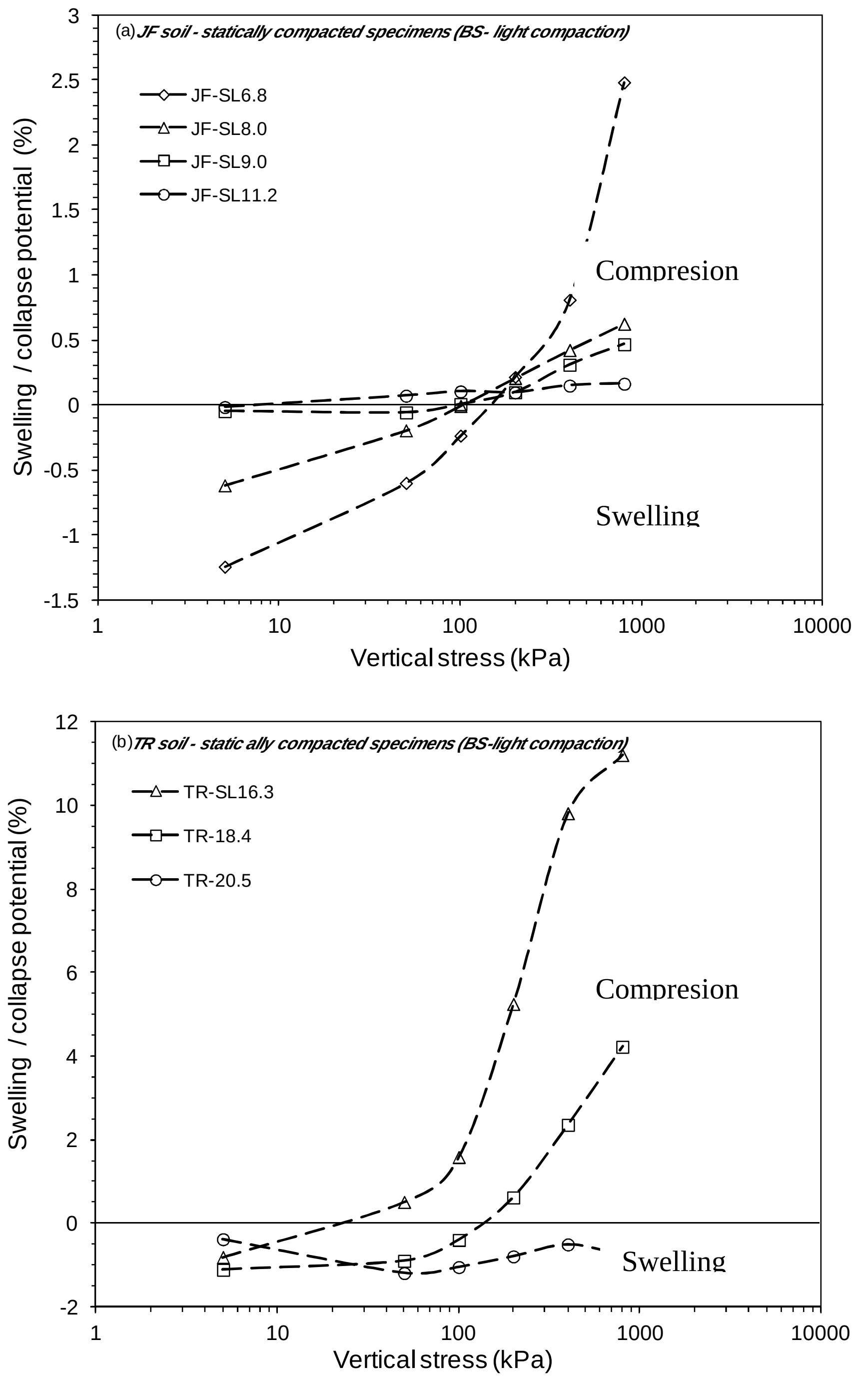



***Fig. 3.7 Swelling / collapse potential versus vertical stress plots for***

(a) ***JF soil and (b) TR soil***

## 3.6 Permeability test

A falling head permeability tests were carried out according to BS 1377-5 (1990) to determine the permeability of the soils used. Specimens were prepared at initial water content equal to the corresponding liquid limit of the soils. The permeability results from the study indicated that the coefficient of permeability ($k_s$) of the specimen of TR soil was 9.18 × $10^{-9}$ m/s as whereas $k_s$ of the specimen JF soil was 4.65 × $10^{-6}$ m/s. The lower value of $k_s$ for TR soil is mainly due to a higher percentage of clay size fractions. The range of $k_s$ for both soils fall within the range of $k_s$ for silty soils (Lambe & Whitman, 1969).

## 3.7 Specimen preparation for measuring and imposing soil suction

All soil specimens used in the study were prepared from the selected soils that were firstly air-dried and then sieved through a 2 mm sieve. This process enabled removing all large particles and pebbles from the soils. Soil-water mixtures were prepared by adding predetermined quantities of distilled water to the soils. Distilled water was added to the soils in small amount and thoroughly mixed until uniform mixtures were obtained. The mixtures were then placed in sealed plastic bags in airtight containers and were allowed to cure overnight for moisture equilibrium to take place. The mixtures were further made to pass through a 2.0 mm sieve to eliminate large-size crumbs that were formed during the mixing operation. At low water contents, the mixtures could be easily sieved; however, as the water content increased it was necessary to force sieve the mixtures. It was more difficult to sieve the soil-water mixtures of TR soil at higher water contents. The mixtures were placed back again in sealed plastic bags in airtight containers.

Soil specimens for the null-type axis-translation and SWCC tests were prepared from both BS-light and BS-heavy compaction samples. Thin walled stainless-steel tube samplers with bevelled edge and inside diameter of 42 mm were used to extrude the compacted specimens from the compaction mould. Samples were taken from the remaining soil to determine the compaction water contents of the specimens. The dry densities of the tested specimens were calculated based on the volume-mass relationships.

In addition to the dynamically compacted specimens, soil specimens were also prepared by statically compacting soil-water mixtures for the null-type axis-translation, SWCC, filter paper and chilled mirror tests. Statically compacted specimens were prepared by compacting soil-water mixtures in single lift in a specially fabricated mould.

Figure 3.8 shows the compaction mould used in this study. The main components of the compaction mould are a brass base, a stainless steel central section, stainless steel specimen ring, a locking collar, a piston and three locking bolts. The central section holds a specimen ring into position and at the same time accommodates soil-water mixture during the compaction process. The central section also guides the piston in the vertical direction during compaction. The inside of specimen rings was covered with light coating of silicon grease prior to placing a soil-water mixture. The compaction of soil specimens were performed using a stress controlled compression testing machine. The targeted compaction dry densities and water contents of the statically compacted soil specimens were corresponding to the specimen conditions of the dynamically compacted specimens. At the end of the compaction process, the specimens were weighed, the diameter and height were measured at three positions of the specimens.

All specimens for all laboratory tests were prepared in a similar manner in order to produce the same structure and conditions. Typically, the specimens prepared for null-type and SWCC tests were 12 mm thick and 45 mm diameter. For filter paper tests the specimens were 20 mm thick and 45 mm in diameter and for chilled-mirror tests the specimens were 7 mm thick and 37 mm in diameter.


***Fig. 3.8 Static compaction mould, (a) components of compaction mould and (b) assembled compaction mould***

### 3.8 Suction-water content SWCC tests

This section presents the details of experimental methods adopted for establishing the soil-water characteristic curves (SWCCs). Pressure plate and salt solution tests were carried out to obtain the SWCCs, both during drying and wetting processes.

#### 3.8.1 Pressure plate tests

Pressure plate extractors work on the principle of axis-translation technique. Axis-translational technique refers to elevating pore air pressure ($u_a$), while maintaining a constant pore water pressure ($u_w$) (usually, $u_w = 0$).

The suction-water content SWCCs of compacted saturated specimens were determined by pressure plate tests. Two type of pressure plate devices were used for establishing drying and wetting SWCCs. The drying SWCCs were established using a 5-bar pressure plate extractor manufactured by Soil moisture Equipments Corporation in accordance with ASTM D6836-02. A 2-bar volumetric pressure plate extractor from the same manufacture was used to generate the SWCCs along the wetting paths between suctions 200 and 4.0 kPa.

### *3.8.1.1 Apparatus description*

A 5-bar pressure plate extractor (Fig. 3.9) consists of a pressure chamber, and an air supply system, and high air-entry ceramic disk, covered on one side by a neoprene membrane, sealed to the edges of the ceramic disk. Two layers of plastic screens are attached to the under surface of the ceramic plate to provide space for water flow between the ceramic disk and the neoprene membrane (Leong et al., 2004). The disk is generally made of sintered kaolin soil (Soil Moisture Equipment Corp., 2004) and the diameter of the ceramic disk ranges between 260 mm and 280 mm. The water outlet in the pressure plate apparatus was connected to a burette for flushing purpose and for collecting water that expelled out of the soil specimens. The air pressure required for the test is applied through an external compressed air supply line which is connected to the chamber via a regulator.


***Fig. 3.9 5-bar pressure plate extractor***

Prior to commencement of a test, in order to saturate the ceramic disk, the water compartment was filled with distilled water, water was also poured over the ceramic disk, and air pressure was incrementally increased up to 100 kPa for several hours with water on the disk. The saturation process was stopped when no air bubbles were noticed in the burette. Once the ceramic disk was saturated, air cannot pass through the ceramic disk due to the ability of the contractile skin that resists the flow of air (Fredlund and Rahardjo, 1993). The ceramic disk acts as a membrane between the pore air and pore water.

#### *3.8.1.2 Pressure plate test procedure*

Compacted and initially saturated slurried specimens were prepared in stainless steel specimen rings for establishing the drying suction-water content SWCCs. Saturation of the compacted soil specimens were performed by placing them on filter paper and soaking in a water bath for 24 hours to achieve fully saturated conditions. The initial weights of the specimens after saturation were recorded. The saturated specimens were then placed on the previously saturated ceramic disk inside the pressure plate and the lid was closed. In order to avoid loosing of soil particles, a pre-wetted Whatman 5 filter paper was placed beneath the saturated specimen (Klute, 1986). Additionally, to provide a good contact between the specimens and the ceramic disk prior to placement of the specimen, a thin layer of water was left on the ceramic disk (Cresswell et al., 2008). The air pressure was then regulated to the desired value and the water compartment is maintained at zero pressure (open to atmosphere).

Suction values of 5, 10, 20, 50, 100, 200, 300, and 400 kPa were considered for establishing the drying SWCCs. The weight of the specimen at each imposed suction level was monitored frequently by weighing the mass of specimens at every alternate day. The ceramic disk was re-saturated before placing the soil specimens back in the pressure plate. Equilibrium was considered to have reached when there was no significant reduction in the weight of the specimens.

Weighing of the specimens was performed along with the rings with the filter paper attached. The results of weight measurements of the specimens were corrected for each ring and filter paper. The weight of the specimen ring remained constant throughout the test while the weight of the filter paper varied due to its different water content at different suctions. In order to determine the weight of the filter paper at each applied suction, an independent test was performed in which a same type and size filter paper was placed along with the specimens in the pressure plate. The corrected net weight of the specimens was calculated by subtracting the weight of the wet filter paper and the weight of each ring from the measured weight of each specimen.

At the end of pressure plate tests (suction equal to 400 kPa), the tests were terminated and the specimens were removed and weighed. The water contents of each specimen at all suction levels were then back-calculated based on the change in weight at each applied suction, the final water content, and the dry weight of the specimens.

### 3.8.2 Salt solution tests

At high suction values (i.e., suctions higher than 3000 kPa), the salt solution method or vapour equilibrium technique was used to determine wetting and drying SWCCs. In this technique, total suction is imposed by controlling the relative humidity in the soil pore gaseous phase. Salt solution at a particular concentration and a constant temperature can be used to create a fixed vapour pressure environment under equilibrium conditions (Fredlund et al., 2011).

Saturated salt solutions were used to induce total suctions in soil specimens by maintaining predetermined relative humidity of the vapour space in desiccators. Saturated salt solutions of $K_2SO_4$, $KNO_3$, KCl, NaCl, $K_2CO_3$, and LiCl, were used for inducing suctions of 3.4, 9.1, 21.9, 38.3, 114.1 and 277 MPa, respectively. The test setup in the study is shown in Fig. 3.10. The tests were carried out in closed-lid desiccators and in a temperature controlled room (i.e., 21°C ±0.5°C). The relative humidity in the vapour space above a salt solution is related to total suction via Kelvin’s equation (Eq. 2.3) (Fredlund & Rahardjo, 1993). The saturated salt solutions used in this study along with the equilibrium relative humidity and suctions are shown in Table 3.3.

***Fig. 3.10 test setup for desiccator tests***

***Table 3.3 Relative humidity imposed by saturated salt solutions and corresponding suctions at 21°C***

| Saturated salt solution | RH (%)* at 21°C | Suction (MPa) (Eq.3.2) |
|---|---|---|
| LiCl | 13 | 277 |
| $K_2CO_3$ | 43.2 | 114.1 |
| NaCl | 75.4 | 38.3 |
| $KNO_3$ | 93.5 | 9.1 |
| $K_2SO_4$ | 97.5 | 3.4 |

** After O'Brien (1948) and ASTM E 104-02 (2007)*

$\psi = -135749 \times \ln\left(\frac{RH}{100}\right)$ - *suction and relative humidity relationship at reference temperature of 21 °C*

### *3.8.2.1 Salt solution test procedure*

The salt solution tests were carried out after completion of the pressure plate tests. About one third of the soil specimens were oven dried to determine the final water contents of the specimens at the end of pressure plate tests and the initial water contents for the specimens at the start of the salt solution tests. The rest of soil specimens (about 20 g) were placed in the glass desiccators containing saturated salt solutions of $K_2SO_4$, $KNO_3$, KCl, NaCl, $K_2CO_3$, and LiCl. The soil specimens were weighed periodically every week during the drying process until there was negligible change in mass of the soil specimens. At the end of salt solution tests during the drying process, the soil specimens were placed back again in the desiccators in reverse order to establish the wetting curve branch of the SWCCs. Changes in mass of soil specimens during drying and wetting processes enabled determining the water content of specimens at each total suction value.

### 3.8.3 Volumetric pressure plate test

The wetting SWCC can be established using a volumetric pressure plate apparatus (Soilmoisture, 2008). A 2-bar volumetric pressure plate extractor from Soilmoisture Equipment Corporation (Fig. 3.11) was used in this study.

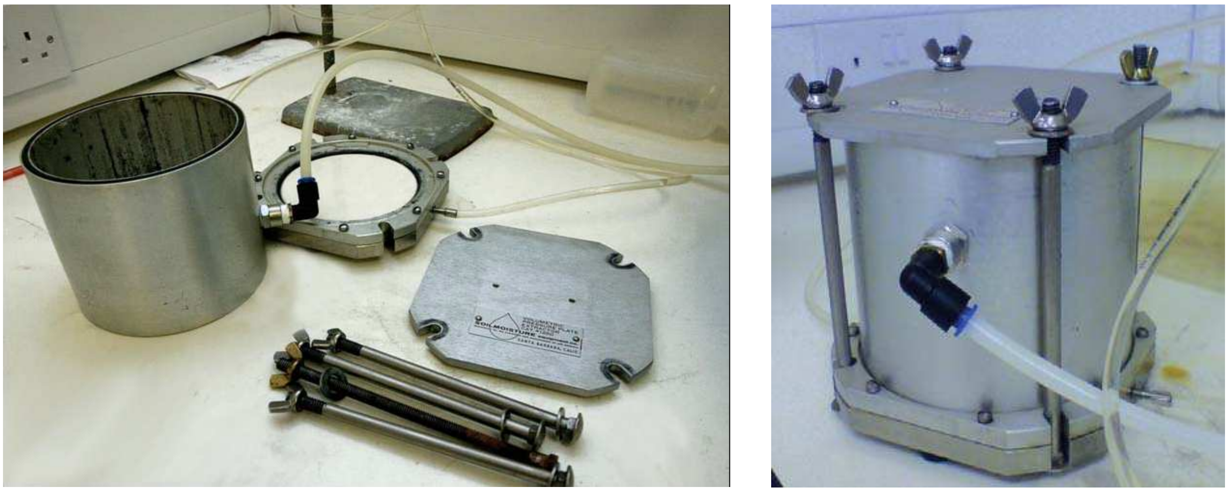


***Fig. 3.11 2-bar volumetric pressure plate***

#### *3.8.3.1 Test Procedure*

The ceramic disk of the volumetric pressure plate extractor was saturated before the tests by submerging it in de-aired water and applying low vacuum to remove entrapped air bubbles. Burettes were connected to the inlet and outlet of the volumetric pressure plate. The burettes were used as the water reservoir that supplied water to the soil specimens during the wetting tests.

The wetting tests using the volumetric pressure plate extractor were carried out after completion of the salt solution tests (section 3.8.2). The wetting SWCCs were established for applied suctions of 200, 100, 50, 20, 10, and 4 kPa. The weight of soil specimens were monitored during the tests period to ensure suction equalization at each applied suction. The final weight and the final water contents of the specimens were determined after completion of the tests. Back-calculation based on the change in weight at each applied suction, the final water content, and the dry weight enabled determining the water content of specimens at each applied matric suction value.

## 3.9 Suction measurements

The details of experimental methods adopted for measuring and imposing suctions in the soils are presented in the following sections. Laboratory tests that were carried out include; null-type axis-translation test (matric suction), filter paper test (total and matric suction), and chilled-mirror test (total suction).

### 3.9.1 Null-type axis-translation device

A single wall triaxial cell assembly was used to carry out the null-type axis-translation tests. The photograph and schematic diagram of the device is shown in Fig. 3.12. The main components of the device are; a plexiglass air pressure chamber, a base pedestal fitted with a high air-entry ceramic disk (air-entry value = 500 kPa), pressure transducers for measuring water pressure below the ceramic disk and air pressure in the pressure chamber, and a flushing system comprised of inlet and outlet valves.

The high entry ceramic disk was sealed into the bottom pedestal of the triaxial apparatus using epoxy resin. A strain indicator was used as a read-out for the pressure transducers. The base pedestal of the device was modified by providing concentric flushing grooves in the water compartment (Fig. 3.13). The water pressure transducer and the inlet valve (1/4" BSP ball-valve) were connected to a de-airing block that carried a bleed valve. The unit was then directly fitted to the port on the water compartment via a 1/4" BSP ball-valve.

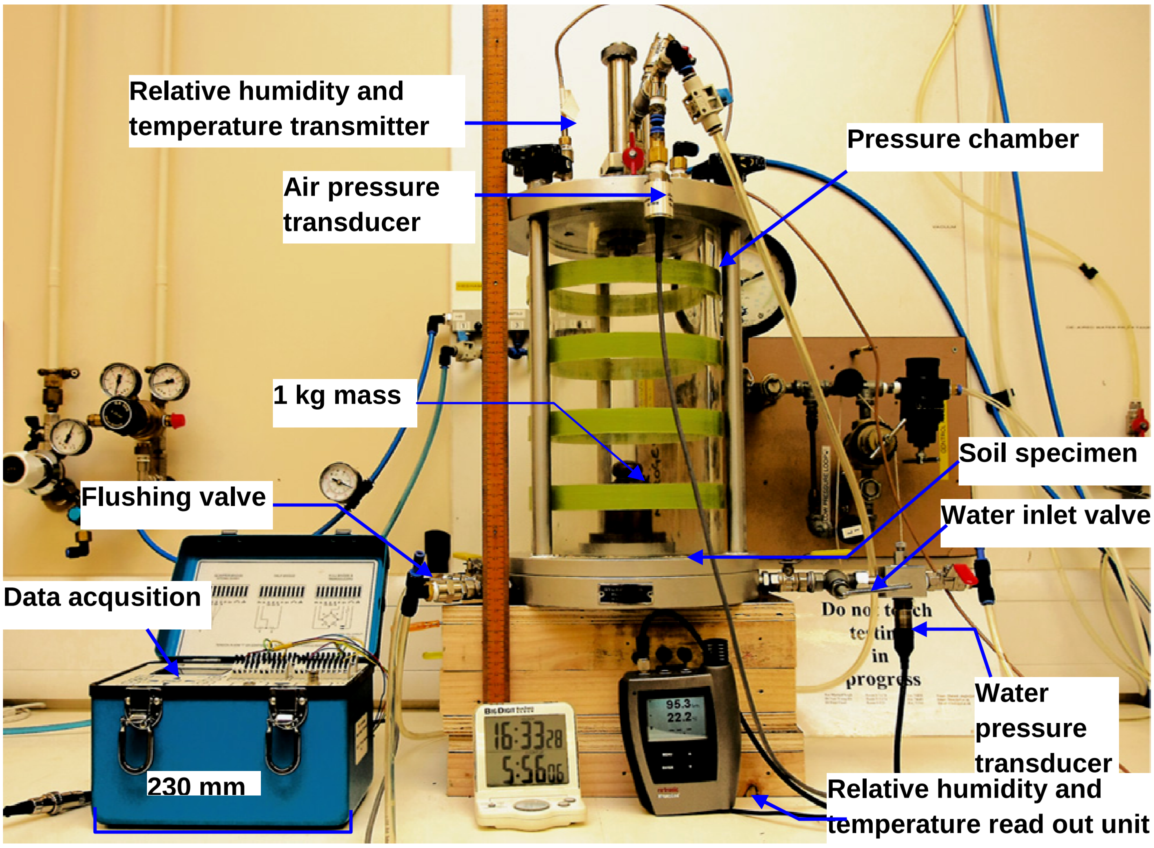



*Fig.3.12 -Photograph of the null-type axis-translation device used in this study*

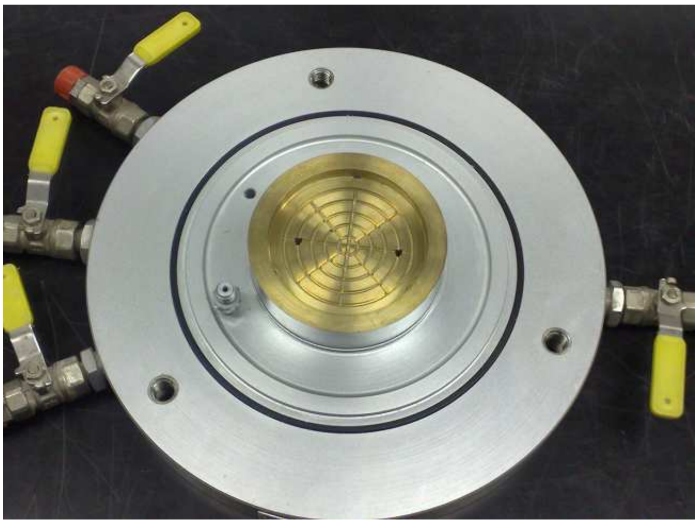


***Fig. 3.13 The grooved water compartment below the high-entry ceramic disk***

Saturation of the ceramic disk was carried out by applying the chamber air pressure in the presence of water head above the ceramic disk for several days while flushing the water compartment beneath the ceramic disk regularly with distilled de-aired water.

The response of the transducer to a change in pressure may be used to check the completeness of the saturation process (Olson & Langfelder, 1965). The air pressure was applied to the water surface above the ceramic disk and the pore water pressure in the water compartment was recorded. It was found that the transducer connected to the water compartment record the same value of applied air pressure within few seconds. Olson & Langfelder (1965) stated that if a small amount of air bubbles exist in the system, the pressure will build up slowly because water must flow through the ceramic disk in order to diminish the volume of bubble such that the volume is compatible with the new pressure condition.

#### *3.9.1.1 Test procedure for Null-type axis-translation test*

The measurements of matric suction were essentially followed the procedure adopted by Olson & Langfelder (1965). The test procedure started with wiping the ceramic disk with wet paper towel and the soil specimen was then placed on the saturated ceramic plate. To ensure a good contact between the specimen and the ceramic disk, a 1 kg mass was placed on the top of the specimens (Olson & Langfelder, 1965). The soil specimen tended to draw water up through the ceramic disk immediately after it was placed on top of the ceramic disk, and the pore-water pressure transducer started recording a negative value. The apparatus was then quickly assembled and the air pressure inside the pressure chamber was increased in increments to keep the pore water at atmospheric pressure (zero gauge reading). Equilibrium was achieved when the reading of air pressure was held constant and the pore water pressure showed no change. At equilibrium, the matric suction was the applied air pressure in the chamber as the pore water pressure was maintained at zero during the tests. Once the equilibrium was reached, the apparatus was disassembled and the soil specimen was quickly weighed and the water content was measured by oven drying method.

### 3.9.2 Suction measurement using filter paper method

The filter paper method is an inexpensive and relatively simple laboratory test method, from which both total and matric suction measurements of soils are possible. The filter paper tests used in the present study were carried out according to ASTM D5298-10 for measuring matric suction using “contact” filter paper technique, and total suction using “non contact” filter paper technique. Fig. 3.14 shows the arrangement of filter paper contact method (to measure matric suction) and non-contact method (to measure total suction).

#### *3.9.2.1 Procedure for measuring matric and total suctions*

In this study, filter paper in contact and in non contact with the soil specimen was used to measure matric and total suctions. The filter paper test procedure is standardised in ASTM D5298-10, and was followed in this study. The procedure was undertaken using Whatman No. 42 filter paper.

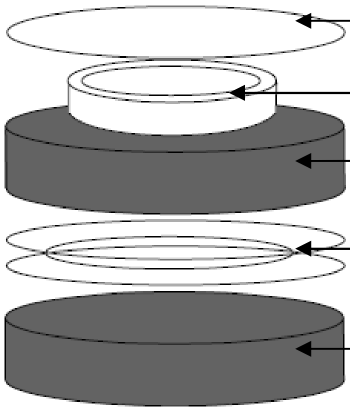



***Fig. 3.14 Measuring matric and total suction using contact and noncontact filter paper method for, respectively (modified from Bulut, et al., 2001).***

Filter papers were firstly oven dried in order to maintain consistency in mass at 105°C and then were allowed to cool to room temperature in a desiccator. To measure matric suction, a filter paper was sandwiched in between two sacrificial filter papers placed in between two identical halves of a soil specimen. The two halves of the soil specimen were then brought together and sealed with electrical tape to keep them together in order to create good contact. The soil specimen was placed in the jar and PVC ring was kept on top of the specimen. A filter paper was suspended above the soil specimen for total suction measurements. An equilibrium period of 14 days was adopted for all tests. The filter papers were then removed after 14 days equilibration time and immediately weighed to the nearest 0.0001g with an electronic balance. The filter papers were oven dried for 24 hours and weighed again to determine the filter paper water content. The water content of the filter paper was used to determine matric and total suctions using calibration curves. The calibration curves of the filter paper used were established in this study.

#### *3.9.2.2 Filter paper calibration curve test*

Calibration of the filter paper (contact and non contact) used in this study were conducted to establish the filter paper water content versus suction relationship. The non-contact calibration tests for the Whatman No. 42 paper were performed using molal solutions of sodium chloride (NaCl). The volumetric pressure plate was used to establish contact filter paper calibration curve. The procedure for the calibration tests was essentially identical to that for soil testing.

For the non contact calibration tests, sodium chloride (NaCl) solutions were prepared in a temperature controlled room (21°C ±0.5°C) at values of molality ranging from 0.003 to 2.700 (Table 3.3). A 200 ml glass jars was filled with approximately 120 ml of different concentrations of NaCl solution. A small plastic cup was inserted into the jar and an oven dried filter paper (after being cooled in desiccators) was then placed on the top of the plastic cup (Fig. 3.15). The jars were sealed tightly with electrical tape and placed into the insulated chest where a constant temperature of approximately 22.0 °C was kept during the equilibration process. After two weeks of equilibration time, the water contents of the filter papers were determined by oven drying method (T = 105°C). The calibration curve was established using the calculated osmotic suction and the measured filter paper water contents.

For contact filter paper calibration tests, initially dry filter papers were placed in the volumetric pressure plate and independent values of air pressures of 5, 10, 20, 50, 100, and 200 kPa were applied. An equilibrium time of 7 to 10 days were considered. Once the equilibration was achieved, the water contents of the filter paper were determined. All measurements were carried out using a 0.0001g electronic balance.

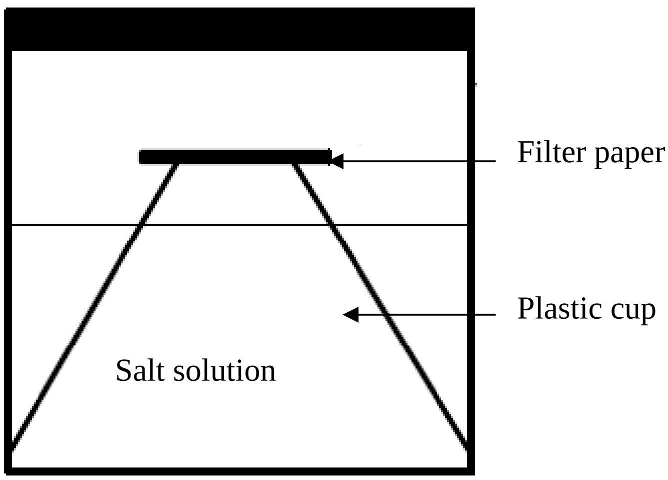



***Fig. 3.15 Non-contact calibration tests***

***Table 3.3 Total suction of NaCl at 20°C (adopted from Lang, 1967)***

| NaCl molality | Suction (kPa) | NaCl molality | Suction (kPa) |
|---|---|---|---|
| 0.002 | 9.8 | 0.4 | 1791 |
| 0.005 | 24.2 | 0.5 | 2241 |
| 0.01 | 48 | 0.7 | 3151 |
| 0.02 | 95 | 0.9 | 4102 |
| 0.05 | 230 | 1.2 | 5507 |
| 0.1 | 454 | 1.7 | 8000 |
| 0.2 | 900 | 2.2 | 10695 |
| 0.3 | 1344 | 2.7 | 13641 |

In order to investigate the hysteresis in drying and wetting calibration curves for Whatman No. 42 filter paper, a similar test procedure to that mentioned above was followed. In this case, wet filter papers were used. The test results of drying and wetting calibration tests on filter papers are presented in Chapter 8.

### 3.9.3 Chilled-mirror dew-point technique

Chilled-mirror dew-point technique has been used by several researches (e.g., Leong et al., 2003; Agus & Schanz, 2005; Thakur et al., 2006; Campbell et al., 2007) for measuring total suctions of soils. Figure 3.15 shows the WP4-C chilled-mirror dew-point device used in this study and the schematic of the device.

The working principle of the chilled-mirror dew-point technique is based on the thermodynamic relationship between relative humidity, temperature and total soil suction according to Kelvin's equation.

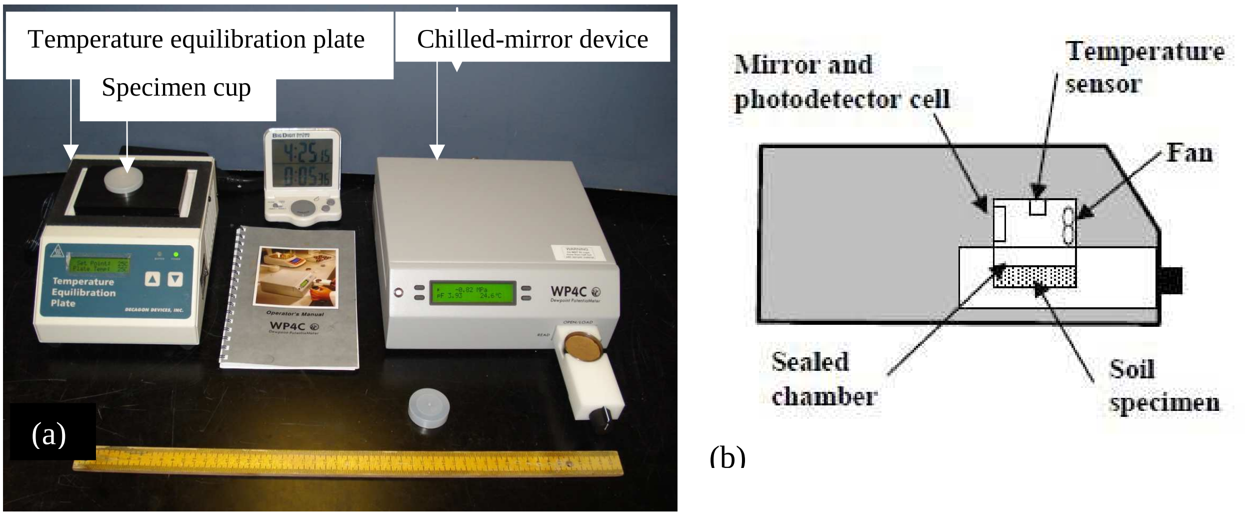



***Fig. 3.15 WP4-C model of chilled-mirror dew point device (a) photograph of the device and (b) schematic of chilled-mirror dew point device (Leong et al., 2003)***

The device consists of a sealed chamber with a fan, a mirror, a photoelectric cell, and an infrared thermometer. A soil specimen fills about half the capacity of a stainless steel cup and is placed in the device in a closed chamber that contains a mirror and a photodetector cell. Detection of the exact point at which condensation first appears on the mirror is observed by a beam of light directed onto the mirror and reflected into a photodetector cell. A thermocouple attached to the mirror records the temperature at which condensation occurs (Leong et al., 2003). A fan is included in the sealed compartment to reduce equilibrium time between the specimen and the surrounding air. The device also equipped with a temperature controller to set the temperature of the sample at which relative humidity measurement is to be made. The deceive come with a temperature equilibrium plate that used to bring the temperature of the specimen cup to the set-point temperature of the device (Fig. 3.15*a*).

The relative humidity is computed using the dew-point temperature of the air and the specimen temperatures, which is measured with an infrared thermometer. Kelvin's equation (Eq. 3.3) is then used to calculate the total suction of the soil specimen. The calculations are performed by software within the device and displayed on an LCD panel in MPa unit along with the specimen temperature. The device is able to measure suction to an accuracy of ± 0.05 MPa from 0 to 5 MPa and 1% from 5 to 300 MPa.

#### *3.9.3.1 Test procedure for suction measurement using chilled-mirror device*

Test procedures for measuring suction using WP4-C started by calibrating the device with a standard solution provided by the manufacturer. The device was first set to a set-point temperature equal to or slightly higher than the estimated highest room temperature (T = 23°C). The equilibration solution (Potassium Chloride (KCl)) was poured in the specimen cup and placed on temperature equilibrium plate to bring the temperature of the specimen cup to the set-point temperature of the device. The specimen cup with the salt solution was then placed in the WP4C's specimen drawer and the drawer knob was turned to the READ position. Once the equilibrium was reached, the value total suction value was then calculated and displayed on an LCD panel in MPa unit along with the specimen temperature.

After completing the calibration of the device, the soil specimens were placed in the specimen cup covering the bottom of the cup and fill about the half of it. Similar procedures to those used for calibration the device were carried out for total suction measurements of the soil specimens. The water contents of soil specimens after completion of total suction measurements were determined by oven drying method.

## 3.10 Water content-void ratio relationships (shrinkage paths)

Clod tests were carried out for slurried and compacted soil specimens to obtain the relationship between the change in water content and the void ratio during the shrinkage process. The shrinkage curves were used in conjunction with suction-water content SWCCs results to establish the suction-void ratio SWCCs and suction-degree of saturation SWCCs of the soils.

### 3.10.1 Clod test

Commercially available Unibond Waterproof PVAc glue was used for coating the soil specimens in this study. Krosley et al. (2003) suggested using Elmer's glue as an alternative encasement material for the Clod test. The PVAc glue was found to be a substitute for its US counterparts, Elmer's glue (Tadza, 2011). The glue allows water vapour to escape from the Clod during the drying process, but prevents liquid water from flowing into the Clod during mass measurement in water (Krosley et al., 2003). The PVAc glue was first diluted with deionised water in order to improve the workability of the glue. A ratio of 10 part of glue to 1 part of deionised water was considered. In order to handle and coating the Clod specimens with the encasement glue, compacted saturated soil specimens were placed in pressure plate and suction of 4.0 kPa were applied.

Figure 3.16 shows the soil specimens in the Clod tests. The Clod specimens were hung by threads and allowed to dry out at an ambient laboratory temperature. As the glue required some time to solidify immediately after coating the soil specimens, the determination of the initial volume in Clod tests was quite difficult. The mass of the soil specimens were measured about an hour after the specimens were coated with glue, as the surface of the coated specimens needed to harden before being submerged in water.

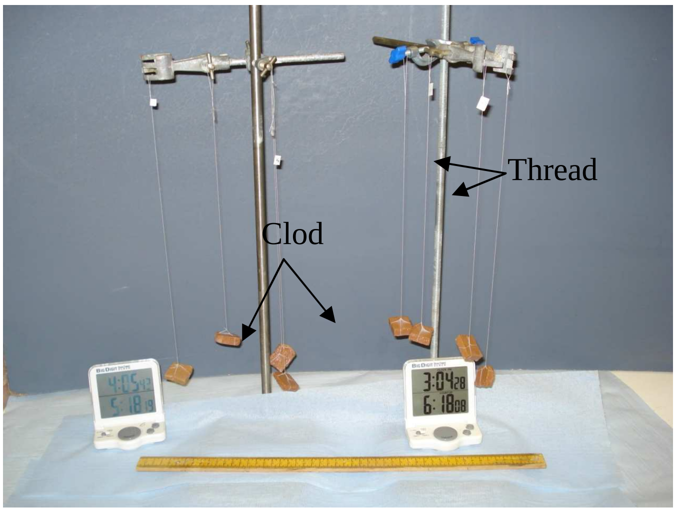



***Fig. 3.16 Soil specimens in clod test***

To determine the volume of soil specimens during the drying process, the mass of the Clod in air and in water were measured. The void ratios of the soil specimens were calculated using volume-mass relationships. Volume measurements were carried out until no further reduction in the mass of the Clod was observed.

The initial total mass of the Clod, $M_{clod(i)}$, comprises of the initial total mass of the soil, $M_{soil(i)}$, and the initial mass of glue, $M_{glue(i)}$ (Eq. 3.4), where *i* stands for the initial condition. Similarly, at any given time *t*, the total volume of the Clod, $V_{clod(t)}$, comprises of the volume of specimen, $V_{soil(t)}$, and the volume of glue, $V_{glue(t)}$. The total volume of the Clod, $V_{clod(t)}$, can be determined by measuring the mass of the Clod in air, $M_{air(t)}$, and the mass of Clod in water $M_{water(t)}$ (Eq. 3.5 ). By knowing $M_{glue(i)}$, the mass fraction of the glue at any given time during drying process $(g_{f(t)})$ from Fig. 4.3, the density of the glue $( \rho_{glue})$, and by applying volume-mass relationships, the volume of the glue, $V_{glue(t)}$, can be calculated from Eq. 3.7. The water content of the soil specimen, $w_{soil(t)}(\%)$, can be calculated by knowing the initial water content of the soil specimen, $w_{soil(i)}(\%)$, and the dry mass of the soil specimen, $M_d$, from Eq. 3.8. The dry density of the soil, $\rho_{dsoil(t)}$, and the void ratio, $e_{soil(t)}$, can be calculated from Eqs. 3.9 and 3.10.

$$M_{clod(i)} = M_{soil(i)} - M_{glue(i)} \qquad \text{Eq. 3.4}$$

$$V_{clod(t)} = M_{air(t)} - M_{water(t)} \qquad \text{Eq. 3.5}$$

$$V_{soil(t)} = V_{clod(t)} - V_{glue(t)} = V_{clod(t)} - \left[\frac{\left(M_{glue(i)} x\ g_{f\langle t\rangle}\right)}{\rho_{glue}}\right] \qquad \text{Eq. 3.6}$$

$$V_{soil(t)} = V_{clod(t)} - \left[\frac{M_{glue(t)}}{\rho_{glue}}\right] \qquad \text{Eq. 3.7}$$

$$w_{soil(t)} = \left(w_{soil(i)}\right) - \left[\frac{\left(M_{glue(i)} x\ g_{f\langle t\rangle}\right)}{\rho_{glue}}\right] \qquad \text{Eq. 3.8}$$

$$\rho_{d\ soil(t)} = \left[\left(\frac{\left(M_{air(t)} - M_{glue(t)}\right)}{V_{soil(t)}}\right) \div \left(1 + \frac{w_{soil(t)}}{100}\right)\right] \qquad \text{Eq. 3.9}$$

$$e_{soil(t)} = \left(\frac{G_s}{\rho_{d\ soil(t)}} - 1\right) \qquad \text{Eq. 3.10}$$

### *3.10.1.1 Calibration of glue mass*

The PVAc glue is a water based material that tends to loose water during solidification. The amount of water lost from the glue during the drying process can be determined by conducting an independent test by smearing a known mass of diluted glue onto a light plastic sheet (Tadza, 2011). Measuring the changes in the mass of the glue with elapsed time was performed using sensitive 0.0001g electronic balance. The change in the mass with elapsed time for three similar tests is shown in Fig. 3.17.

It can be seen from Fig. 3.17 that the loss of water from the diluted glue was significant within about first eight hours and the glue mass fraction reached a constant value of about 0.38 after twenty four hours. A value of glue mass fraction correction of 0.38 was used for corrected the mass measurements for soil specimens carried out after twenty four hours period, while variable glue mass fractions was used to correct the volume measurement for soil specimens within first twenty four hours.

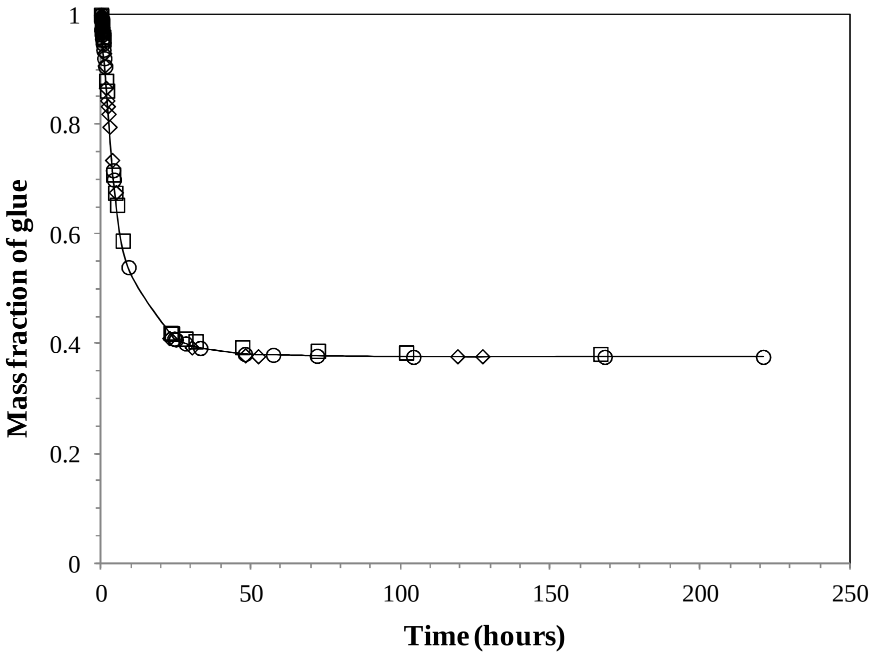



***Fig. 3.17 Glue mass fraction calibration curve***

A reduction in the water content of glue may cause a change in the density. The variation of glue density was considered to be insignificant and a single value of density of 1.05 $Mg/m^3$ was considered for the calculations.

## 3.11 Concluding remarks

In this chapter, the physical properties of JF and TR soils, such as the liquid limit, the plastic limit, the shrinkage limit, the specific gravity, and the grain size distribution are described. The JF and TR soils used on this study were classified as SML and CI based on British standard (BS) classification system.

Compaction, odometer and permeability tests as well as procedures adopted for specimen preparation are presented. The optimum water contents for JF soil were found to be 11.2% for BS-light compaction effort and 9.3% for BS-heavy compaction effort. For TR soil, the optimum water contents were found to be 20.1 and 15.4% for BS-light and BS-heavy compaction efforts, respectively.

Testing procedures and apparatus used for establishing drying and wetting suction-water content SWCCs (pressure plate, slat solution tests) are explained in detail. Additionally, total and matric suction measurements using null-type axis translation device, filter paper (contact and non contact) methods, and working principle of chilled-mirror device are presented. Test procedure for determination of void ratio-water content relationship (shrinkage curves) by Clod test is also presented.

# CHAPTER 4

# SUCTION-WATER CONTENT SWCCs

## 4.1 Introduction

The soil-water characteristic curve (SWCC) presents the fundamental property for the study of unsaturated soils (Fredlund et al., 2012). The SWCC presents a relationship between the amount of water in the soil (i.e. gravimetric or volumetric water content) and suction. Other forms of the SWCC are the relationship between soil suction and void ratio and between soil suction and degree of saturation. Many properties of unsaturated soils, such as the hydraulic conductivity, the shear strength and the volume change can be related to the amount of water present in the soil pores at any suction, which can be obtained from the SWCC.

The experimental drying and wetting suction-water content SWCCs of the soils used in this study (Jaffara soil (JF) and Terrarosa soil (TR)) are presented in this chapter. The suction-water content SWCCs were established for slurried specimens and compacted saturated specimens of both soils. In order to obtain the SWCCs of the soils for a wide range of suction, two experimental techniques were used, namely the axis-translation technique and the vapour equilibrium technique. Soil specimens used for establishing the SWCCs were prepared at various compaction conditions in order to investigate the influence of the initial compaction conditions on the SWCC. The moulding water content, the dry density, and compaction type and effort were varied.

It is important to note that, the total volume of the soil specimen may change due to application of suction. In the case of deformable soils, a change in total volume of the soil may be significant. The interpretation of the SWCC for a low volume change soil, such as that for sand and silt is generally based on the assumption that the initial void ratio remains constant throughout the test and changes in the water content becomes the predominant function of relevance. The relevance of volume measurements of soil specimens during tests will be discussed in more detail in chapter 5.

The objectives of this chapter were to study various factors which influence the suction-water content SWCC, such as (*i*) the initial water content, (*ii*) the compaction energy which in turn affects the initial dry density, (*iii*) the compaction type, and (*iv*) the soil types. In addition, the applicability of the currently available best-fit models and the effect of various model parameters on the SWCCs were examined in detail.

This chapter is divided into several sections which include the experimental programme adopted, followed by the drying and wetting suction-water content SWCCs results obtained for both soils and presentation of the effects of initial compaction conditions on the SWCCs. The concluding remarks are presented towards the end of the chapter.

## 4.2 Experimental programme

Laboratory tests were carried out to study the influence of the initial compaction conditions on the suction-water content SWCC. The compaction conditions were selected so as to enable a comparison between the SWCCs for different compaction water contents but equal dry density, and between the SWCCs of specimens prepared at different densities, but with equal compaction water content. In addition, specimens were prepared by applying both dynamic and static compaction efforts.

### 4.2.1 Soil specimen preparation

Dynamically compacted soil specimens were prepared from both BS-light and BS-heavy compaction samples. Thin walled stainless-steel tube samplers with bevelled edge and inside diameter of 42 mm were used to extrude the compacted specimens from the compaction mould. Samples were taken from the remaining soil to determine the compaction water contents of the specimens. The dry densities of the tested specimens were calculated based on the volume-mass relationships.

In addition to the dynamically compacted specimens, soil specimens were also prepared by statically compacting soil-water mixtures in single lift in a specially fabricated mould (Sec. 3.7). The targeted compaction dry densities and water contents of the statically compacted soil specimens were corresponding to the specimen conditions of the dynamically compacted specimens.

Fourteen specimens were tested from each type of soil (three specimens for dynamically-heavy compaction, three for dynamically-light compaction, three for static-heavy compaction, and five for static-light compaction). In each case, three duplicate soil specimens were prepared in the same manner; one was used to determine the initial water contents of the saturated specimens and further two were used to determine the average water contents corresponding to all the applied suction steps. Additionally, saturated slurry specimens from both soils were prepared by mixing air-dried soil with deionised water to targeted water content of 1.1 times the liquid limit values. In total 88 specimens were prepared for the SWCC tests, 44 for each soil. The specimen conditions chosen for the SWCC tests are shown in Figs. 4.1 and 4.2 and Tables 4.1 and 4.2.

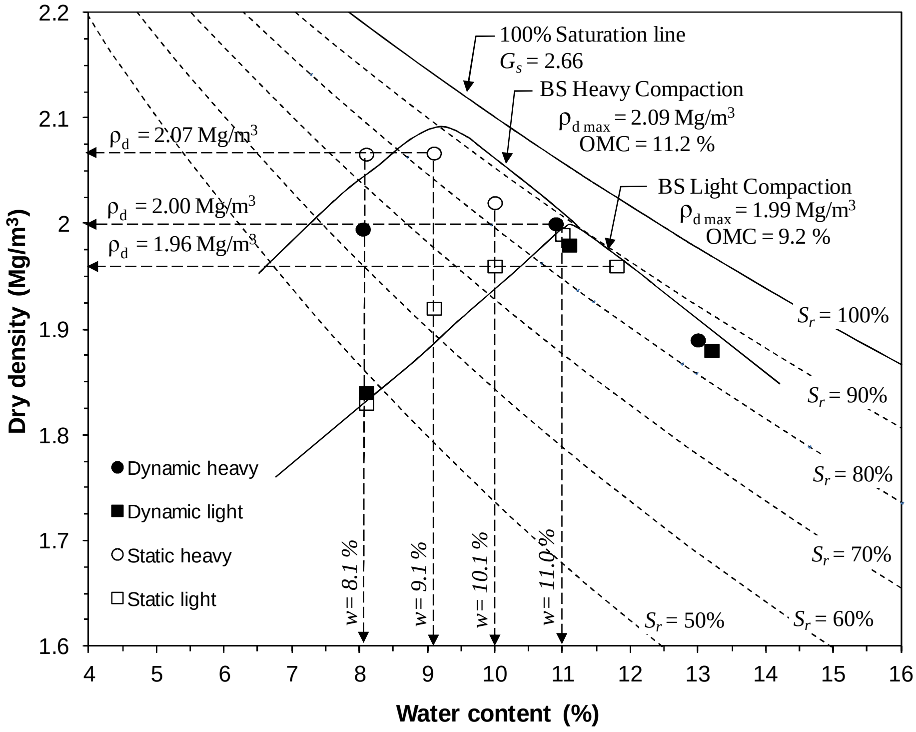



*Fig. 4.1 B.S compaction curves of JF soil and initial specimen conditions for SWCC tests*

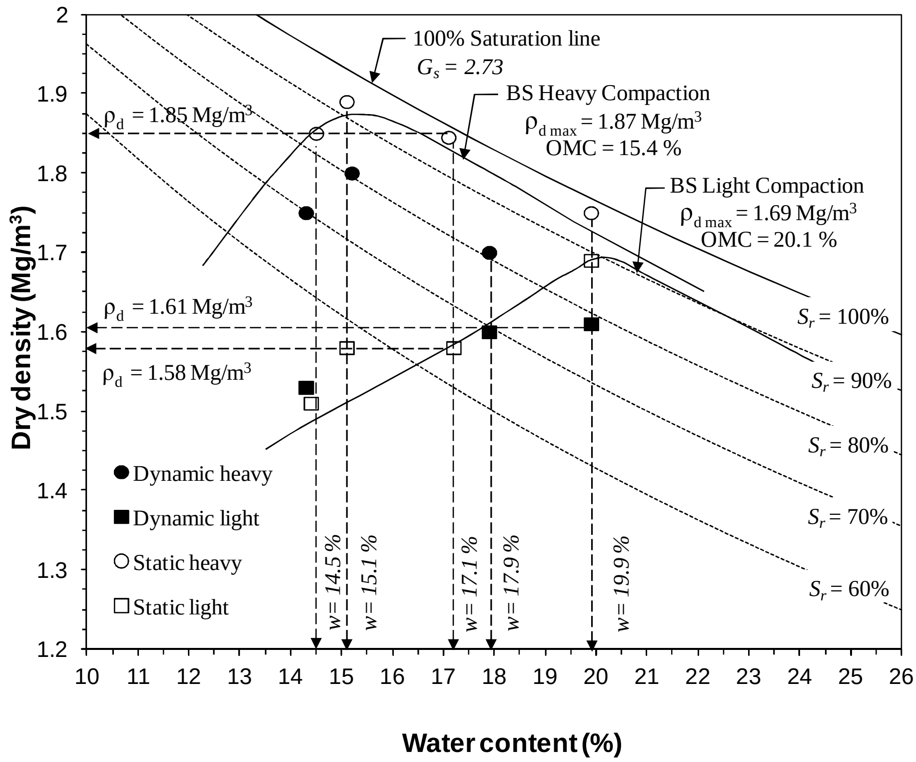



*Fig. 4.2 B.S compaction curves of TR soil and initial specimen conditions for SWCC tests*

***Table 4.1 Initial compaction conditions of JF soil for SWCCs tests***

| No. | Compaction type, effort | Initial compaction conditions | | | | |
|---|---|---|---|---|---|---|
| | | Specimen notation | Water content (%) | Dry density ($Mg/m^3$) | Void ratio | Degree of saturation (%) |
| 1 | Dynamic heavy compaction | JF-DH8 | 8.1 | 1.99 | 0.337 | 64.0 |
| 2 | | JF-DH11 | 10.9 | 2.00 | 0.330 | 87.9 |
| 3 | | JF-DH13 | 13.0 | 1.89 | 0.407 | 84.9 |
| 4 | Dynamic light compaction | JF-DL8 | 8.1 | 1.84 | 0.446 | 48.4 |
| 5 | | JF-DL11 | 11.0 | 1.98 | 0.343 | 85.2 |
| 6 | | JF-DL13 | 13.2 | 1.88 | 0.415 | 84.6 |
| 7 | Static heavy compaction | JF-SH8 | 8.1 | 2.06 | 0.288 | 74.0 |
| 8 | | JF-SH9 | 9.1 | 2.07 | 0.287 | 84.9 |
| 9 | | JF-SH10 | 10.0 | 2.02 | 0.317 | 84.0 |
| 10 | Static light compaction | JF-SL8 | 8.1 | 1.83 | 0.454 | 47.5 |
| 11 | | JF-SL9 | 9.1 | 1.92 | 0.385 | 62.8 |
| 12 | | JF-SL10 | 10.0 | 1.96 | 0.357 | 74.5 |
| 13 | | JF-SL11 | 11.0 | 1.99 | 0.337 | 86.9 |
| 14 | | JF-SL12 | 11.8 | 1.96 | 0.357 | 87.9 |

*JF = JF soil, DH = dynamic heavy compaction, DL = dynamic light compaction, SH = static heavy compaction, SL = static light compaction, No. = initial compaction water content*

***Table 4.2 Initial compaction conditions of TR soil for SWCCs tests***

| No. | Compaction type, effort | Initial compaction conditions | | | | |
|---|---|---|---|---|---|---|
| | | Specimens notation | Water content (%) | Dry density (Mg/m$^3$) | Void ratio | Degree of saturation (%) |
| 15 | Dynamic heavy compaction | TR-DH14 | 14.3 | 1.75 | 0.558 | 69.9 |
| 16 | | TR-DH15 | 15.2 | 1.80 | 0.514 | 80.5 |
| 17 | | TR-DH18 | 17.9 | 1.70 | 0.604 | 80.9 |
| 18 | Dynamic light compaction | TR-DL14 | 14.3 | 1.53 | 0.782 | 49.9 |
| 19 | | TR-DL18 | 17.9 | 1.60 | 0.704 | 69.3 |
| 20 | | TR-DL20 | 19.9 | 1.61 | 0.693 | 78.3 |
| 21 | Static heavy compaction | TR-SH14 | 14.5 | 1.85 | 0.474 | 83.5 |
| 22 | | TR-SH15 | 15.1 | 1.89 | 0.442 | 93.1 |
| 23 | | TR-SH17 | 17.1 | 1.84 | 0.482 | 96.8 |
| 24 | | TR-SH20 | 19.9 | 1.75 | 0.558 | 97.3 |
| 25 | Static light compaction | TR-SL14 | 14.4 | 1.51 | 0.805 | 48.8 |
| 26 | | TR-SL15 | 15.1 | 1.58 | 0.725 | 56.8 |
| 27 | | TR-SL17 | 17.2 | 1.58 | 0.725 | 64.6 |
| 28 | | TR-SL20 | 19.9 | 1.69 | 0.613 | 88.5 |

*TR = TR soil, DH = dynamic heavy compaction, DL = dynamic light compaction, SH = static heavy compaction, SL = static light compaction, No. = initial compaction water content*

### 4.2.2 Saturation of compacted soil specimens

Prior to the SWCC tests, compacted soil specimens were saturated by placing them along with the rings on filter paper and soaking in water bath allowing water to imbibe from the bottom. The water level was kept below the top of the specimen ring (about 2 mm) so that the entrapped air present inside the void of the specimen could be released during the saturation process. Trial studies showed that 24 hrs was sufficient for saturating the soil specimens. The initial weight of the specimen after saturation was recorded and then the saturated specimens were placed in pressure plates.

The water contents of the soil specimens at all applied suction steps were calculated based the final water contents of the specimens after the end of the tests. Comparison of the water contents at each applied suction based on the change in the mass of the specimens and the measured water contents for the duplicate specimens indicated that the differences in the water contents were within acceptable error of about ± 0.4%.

### 4.2.2 Testing methods

Two types of tests were performed to establish the SWCCs of JF and TR soils. The axis-translation technique (pressure plate tests) was adopted to control matric suction in the range 5 to 400 kPa, whereas the vapour equilibrium technique (salt solution tests) was used to impose total suction in the range 3 to 300 MPa.

#### *4.2.2.1 Pressure plate test*

A 5-bar pressure plate extractor manufactured by Soilmoisture Equipment Corporation was used in the laboratory to establish the drying SWCCs in accordance with ASTM D 6836-02. The pressure plate extractor can only be used to establish the drying paths. A 2-bar volumetric pressure plate extractor was used to generate the SWCCs along the wetting paths between suction of 200 and 4 kPa.

The ceramic disk of the pressure plates were saturated using distilled deaired water. The water compartment below the ceramic plate was filled with distilled deaired water and a sufficient amount of water was also subsequently poured on the ceramic plate surface. A small air pressure of about 10 kPa was applied to pressurise water on the ceramic plate and then was gradually and incrementally increased to about 100 kPa for several hours. The saturation process was terminated when no air bubbles were observed to come out of the water compartment and flow to the burette.

For the SWCCs tests, the compacted saturated soil specimens were placed on the ceramic disk and an air pressure was applied. In order to reduce the possibility of material loss due to the handling during weighing measurements, filter papers were provided at the bottom of each specimen. Suctions of 5, 10, 20, 50, 100, 200, 300 and 400 kPa were considered for establishing the drying paths. The weight of the specimen at each imposed suction level was monitored frequently by weighing the mass of specimens at every alternate day. Equilibrium was considered to have occurred when there was no significant reduction in the weight of the specimens over successive measurements and based on the water content versus time plot. It was noted that the equilibrium time was about ten days for specimens of JF soil and about eight days for specimens of TR soil. After each suction equilibration, the ceramic disks were re-saturated before applying the next matric suction increment.

At the end of pressure plate tests (suction equal to 400 kPa), the tests were terminated and the specimens were removed and weighed. About one third the specimens were oven dried and their water contents and dry mass were obtained. The water content of each specimen at previous stages were then back-calculated based on the change in the weight at each stage, the final water content, and the dry weight. The rest of the specimens (in most cases mass of specimens were about 20 g) were used for the salt solution test.

#### *4.2.2.2 Salt solution test*

In a salt solution test, total suction is imposed by controlling the relative humidity in an air space above saturated salt solutions in a closed system. Several salt solutions were used to impose total suction in the soil specimens by changing the relative humidity of the vapour space in the desiccator. The salt solution tests were used to determine drying and wetting SWCCs in the high suction range. The results from salt solutions tests were used in conjunction with pressure plate test results to generate a complete SWCC.

The imposed suction in a salt solution test is based on the thermodynamic relationship between total suction (or the free energy of the soil-water) and the partial pressure of the pore-water vapour (relative humidity, *RH*) (Edlefsen & Anderson, 1943; and Richards, 1965). Total suction can be determined by measuring the vapour pressure adjacent to the soil-water or the RH in the soil by applying Kelvin's equation (Fredlund & Rahardjo, 1993). In this case, a saturated salt solution is kept within a closed desiccator. The RH of the air within the desiccator comes to equilibrium with the evaporation of water from the saturated salt solution (Romero, 2001).

In order to verify the imposed suction in the desiccator tests, non contact filter paper (initially dry) and chilled-mirror dew point meter (WP4C) were used. The test results from WP4C and filter paper measurements are shown in Fig. 4.3 and Table 4.3. It can be seen that the targeted suctions are within the measurements accuracy range of the WP4C. Additionally, overall good agreements were noted between the targeted suction and the calculated suction based on filter paper method.

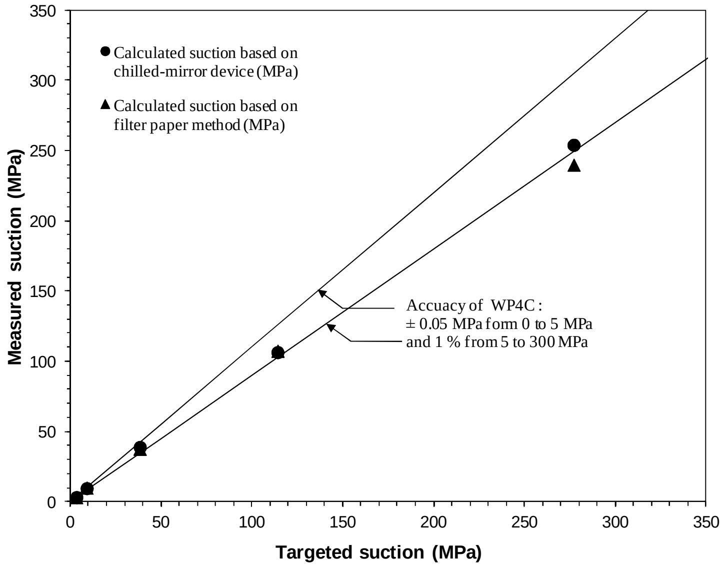



***Fig. 4.3 Comparison between calculated and measured total suctions of salt solutions***

***Table 4.3 Relative humidity imposed by saturated salt solutions and corresponding suctions at 21°C***

| Saturated salt solution | Targeted RH (%)* at 21 °C | Targeted suction (MPa) (Eq.3.3) | Calculated suction based on filter paper method (MPa)+ | Calculated suction based on chilled-mirror device (MPa) |
|---|---|---|---|---|
| LiCl | 13.0 | 277 | 239 | 254 |
| $K_2CO_3$ | 43.2 | 114.1 | 107.4 | 104.5 |
| NaCl | 75.4 | 38.3 | 37.7 | 38.96 |
| $KNO_3$ | 93.5 | 9.1 | 10.02 | 9.65 |
| $K_2SO_4$ | 97.5 | 3.4 | 3.22 | 3.3 |

* *After O'Brien (1948) and ASTM E 104-02 (2007)*

$\psi = -135749 \times \ln\left(\frac{RH}{100}\right)$ - *suction and relative humidity relationship at reference temperature of 21 °C*

\+ *From filter paper calibration equation (Eq. 8.2)*

The salt solution tests were carried out after completion of the pressure plate tests. The soil specimens were placed in the glass desiccators containing various salt solutions for at least four weeks to impose different suction values. Five selected aqueous salt solutions were used to induce a range of total suction of 3300 to 277000 kPa. Table 4.3 shows the salt solution types and the corresponding suctions at a temperature of 21°C. Monitoring the variations in the weight of soil specimens during the test period enabled ensuring suction equalization.

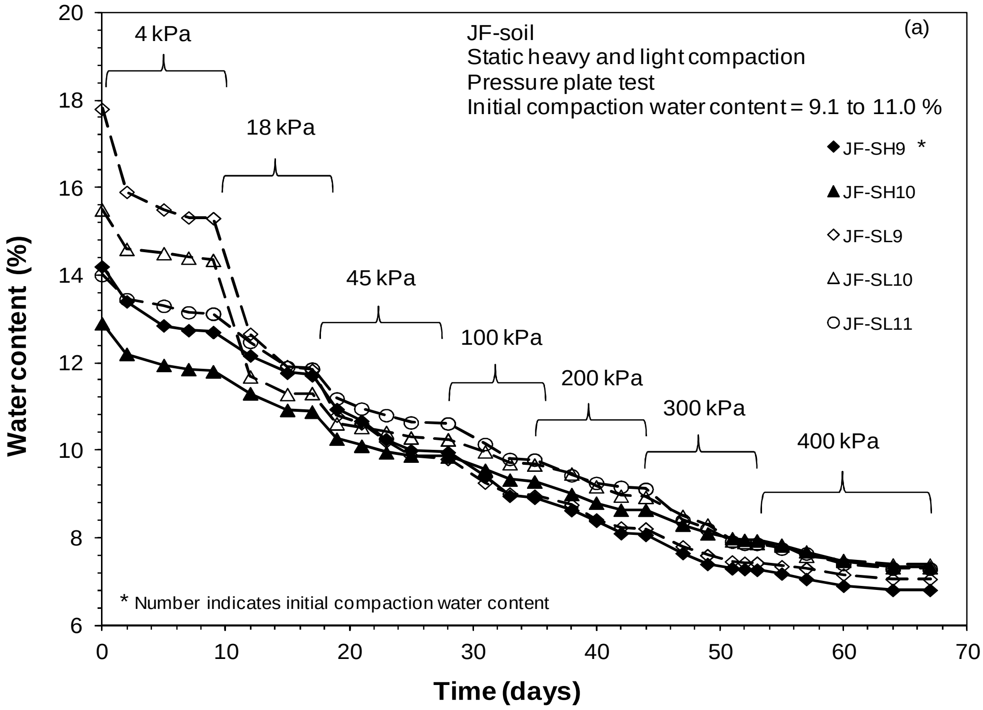
### 4.3 Results and discussion

In the following sections, the suction equilibration time for drying SWCCs of JF and TR soil specimens is presented followed by the influence of initial compaction conditions and soil type on the SWCC test results. The best-fit of the experimental results with the models proposed by van Genuchten (1980) and Fredlund & Xing (1994) are also presented.

#### 4.3.1 Equilibrium time

The suction equilibration time depends upon several factors, such as suction level, temperature, soil type and the size of the soil specimen (Oliveira & Marinho, 2006; Khoury & Miller, 2008).

Typical test results for water content change versus time for drying SWCCs of JF and TR soil specimens in pressure plate tests are presented in Figs. 4.4*a* and 4.5*a*. For any applied suction fairly rapid decrease in the water content was observed within the first 2 days followed by a more gradual change in water content until the equilibrium was reached. The equilibrium time in the pressure plate test varied from 4 to 12 days for the specimens of JF soil and about 4 to 7 days for the specimens of TR soil. The test results show that the amount of water drained out form the soil specimens at low suction range were greater than that occurred at high suction range.



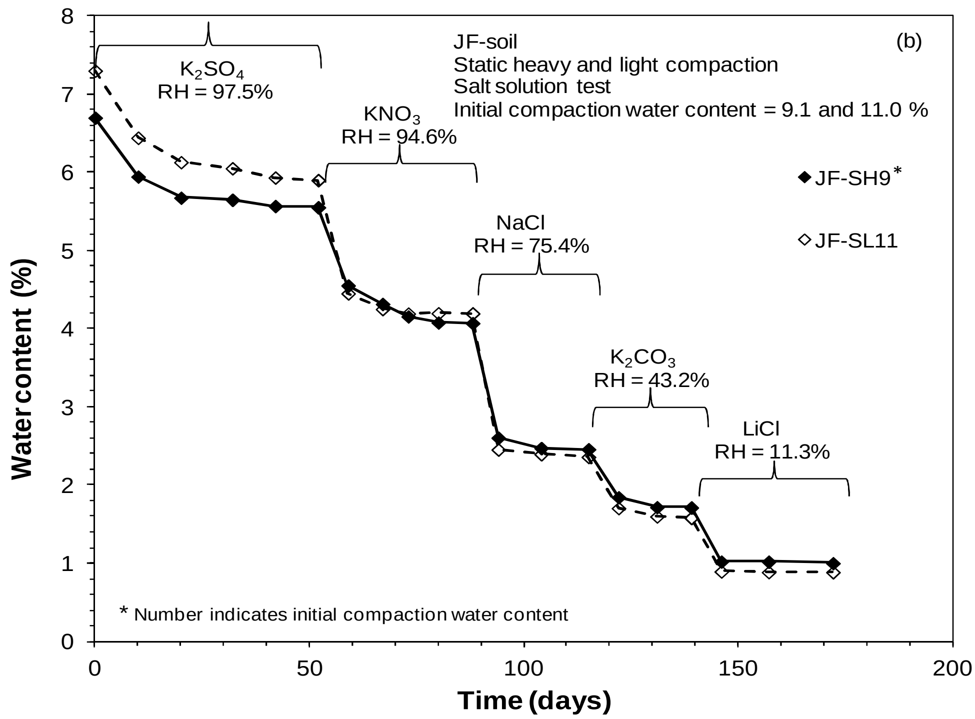




*Fig. 4.4 Equilibrium time versus change in water content in pressure plate and salt solution tests for JF soil specimens*

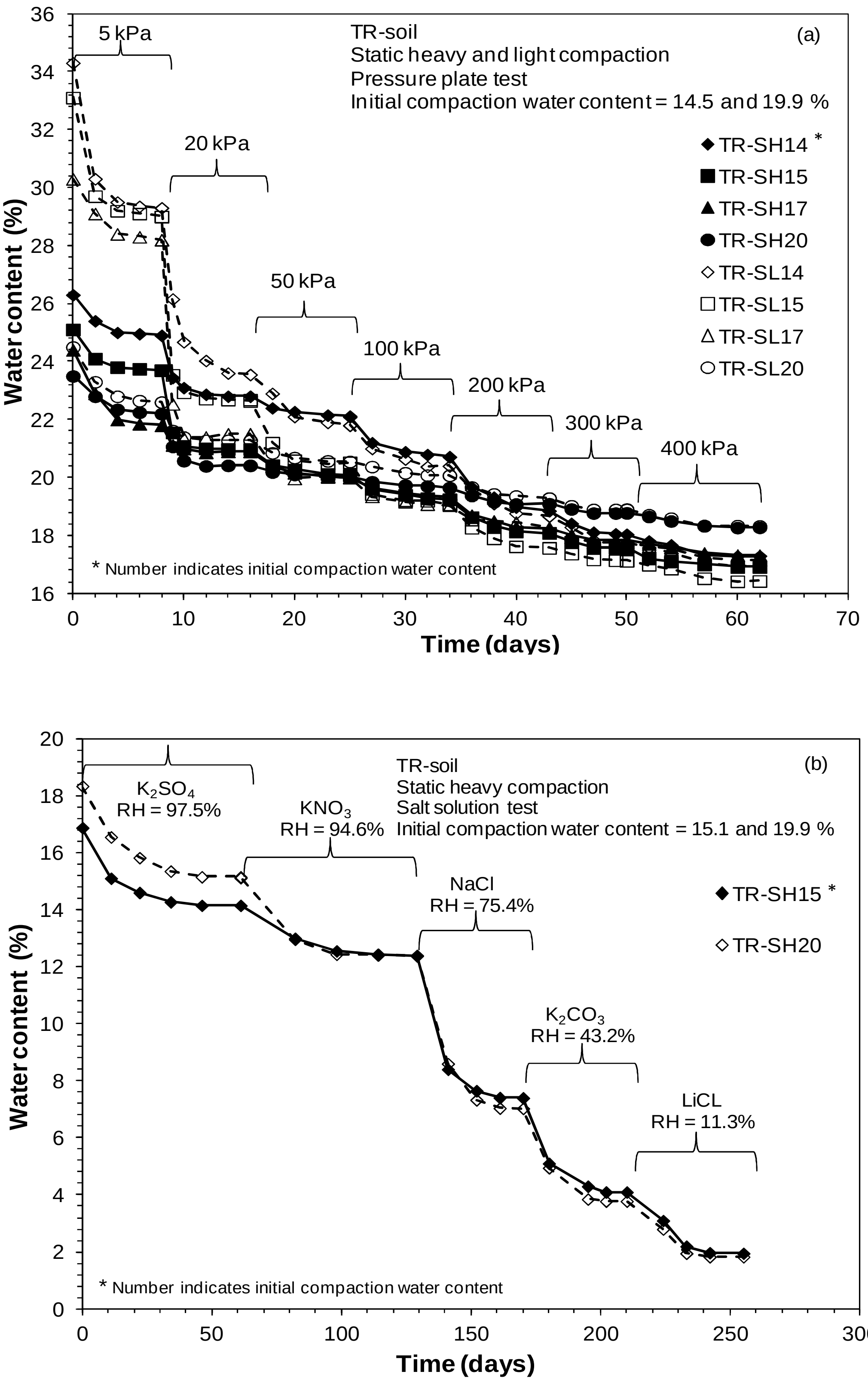



***Fig. 4.5 Equilibrium time versus change in water content in pressure plate and salt solution tests for TR soil specimens***

The test results in terms of elapsed time versus water content decrease in the salt solution tests are shown in Figs. 4.4*b* and 4.5*b*. For clarity only representative specimens were chosen as the difference in final water content of the soil specimens at high suction level were less than 0.5%. It can be seen in Figs. 4.4*b* and 4.5*b* that as the relative humidity increased the time required for the soil specimens to equilibrate increased. In case of using $K_2SO_4$, where the RH = 97.5%, the soil specimens required about 6 weeks to achieve the equilibrium, whereas at low RH conditions (e.g. $K_2CO_3$, (RH = 43.2%)) the equilibrium time was about 3 weeks.

### 4.3.2 Effect of compaction conditions

The distribution of the pore sizes both within and between the aggregates of soils is affected by the compaction method used for preparing soil specimens (Sivakumar, et. al., 2007). Many studies have reported the effect of soil structure and fabric on the pore size distribution, which in turn influenced the SWCC (e.g. Delage et al., 1996; Romero et. al., 2003; Lloret et al., 2003). Various factors, such as initial compaction water content, void ratio, soil type, stress history, and compaction method have been studied by several researchers to investigate the effects of various parameters on the SWCC (Vanapalli et al., 1999; Leong & Rahardjo, 2002). Some of these studies have clearly showed that structure and fabric effects owing to compaction methods may better be visualized by mercury intrusion porosimetry. Since the primary intent of the thesis was to critically evaluate some commonly used suction measurement techniques, studies concerning fabric and structure of compacted soils are beyond the scope of the thesis.

In order to examine the effect of initial compaction conditions on the SWCCs of the soils, the soil specimens for each soil were grouped based on the compaction water content, the compaction dry density and the compacted degree of saturation. The SWCCs of soil specimens prepared both using static and dynamic compaction types are considered. The test results of soil specimens for both BS-heavy and BS-light compaction efforts are presented.

#### *4.3.2.1 Effect of compacted water content*

Soil specimens that had similar initial compaction dry densities and different initial compaction water contents were chosen to study the effect of the of initial compaction water content on the SWCCs of the soils. Three levels of initial dry density were selected for both JF and TR soils.

Figure 4.6 presents the drying and wetting SWCCs of the specimens of JF soil, JF-SL10 (dry of optimum) and JF-SL12 (wet of optimum) ($\rho_d$ = 1.96 Mg/m$^3$), JF-DH8 (dry of optimum) and JF-DH11 (wet of optimum) ($\rho_d$ = 2.00 Mg/m$^3$) and JF-SH8 (dry of optimum) and JF-SH9 (optimum) ($\rho_d$ = 2.07 Mg/m$^3$). Similarly, the drying and wetting SWCCs of the specimens of TR soil, TR-SL15 (dry of optimum) and TR-SL17 (dry of optimum) ($\rho_d$ = 1.58 Mg/m$^3$), TR-DL18 (dry of optimum) and TR-DL20 (optimum) ($\rho_d$ = 1.61 Mg/m$^3$) and TR-SH14 (dry of optimum) and TR-SH17 (wet of optimum) ($\rho_d$ = 1.85 Mg/m$^3$) are presented in Fig. 4.7.

The test results are presented in terms of the gravimetric water content. The data points in Figs. 4.6 and 4.7 represent actual experimental test results in which vertical dotted lines were used to split up the results obtained from pressure plate and salt solution tests (desiccators tests). The solid lines in Figs. 4.6 and 4.7 represent the best-fit curves using van Genuchten (1980) and Fredlund & Xing (1994) equations which will be discussed in section 4.4.

It can be observed from the test results shown in Figs. 4.6 and 4.7 that at a particular compaction dry density there is a difference in the initial part of the SWCCs near to saturation and at small applied suctions in which capillary forces are present. As the suction increases the difference between the SWCCs is gradually reduces and tend to converge. Fredlund & Xing (1994) stated that at zero matric suction, the gravimetric water content is called the saturated gravimetric water content and is representative of the total capacity of the soil pores to hold water. Figures 4.6 and 4.7 showed that a decrease in the initial compaction

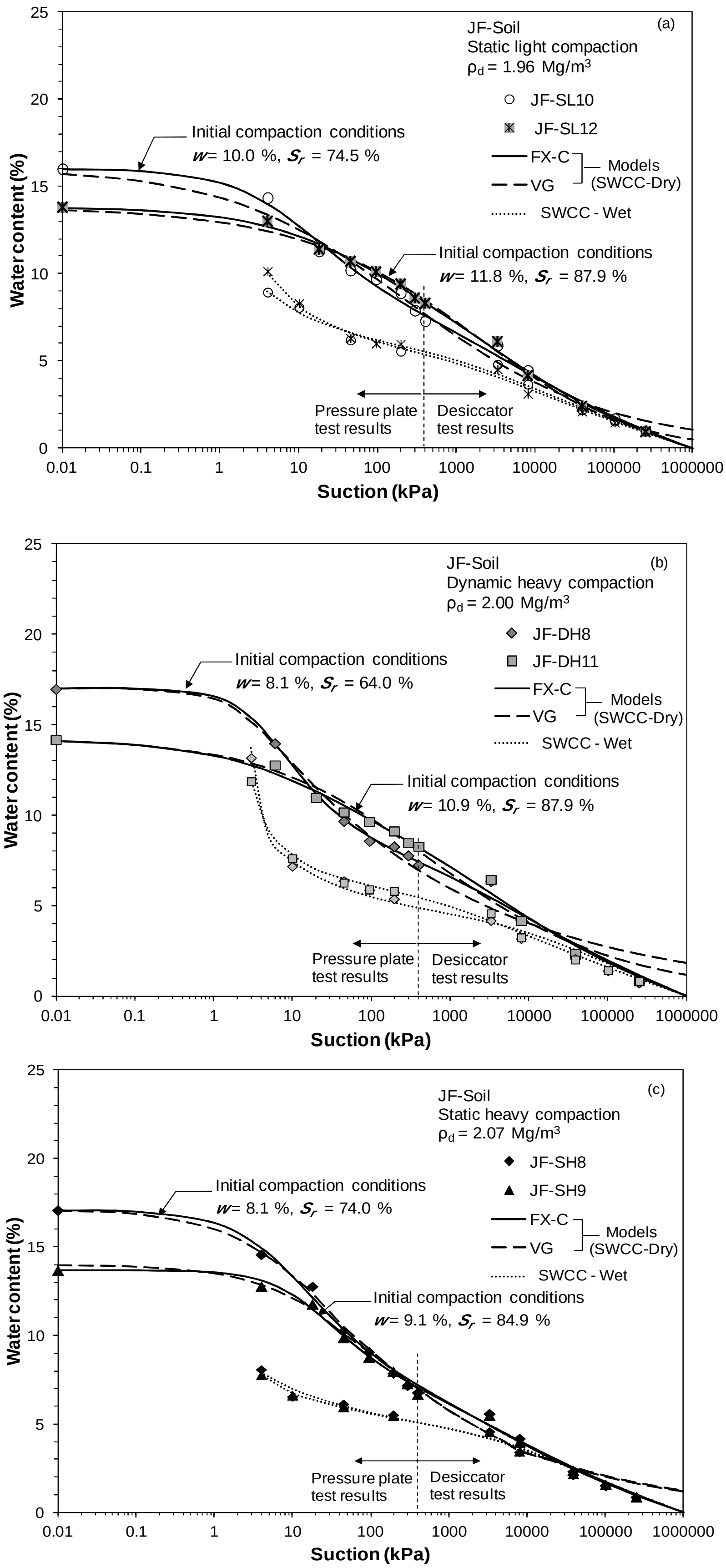



***Fig. 4.6 Influence of compacted water content on SWCC of JF soil specimens***

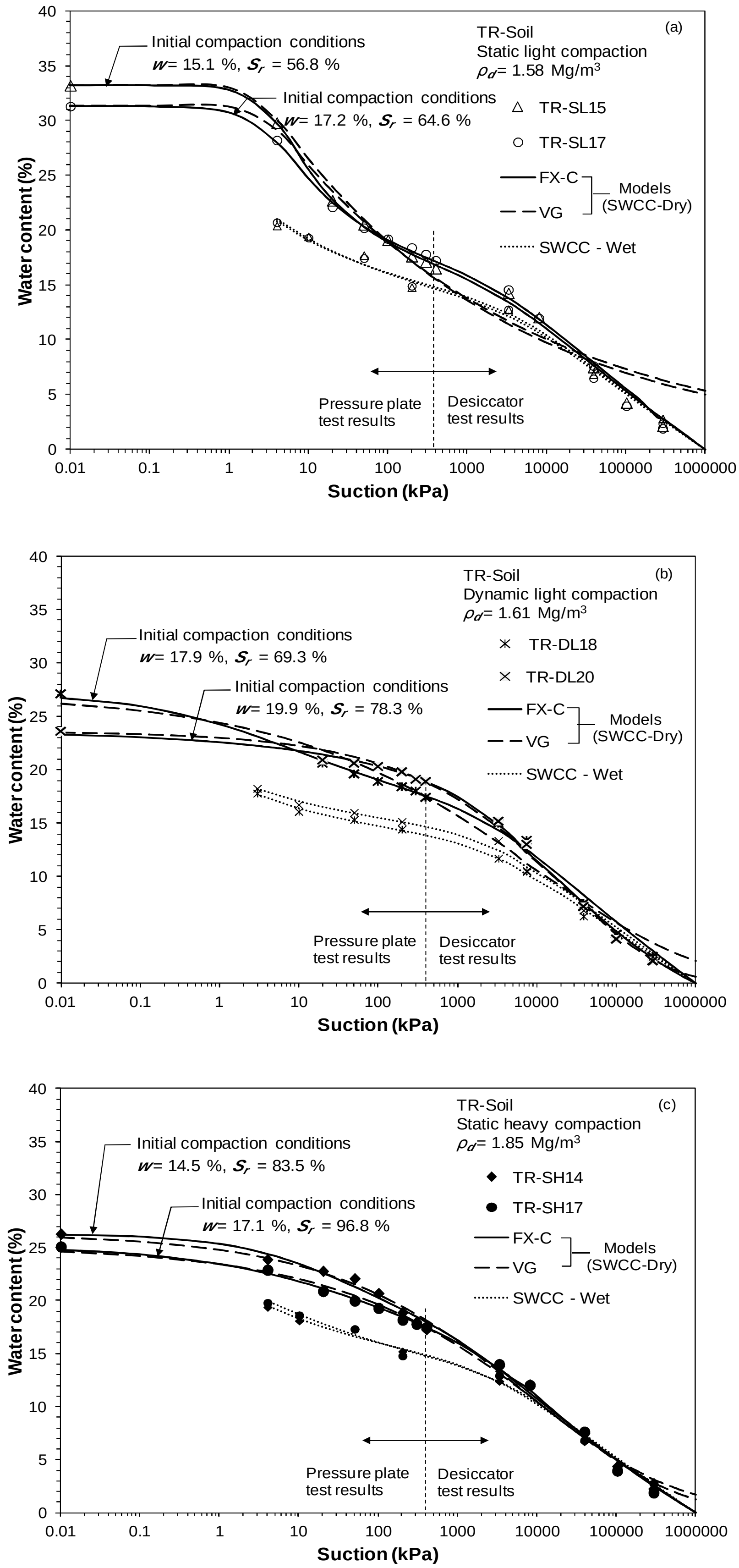



***Fig. 4.7 Influence of compacted water content on SWCC of TR soil specimens***

water content results in an increase in the saturated gravimetric water content. This can be attributed to an increase in the volume (i.e., void ratio) of the specimens during the saturation process.

It can be noted in Figs. 4.6*a* and *b* that the SWCC of the JF soil specimen with lower initial compaction water content crossed the SWCC of the JF soil specimen with higher initial water content at a suction of 20 kPa and a water content of about 11.0%. At the crossover point, the relative positions of the curves are reversed until the SWCCs converge at higher suctions. As the compaction dry density increased to $\rho_d$ = 2.07 Mg/m$^3$ (Fig. 4.6*c*), specimens JF-SH8 and JF-SH9 converge at a suction of 100 kPa and a water content of about 8.0%. Similar behaviour was seen for TR soil specimens in Fig. 4.7. The soil specimens TR-SL15 and TR-SL17 ($\rho_d$ = 1.58 Mg/m$^3$) approach each other at a suction of 40 kPa and a water content of about 20.0% (Fig. 4.7*a*), whereas the specimens TR-DL18 and TR-DL20 ($\rho_d$ = 1.61 Mg/m$^3$) and TR-SH14 and TR-SH17 ($\rho_d$ = 1.85 Mg/m$^3$) crossover at suctions of about 10 and 300 kPa and water content of about 22% and 17%, respectively (Figs. 4.7*b* and *c*), before tending to converge at higher suctions. At the same applied suction beyond the crossover point, specimens with higher initial compaction water content (wet of optimum) have higher water content than specimens with lower initial compaction water content (dry of optimum).

The SWCCs during the wetting process are also presented in Figs.4.6 and 4.7. It can be seen that there is a significant difference between the drying and wetting paths for both soil types. However, the specimens compacted at similar dry density, the test results show that the wetting SWCCs are close to each other for both JF and TR soil specimens.

#### *4.3.2.2 Effect of compaction dry density*

In order to investigate the influence of initial compaction dry density on the SWCC, the test results of soil specimens prepared at the same initial compaction water content but with different compaction dry densities for both JF and TR soils are compared in Figs. 4.8 to

4.11. It should be noted that by grouping the test results in this way, the effect of compaction efforts is implicitly considered.

Figures 4.8 and 4.9 present the drying and wetting SWCCs of dynamically and statically compacted specimens of JF soil, respectively. The test results of drying and wetting SWCCs of dynamically and statically compacted specimens of TR soil are shown in Figs. 4.10 and 4.11, respectively.

Figures 4.8 to 4.11 clearly showed that, for a given soil, the smaller the compaction dry density, the greater was the saturation water content. Therefore, the SWCCs of soil specimens prepared with lower dry densities plotted above the SWCCs of soil specimens prepared with higher dry densities for both soils. Additionally, for a given soil and for any initial compaction water content, the initial dry density influenced the saturation water content in that, the smaller the difference between the compaction dry densities, the lesser was the difference in the saturation water contents and the water contents at smaller applied suctions. However, with an increase in the applied suction, the differences in the initial water contents were eliminated. The SWCCs for soil specimens are found to be different at low suctions, but tend to converge at high suctions.

Figures 4.8 to 4.11 present the wetting SWCCs along with the drying SWCCs for JF and TR soil specimens. It can be seen from Figs. 4.8 to 4.11 that the drying and wetting SWCCs are different and the hysteresis effect is considerable for the both type of soils used in this study. However, irrespective to the initial compaction conditions, the wetting SWCCs are found to be similar for any soils.

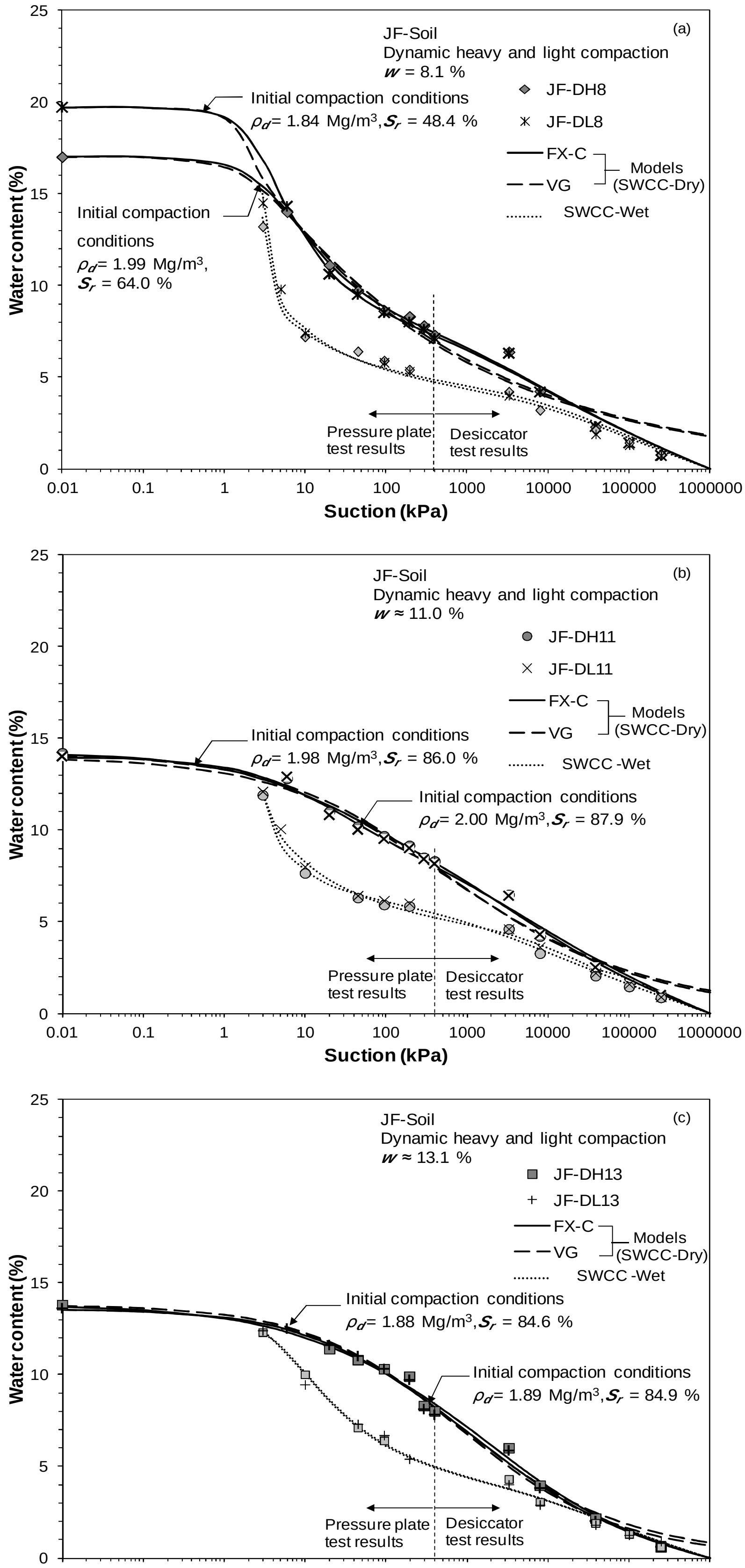



***Fig. 4.8 Influence of compacted dry density on SWCC of JF soil specimens (Dynamic compaction)***

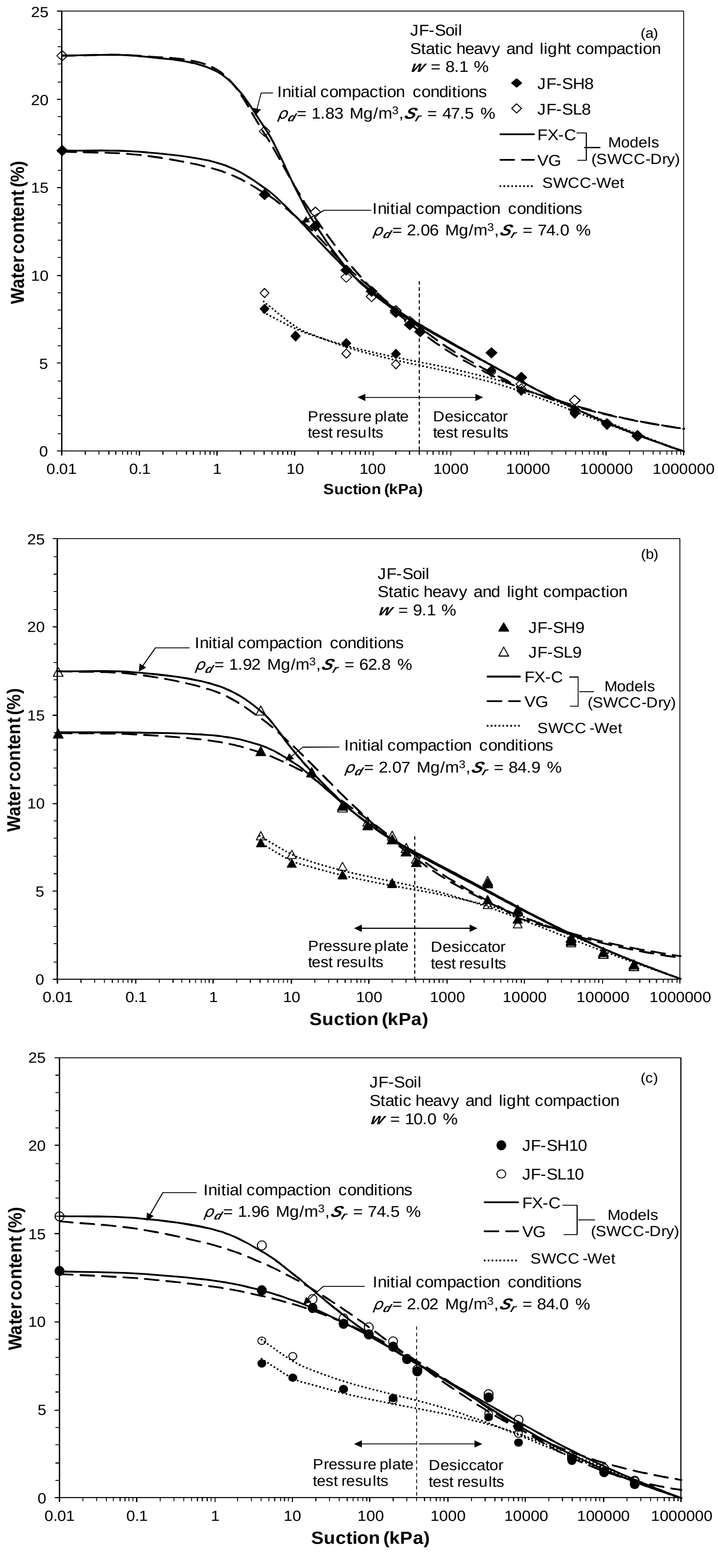



***Fig. 4.9 Influence of compacted dry density on SWCC of JF soil specimens (Static compaction)***

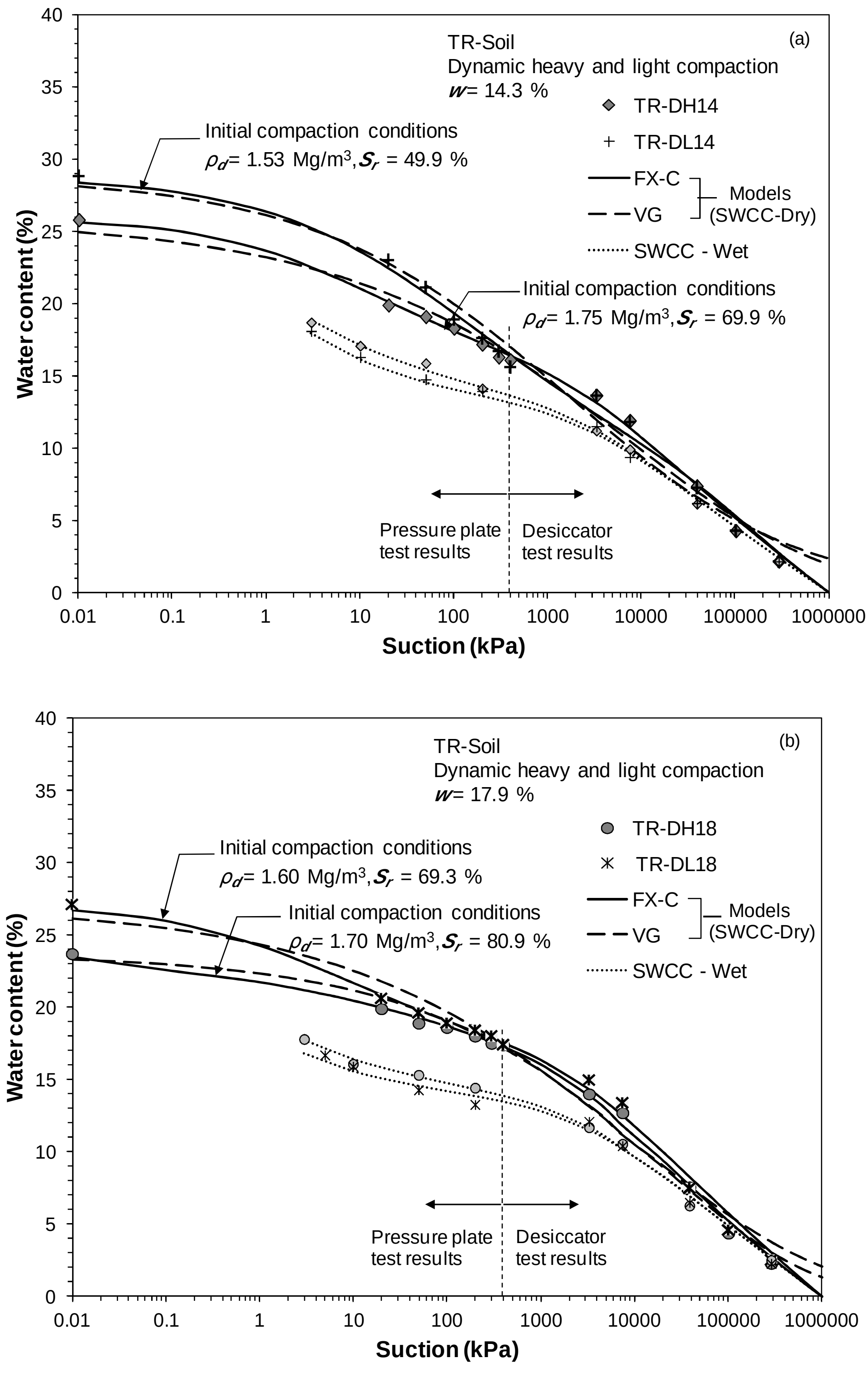



***Fig. 4.10 Influence of compacted dry density on SWCC of TR soil specimens (Dynamic compaction)***

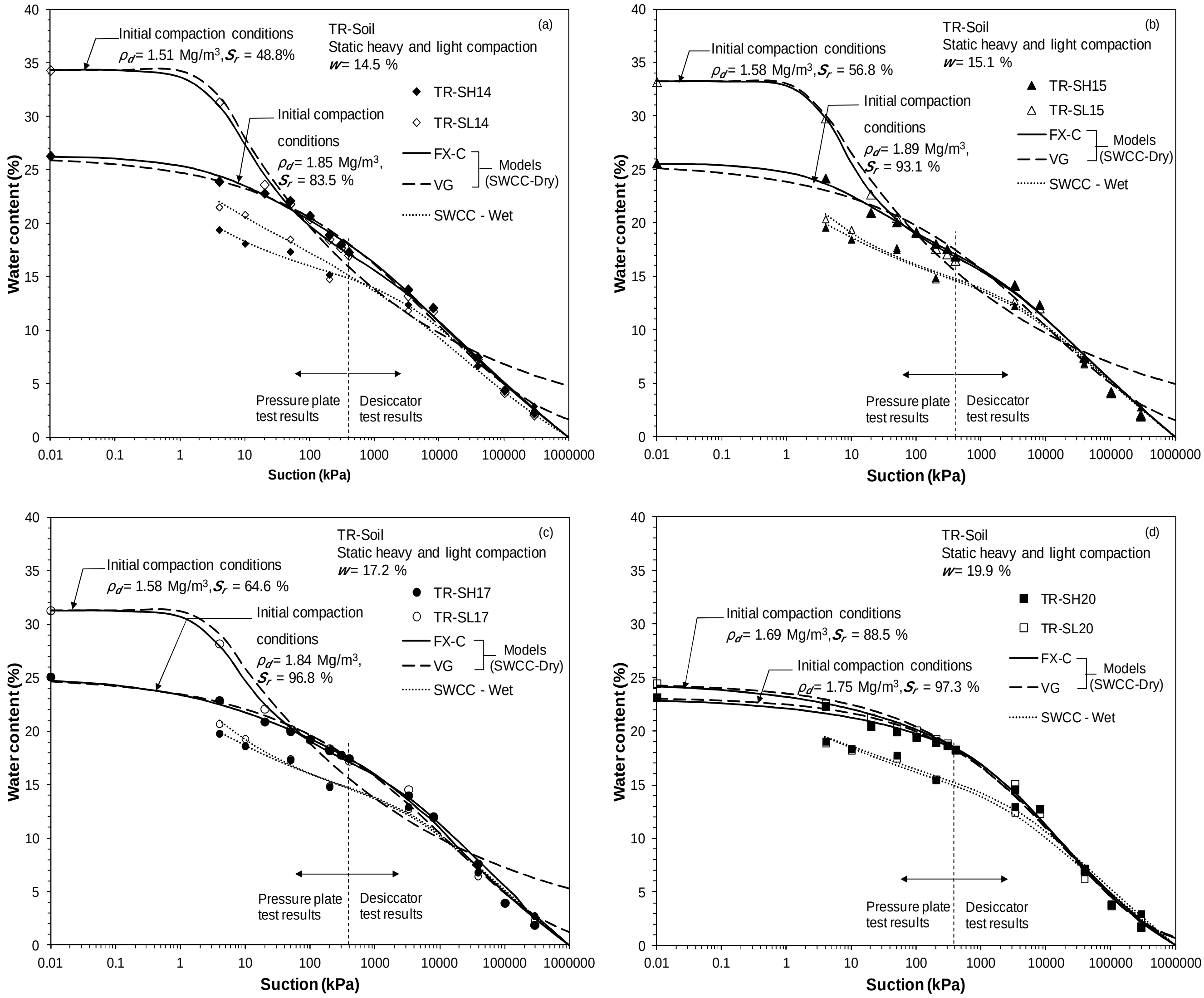



***Fig. 4.11 Influence of compacted dry density on SWCC of TR soil specimens (Static compaction)***

### *4.3.2.3 Effect of compaction type*

In order to study the influence of compaction type (i.e., BS-heavy, BS-light, static-heavy, and static-light), specimens compacted with similar compaction water content and dry density values but with different compaction types are shown in Figs. 4.12*a*, *b*, and *c*. These results show that the compaction type has some effects on the SWCCs of the soils studied.

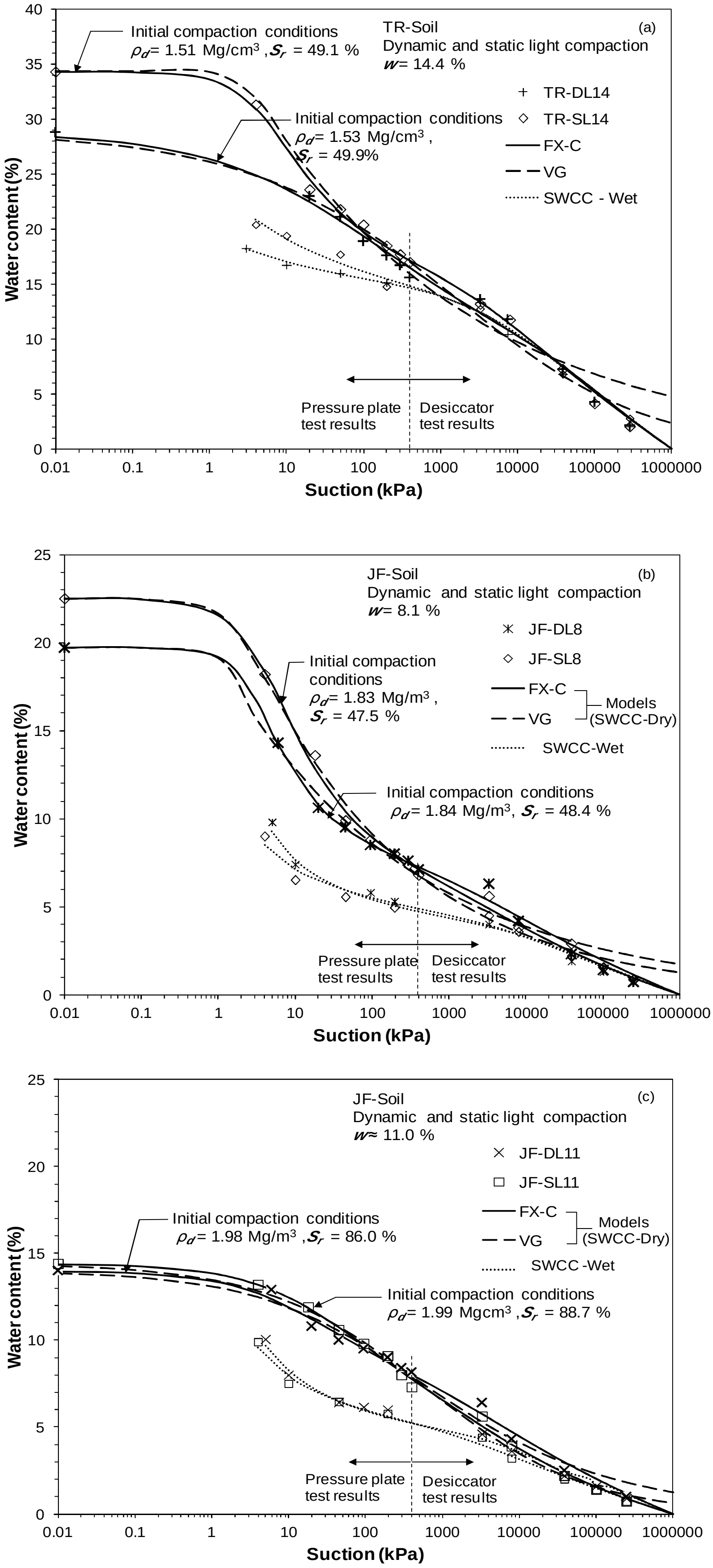



***Fig. 4.12 Effect of compaction type on SWCC of the soils studies***

Form the Figs. 4.12*a*, *b*, and *c*, it can be seen that the saturation water content of dynamically compacted specimens were somewhat lesser than their statically compacted specimens. From the SWCCs of JF soil specimens (Figs. 4.12 *b* and *c*) it was noted that, the difference between the SWCCs at smaller applied suctions and due to the influence of compaction type was less significant with an increase in the initial degree of saturation. Furthermore, the influence of compaction type on the wetting SWCCs of the soil was found to be insignificant.

#### *4.3.2.4 Effect of soil type*

The SWCCs of slurried specimens of JF and TR soils are shown in Fig. 4.13. From Fig. 4.13 it can be seen that, the SWCC of TR soil remained distinctly above that of the SWCC of JF soil, and is attributed due to the difference in the plasticity properties of the two soils (Table 3.1), the higher the percentage of clay present in a soil, the greater water is the water holding capacity under a certain value of suction. Fredlund (2000) and Aubertin et al. (2003) reported that the high adsorptive and capillary forces existing in the fine soil particle resulting from high surface area and smaller pore space.

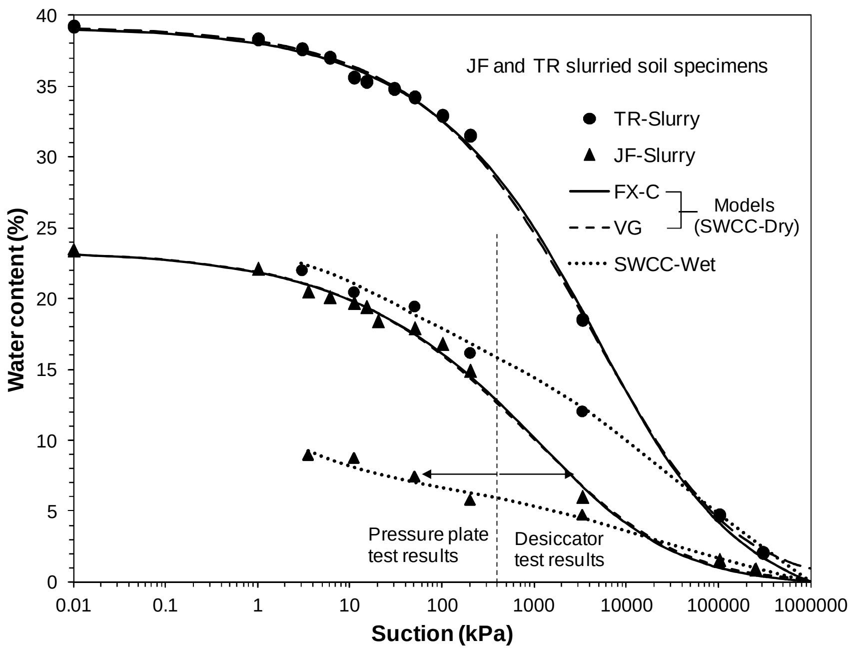



***Fig. 4.13 Effect of soil type on SWCC***

## 4.4 Modelling the soil-water characteristic curves

Several models have been proposed in the past to best-fit SWCCs data for different type of soils (Sillers, 2001). The experimental test results in this study were best fitted with the models developed by van Genuchten (1980) and Fredlund & Xing (1994) with a correction factor using a least squares regression. These models are denoted as VG and FX-C, respectively.

An optimization routine was used to fit the parametric models to the measured data using an iterative approach until the sum of the squared residuals (SSR) differences between the predicted and measured data becomes minimal. The sum of the squared residuals (SSR) is an indication of how well the equations fit the measured data. The minimization process for SSR was performed using Slover subroutine included in Microsoft Excel®. The best fit of each model to the measured data was assumed to be the one that resulted in the minimum SSR value.

The SWCCs data of slurried and compacted specimens were best fitted using VG and FX-C equations, and the results are presented in Figs. 4.6 through 4.13. It can be observed from Figs. 4.6 through 4.13 that the Fredlund & Xing (1994) and van Genuchten (1980) best-fit proposed equations well depict the SWCC results of the both types of soil. Both VG and FX-C equations are adequately identical to predict the SWCCs. However, the FX-C model seems to provide better prediction of the water contents at high suctions.

### 4.4.1 Effect of initial compaction conditions on drying SWCC parameters

The resulting fitting parameters obtained for the drying SWCCs of JF and TR soils using FX-C equation are shown in Tables 4.4 and 4.5, respectively. The effect of the initial compaction conditions on the drying SWCCs were noted by the differences of the SWCC parameters, i.e., the air-entry value, AEV, saturated water content ($w_s$) residual water content ($w_r$) and slopes of the SWCCs.

***Table 4.4 FX-C model fitting parameters of JF-soil specimens***

| Soil specimens | Model parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | AEV (kPa) | a | n | m | $w_s$ (%) | $w_r$ (%) | slope | SSR | $R^2$ |
| JF-Slurry | 15 | 536.9 | 2.306 | 0.404 | 23.4 | 0.014 | 0.0631 | 2.64E-4 | 0.997 |
| JF-DH8 | 2.0 | 2.337 | 0.418 | 1.418 | 17.0 | 9.6 | 0.0731 | 1.82E-4 | 0.984 |
| JF-DH11 | 2.65 | 9.905 | 0.639 | 0.5073 | 14.2 | 2.1 | 0.027 | 1.49E-4 | 0.992 |
| JF-DH13 | 9.2 | 69.690 | 1.005 | 0.434 | 13.8 | 1.8 | 0.0341 | 1.30E-4 | 0.993 |
| JF-DL8 | 1.2 | 2.238 | 0.419 | 1.836 | 19.7 | 9.5 | 0.0527 | 1.86E-4 | 0.994 |
| JF-DL11 | 1.9 | 6.679 | 0.514 | 0.616 | 14.0 | 1.9 | 0.0244 | 1.50E-4 | 0.994 |
| JF-DL13 | 9.2 | 59.277 | 0.875 | 0.532 | 13.6 | 1.8 | 0.0327 | 1.36E-4 | 0.993 |
| JF-SH8 | 1.7 | 5.092 | 0.581 | 0.942 | 17.1 | 5.6 | 0.0459 | 1.42E-4 | 0.994 |
| JF-SH9 | 3.8 | 10.914 | 0.450 | 1.017 | 14.0 | 5.7 | 0.0328 | 6.23E-5 | 0.997 |
| JF-SH10 | 4.7 | 18.194 | 0.657 | 0.549 | 12.9 | 2.3 | 0.0260 | 6.47E-5 | 0.997 |
| JF-SL8 | 1.3 | 3.226 | 0.597 | 1.232 | 22.5 | 7.2 | 0.0842 | 1.74E-4 | 0.997 |
| JF-SL9 | 1.4 | 3.724 | 0.530 | 1.069 | 17.5 | 6.7 | 0.0541 | 8.00E-5 | 0.998 |
| JF-SL10 | 1.5 | 4.632 | 0.537 | 0.822 | 16.0 | 5.1 | 0.0348 | 9.96E-5 | 0.994 |
| JF-SL11 | 3.7 | 16.724 | 0.684 | 0.641 | 14.4 | 2.8 | 0.0319 | 8.12E-5 | 0.997 |
| JF-SL12 | 6.3 | 24.937 | 0.687 | 0.537 | 13.8 | 2.1 | 0.0286 | 7.26E-5 | 0.996 |

*a, m and n = model parameters*

*AEV= air-entry value*

*$w_s$ = saturated water content, $w_r$ = residual water content*

***Table 4.5 FX-C model fitting parameters of TR-soil specimens***

| Soil specimens | Model parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | AEV (kPa) | a | n | m | $w_s$ (%) | $w_r$ (%) | slope | SSR | $R^2$ |
| TR-Slurry | 85.0 | 1836.1 | 1.162 | 0..407 | 38.8 | 4.4 | | 1.03E-4 | 0.999 |
| TR-DH14 | 21.0 | 1.347 | 0.370 | 0.547 | 25.8 | - | - | 2.09E-4 | 0.997 |
| TR-DH15 | 35.0 | 2.387 | 0.363 | 0.521 | 24.1 | - | - | 3.78E-4 | 0.996 |
| TR-DH17 | 105.0 | 83.178 | 0.533 | 0.297 | 23.7 | - | - | 2.27E-4 | 0.996 |
| TR-DL14 | 5.2 | 3.337 | 0.4149 | 1.418 | 28.8 | - | - | 2.38E-4 | 0.997 |
| TR-DL17 | 27.4 | 1.187 | 0.292 | 0.711 | 27.1 | - | - | 3.68E-4 | 0.995 |
| TR-DL20 | 130.0 | 89.654 | 0.572 | 0.330 | 23.6 | - | - | 3.36E-4 | 0.996 |
| TR-SH14 | 21.0 | 6.940 | 0.349 | 0.603 | 26.3 | - | - | 3.34E-4 | 0.996 |
| TR-SH15 | 31.0 | 11.590 | 0.518 | 0.489 | 25.6 | - | - | 4.10E-4 | 0.994 |
| TR-SH17 | 65.0 | 14.225 | 0.538 | 0.384 | 25.1 | - | - | 1.83E-4 | 0.996 |
| TR-SH20 | 153.0 | 189.76 | 0.655 | 0.352 | 23.2 | - | - | 2.88E-4 | 0.994 |
| TR-SL14 | 1.0 | 3.399 | 0.383 | 1.192 | 34.3 | - | - | 2.64E-4 | 0.999 |
| TR-SL15 | 1.9 | 3.216 | 0.312 | 1.751 | 33.2 | - | - | 2.81E-4 | 0.998 |
| TR-SL17 | 2.1 | 3.463 | 0.281 | 1.572 | 30.6 | - | - | 4.62E-4 | 0.996 |
| TR-SL20 | 135.0 | 170.05 | 0.731 | 0.324 | 24.5 | - | - | 2.78E-4 | 0.997 |

*a, m and n = model parameters*

*AEV= air-entry value*

*$w_s$ = saturated water content*

*$w_r$ = residual water content*

The SWCC test results were fitted by Fredlund & Xing (1994)'s model based on the gravimetric water to determine the AEV and residual state for each specimen. The AEV of the soil specimens was obtained by extending the constant slope portion of the SWCC to intersect the line on the portion of the curve for suction at the saturated water content (Vanapalli et al., 1999). Different approaches for determination of AEVs are presented in the following chapter.

The residual water content is defined by the intersection point between a line from the point of inflection on the straight-line portion of the SWCC, and a line from the point at 1,000,000 kPa, tangent to the original curve. Additionally, the slopes of the SWCCs were computed as $[(ws - wr)/(\log\psi_r - \log\psi_a)]$.

It can be seen from Tables 4.4 and 4.5 that the AEVs of JF and TR soils ranged from 1.3 to 10 kPa, and 20 to 180 kPa, respectively. The test results indicated that the AEV increases with an increase in the compaction water content. For a given soil and compaction effort, the AEVs of the specimens prepared at lower compaction water contents were always lower in comparison to specimens with higher compaction water contents (Figures 4.4 to 4.7). In addition, the residual state was noticed for JF soil but was not distinct for TR soil. For the specimens of JF soil, the residual water content was decreased as the initial compaction water content increased. Also, it can be seen from Tables 4.4 and 4.5 that the rate of desaturation (slopes of the SWCCs beyond the AEV) is relatively faster in the case of specimen with lower compaction water content compared to specimen compacted at higher water content. The slope of the SWCCs beyond the air entry value became less negative with increasing in the initial compaction water content.

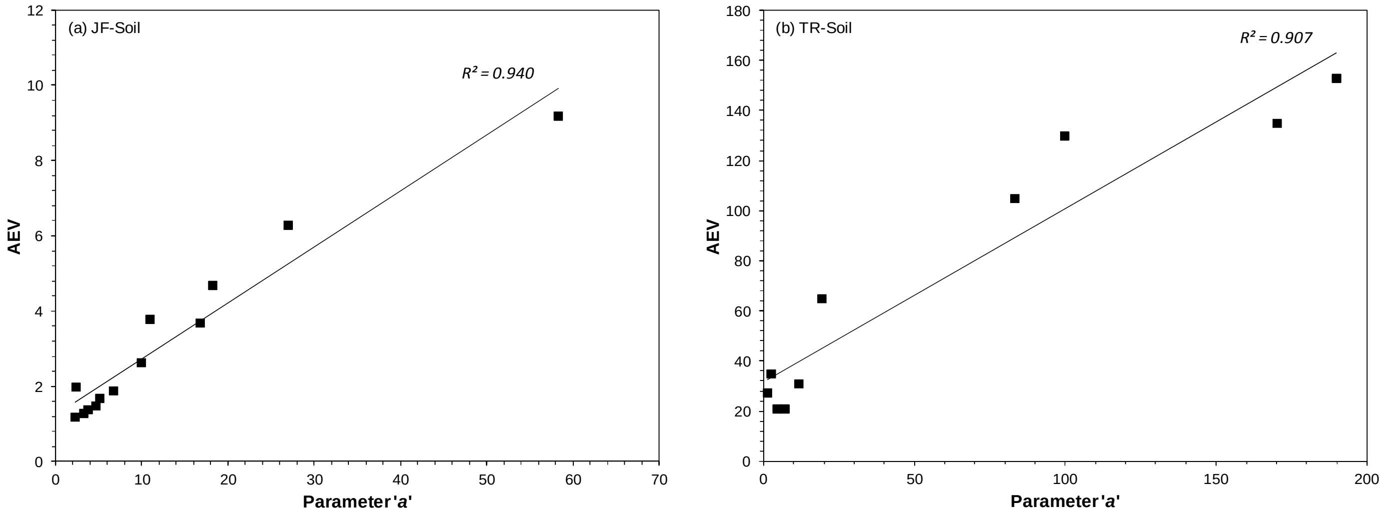
Tables 4.4 and 4.5 and Figs. 4.8 to 4.11 show that at similar compaction water contents, a soil specimens with a high compaction dry density had a higher AEV and lower residual water content than that of a soil specimen with a low compaction dry density. Also, the rate of drying was decreased with increased compaction dry density. The SWCC of specimen prepared at lower dry density found to be slightly steeper than those prepared at higher dry density. The specimen compacted at higher dry density (higher compaction effort) has smaller pores compared to the specimen compacted at lower dry density. The water drainage from the smaller pores occurred at a slower rate, hence desaturation commenced at higher suction value for specimen compacted with higher dry density than those prepared at lower dry density.

It can be seen from Tables 4.4 and 4.5 that the AEV and residual water content for slurry specimen of TR soil is higher than those of slurry specimen of JF soil due to the different percentage of clay fractions present in both soils.

### 4.4.2 Correlation between SWCC parameters and fitting parameters

It can be seen from Table 4.4 and 4.5 that the SWCC parameters (AEV and residual water content) can be correlated to the fitting parameters (*a*, *n*, and *m*) from the Fredlund & Xing (1994)'s equation.

The AEV of the soils and the soil parameter '*a*' are closely related and have an apparent linear relationship as shown in Figs. 4.14*a* and *b*. The fitting parameter (*a*) increases linearly with an increase in the AEV for both soils. Similarly, the soil parameter (*m*) is related to the residual water content ($w_r$). From the test results obtained for JF soil specimens, the fitting parameter (*m*) increases with increasing in the residual water content (Fig. 4.15). However, there is no clear residual state in the case of TR soil. Additionally, the slope of the SWCC for the segment between the AEV and the suction at residual water content can be related to the parameter (*n*). Table 4.4 showed that the slopes of SWCCs decreased with an increase in the compaction water content and dry density of soil specimens. Low values of (*n*) indicate moderate slopes of the SWCCs, whereas higher values of (*n*) indicate steeper slopes. However, no clear correlation was found between the slopes of SWCCs and parameter (*n*).




***Figs. 4.14 Relationship between AEV and parameter 'a' (a) JF soil (b) TR soil***

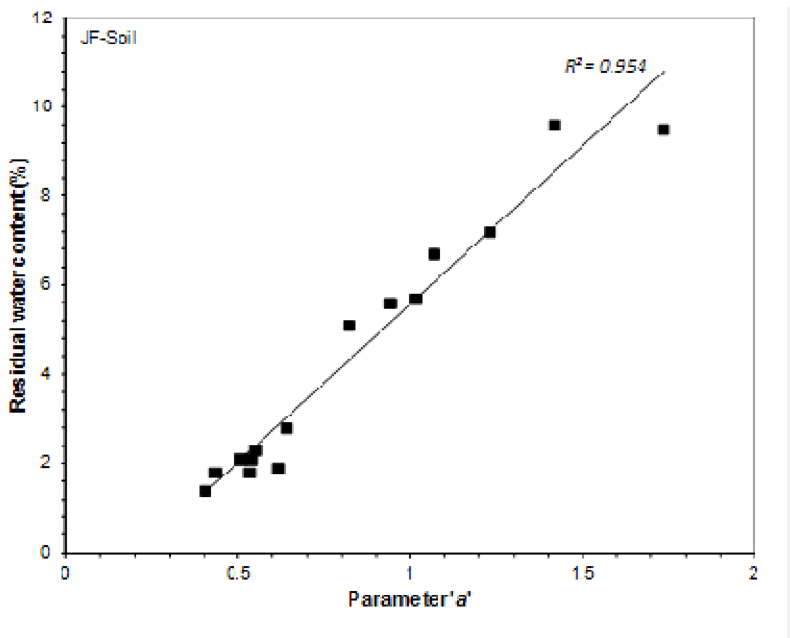



***Fig. 4.15 Relationship between residual water content and parameter 'm' for JF soil specimens***

## 4.5 Concluding remarks

Pressure plate and salt solution tests were carried out to investigate the influence of initial compaction conditions on the drying and the wetting suction-water content SWCCs for JF and TR soils. The test results were fitted with two SWCC models proposed by van Genuchten (1980) and Fredlund & Xing (1994).

The main observations from this chapter can be summarised as follows:

- The saturated water content of the compacted soil specimens increased as the compaction water content and the dry density decreased.
- The SWCCs were found to be strongly influenced by the compaction water content at low suction range. However, at high suction range, the SWCCs were found to be independent of the initial compaction conditions. The AEVs increased with an increase in the compacted water content.
- The SWCCs for any soil at same compaction water content but with different dry densities (produced by applying different compaction effort), showed that the AEV and the residual water content of the soil specimens increased with an increase in the compaction dry density. The SWCCs of the soil specimens at different dry densities were found to be different at low suctions, but tend to become similar as the suction increased.
- TR soil with a higher percentage of clay showed higher AEV than JF soil. At any applied suction, the water content of TR soil was found to be greater than that of JF soil.
- Significant hysteresis was noted between the drying SWCC and the wetting SWCC for both soils. The wetting SWCCs were found to be similar for any soils irrespective to the initial compaction conditions.
- The SWCC curve fitting models proposed by van Genuchten (1980) and Fredlund & Xing (1994) were found to fit very well the experimental test results obtained for drying SWCCs.
- In general, the SWCCs of specimens shifted towards the right hand side of the plot as the initial degree of saturation decreased. This indicted that the suction-water content SWCC is not unique for a specific soil but it depends on the initial compaction conditions of the soil.

# CHAPTER 5

# SUCTION-DEGREE OF SATURATION SWCCs

# AND AIR-ENTRY VLAUES

## 5.1 Introduction

Conventional theory of the soil-water characteristic curve (SWCC) and most of curve fitting equations used to model such a relationship have assumed that the initial void ratio remains constant as the soil suction is increased. This assumption may be true for sands and various coarse-grained soils. However, for fine-grained soils, such as silts and clays, a significant volume change may take place during wetting and drying processes. Therefore, measurements of total volume change of soils are required at each applied suction to establish suction-void ratio and suction-degree of saturation SWCCs.

The suction-water content SWCC in conjunction with the shrinkage curve can be used to establish the suction-void ratio and suction-degree of saturation SWCCs and further the air-entry value of soils (AEV) can be determined precisely (Croney & Coleman, 1954, Fredlund, 1964, Fredlund & Rahaddjo, 1993).

The shrinkage curve for soils can be established from various available methods, such as dimension measurements using callipers or laser retractometer, fluid displacement method using kerdane oil, rubber balloon method, core method and encasement methods using water repellent solutions (viz., molten wax, Dow Saran resin dissolved in Methyl Ethyl Ketone (MEK saran), waterproof Polyvinyl Acetate (PVAc) based adhesives) (Brasher, 1966; McKeen, 1985; Nelson & Miller, 1992; Bradeau et al., 1999; Fleureau et al., 2002; Krosley et al., 2003).

The objectives of this chapter were (*i*) to determine the shrinkage curves of the soils, (*ii*) to use the available parametric models to best-fit the shrinkage curves, (*iii*) to study the effect of compaction conditions on the shrinkage curves, (*iv*) to establish the suction-degree of saturation SWCCs, and (*v*) to determine the AEVs and residual suctions of the soils studied.

The experimental procedures adopted to determine the suction-water content SWCCs and the water content-void ratio relationships (shrinkage curves) of the soils using Clod method are briefly presented. The results of suction-water content SWCCs combined with the shrinkage curve results are used to establish the suction-degree of saturation SWCCs and to determine correctly the AEVs and residual suctions for both soils used in this study. Comparison of suction-void ratio SWCCs with pressure-void ratio relationship (i.e., consolidation test results) are presented. The AEVs of soil specimens determined (*i*) based on the suction-water content SWCCs from pressure plate and desiccator test results and (*ii*) based on the suction-degree of saturation SWCCs, are compared. Suctions based on the plastic limit and shrinkage limit of the soils are also compared with the AEVs and residual suctions determined from suction-water content and suction-degree of saturation SWCCs.

## 5.2 Experimental program

The drying suction-water content SWCCs of the soils were established by allowing the soil specimens to equilibrate at different applied suctions using pressure plate and salt solution tests. The initial conditions of the soil specimens, testing procedures, and test results are presented in Chapter 4.

The shrinkage curves of the soils were established based on determination of the soil bulk density by measuring the weight and volume of the specimen during the drying process from Clod tests. Initially slurried soil specimens and statically compacted soils specimens were prepared from JF and TR soils in the same manner as those that prepared for suction-water content SWCC test.

### 5.2.1 Clod method

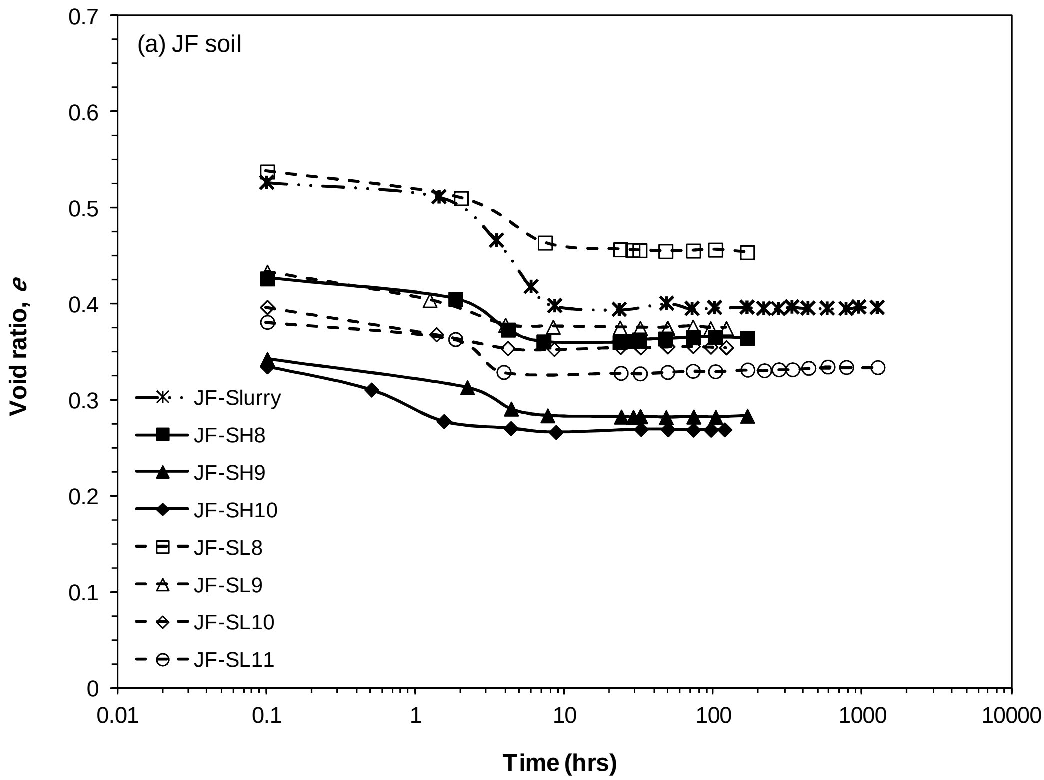
The test procedure adopted for Clod tests are presented in section 3.10 of chapter 3. Initially slurried and compacted saturated soil specimens were first equilibrated in pressure plate at an applied suction of 5 kPa. The soil specimens were then coated with PVAc glue as an encasement material and the Clod, were left to dry in ambient laboratory conditions (T = 22°C and RH = 40%). The changes in volume of clods during the drying process were calculated by Archimedes principle which involves weighing the specimens in air and in water.

## 5.3 Results and discussion

### 5.3.1 Changes of void ratio during drying process in Clod tests

Figures 5.1*a* and *b* show the changes in void ratio, *e*, during the shrinkage process for specimens of JF and TR soils. Detailed calculation procedure concerning determination of the void ratio is presented in Section 3.10.

It can be seen from Fig. 5.1*b* that the initial void ratios of specimens of TR soil remained nearly constant with a decrease in the water content up to about 5 hours for heavily compacted specimens and up to about 80 hours for lightly compacted specimens and further started to decrease. Reductions in the void ratio for heavily and lightly compacted specimens of JF soil occurred at earlier times (after about 2 hours) (Fig. 5.1*a*). Figures 5.1*a* and *b* also show that a constant void ratio was reached after around about 1 day for specimens of JF soil and about 8 days for specimens of TR soil. A change in the void ratio increased during the drying process as the fines content of the soil becomes higher (i.e., for TR soil).



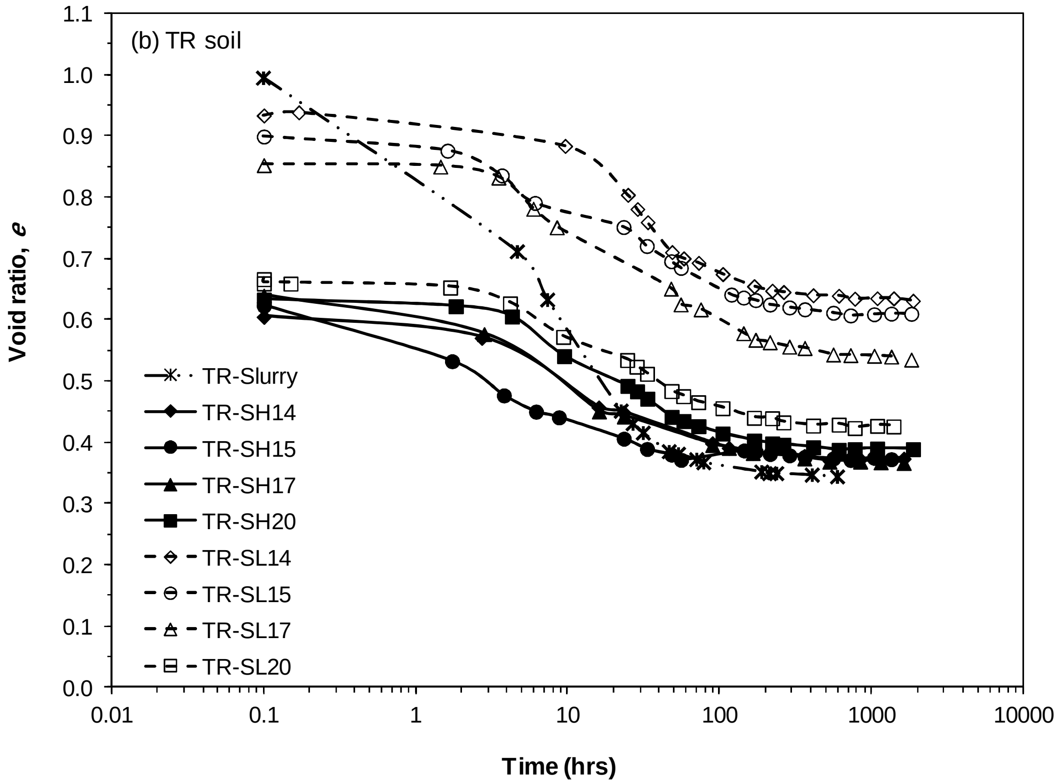




***Fig. 5.1 Elapsed time versus void ratio change in the Clod test for (a) JF soil (b) TR soil***

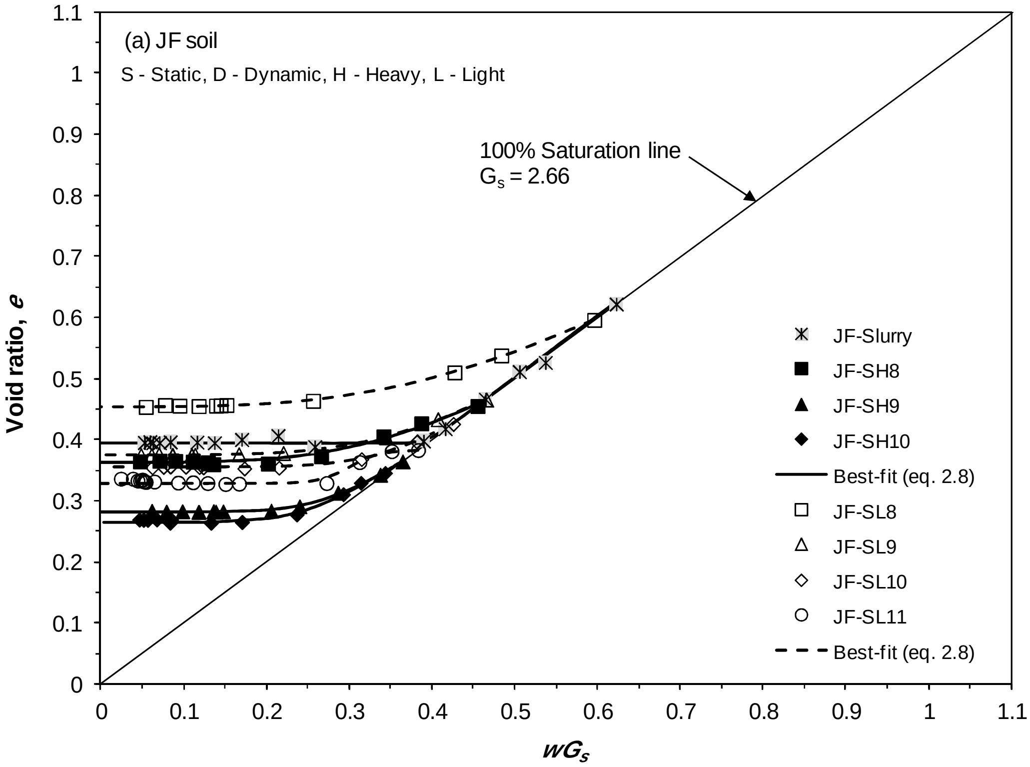
The soil specimens prepared from JF soil desaturated faster than those prepared from TR soil under the same ambient conditions. Specimens of TR soil show a noticeable volume change as compared to the specimens of JF soil as the TR soil contains a relatively high clay percentage. The tests results clearly indicated that the magnitude of shrinkage depends upon the soil type and the liquid limit of the soil.

### 5.3.3 Shrinkage curves

There are four distinct shrinkage zones that can be identified in a typical shrinkage characteristic curve. These are: the structural shrinkage, the normal shrinkage, the residual shrinkage and the zero shrinkage (Haines, 1923). Not all soils may show these four shrinkage zones (Kim et.al., 1992; McGarry & Malafant, 1987). However, studies in the past have shown that compacted soils that have undergone several swell-shrink cycles and natural soils generally exhibited four shrinkage zones (Tripathy et al., 2002).

In order to characterise how soil volume decreases during the drying process, the shrinkage behaviour can be characterized by considering the void ratio ($e$) and the water ratio ($wG_s$) of soils. Continuous shrinkage curves of the soil specimens considered for both JF and TR soils were established from Clod test results. Figures 5.2*a* and *b* show the shrinkage curves (void ratio ($e$) versus ($wG_s$) plots for specimens of JF and TR soils, respectively. The shrinkage curves for initially slurried specimens are also presented in Figs. 5.2*a* and *b* for comparison.

Figure 5.2*a* shows that the initially slurried specimen of JF soil followed the 100% saturation line (i.e. normal shrinkage range). However, the shrinkage curves of compacted soil specimens departed from the 100% saturation line and became unsaturated as soon as the drying process commenced, irrespective of the initial compaction conditions of the specimens. The shrinkage curves of compacted soil specimens of JF soil exhibited either residual and zero shrinkage zones or normal, residual and zero shrinkage zones. No structural shrinkage zone were noted in all cases.



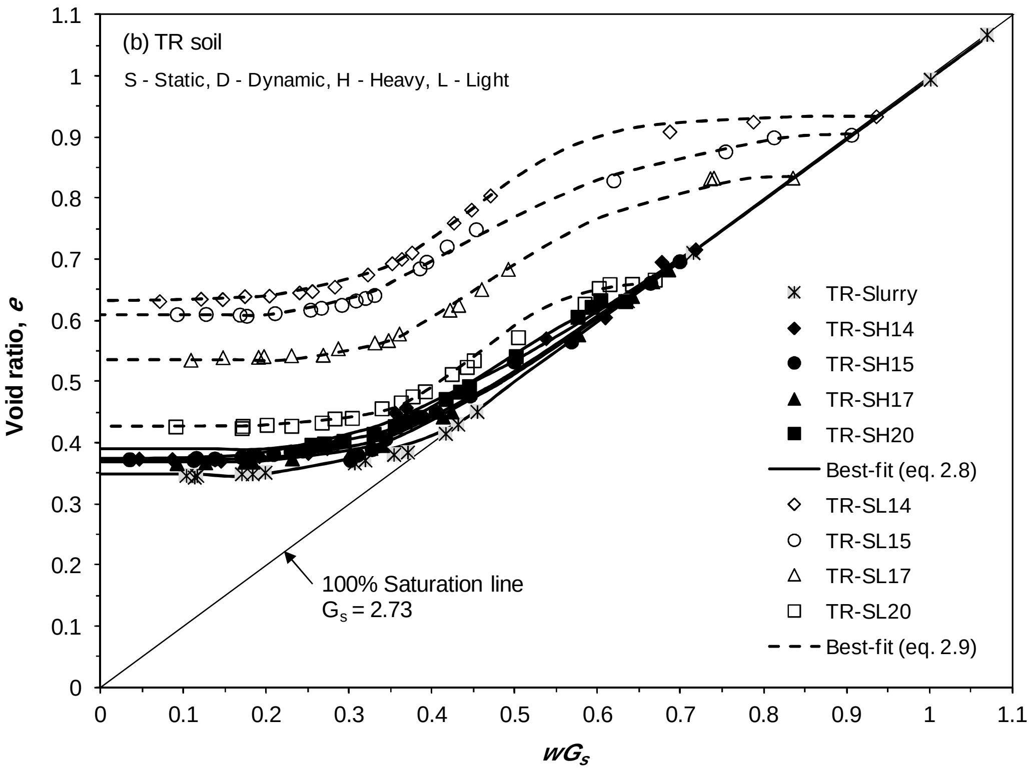



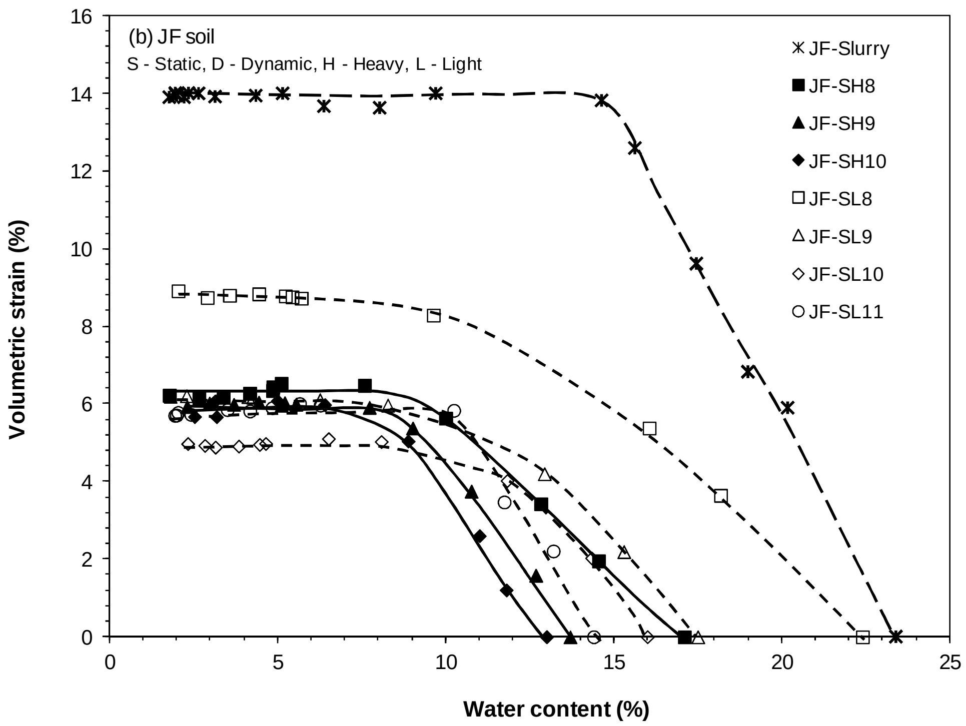

*Fig. 5.2 Shrinkage curves for (a) JF soil (b) TR soil*

Figure 5.2*b* presents the shrinkage curves for the specimens of TR soil. From the test results shown in Fig. 5.2*b*, it can be seen that the initially slurried specimens and the statically-heavy compacted specimens initially followed the 100% saturation line during the drying process (i.e., the normal shrinkage zone). However, the statically–light specimens generally exhibited shrinkage curves with a ‘S’-shape. Additionally, these specimens exhibited larger deformation as compared to the statically–heavy specimens. The relative extent of the different shrinkage zones varied for different compaction conditions. The shrinkage curves of the statically–light TR specimens accompanied by structural, normal, residual, and zero shrinkage zones, whereas the structural shrinkage zone was not noticed for statically–heavy specimens.

Figures 5.3*a* and *b* show the volumetric shrinkage strain versus water content during the drying process for specimens of JF and TR soils. It can be seen from Figs. 5.3*a* and *b* that the void ratio change from an initial saturated state to a completely dry state leads to a total volumetric strain (based on initial void ratio) ranging from 2.4%~8.9% and 14.4%~20.3%, for the compacted specimens of JF and TR soils, respectively.

### 5.3.4 Effect of initial water content and dry density

As compared to the statically-heavy compacted specimens (Figs. 5.1 to 5.3), the statically-light compacted specimens offered less resistance to the volume change during the shrinkage processes for both soils. Hence, the gradient of the normal shrinkage zone for the statically-light compacted specimen is slightly larger than that for the statically-heavy compacted specimen. The normal shrinkage zone for both soils increases as the saturated water content of the specimen increases, and decreases as the compaction effort increases (Fig. 5.2). This due to the lower initial void ratio corresponding to the higher compaction effort.



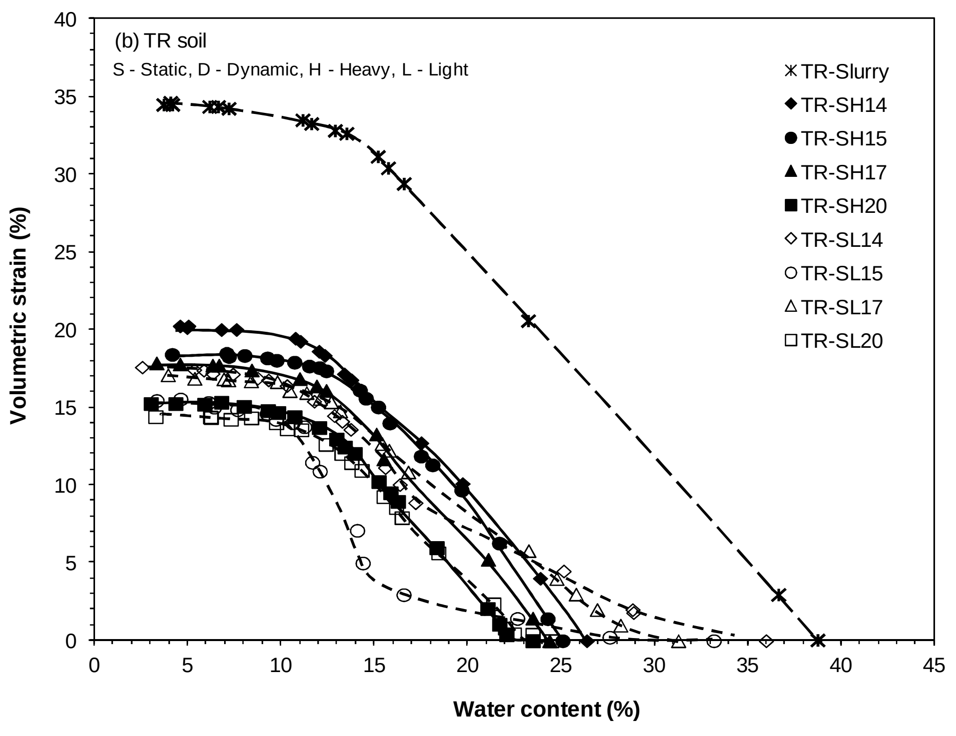




***Fig. 5.3 Volumetric shrinkage strain versus water content for (a) JF soil (b) TR soil***

### 5.3.4 Effect of initial water content and dry density

As compared to the statically-heavy compacted specimens (Figs. 5.1 to 5.3), the statically-light compacted specimens offered less resistance to the volume change during the shrinkage processes for both soils. Hence, the gradient of the normal shrinkage zone for the statically-light compacted specimen is slightly larger than that for the statically-heavy compacted specimen. The normal shrinkage zone for both soils increases as the saturated water content of the specimen increases, and decreases as the compaction effort increases (Fig. 5.2). This due to the lower initial void ratio corresponding to the higher compaction effort.

Furthermore, it can be seen from the results in Figs. 5.1 to 5.3 that the rate of changes in the volume during the initial drying process is increased as the initial compaction water content decreases (i.e., increase in the saturated water content). The volume change during the residual shrinkage zone of the all specimens is negligible in comparison to the volume change during the normal shrinkage zone. In addition, the void ratio at the zero shrinkage (when the specimens are nearly dry) increased as the saturated water content increased. The water ratio ($wG_s$) at which the zero shrinkage zone begins is almost the same for all compacted specimens and is equal to ($wG_s$) = 0.23 and 0.31 for JF and TR soils, respectively.

### 5.3.5 Equations for shrinkage curves

Several approaches exist to model shrinkage curves of soils. The Clod test results were best-fitted using some currently available shrinkage models that are relevant to the soils studied. An equation proposed by Fredlund et al. (1997, 2002) (Eq. 2.8) is used for best-fitting a shrinkage curve that has the form of a hyperbolic curve. For the shrinkage curve which has a S-shape, the four parametric model (MM-model) proposed by McGarry & Malafant (1987) (Eq. 2.9) is generally used. This model is able to describe the four shrinkage zones of the shrinkage curve.

The parameters used for best-fitting the shrinkage curves based on Eq. 2.8 and Eq. 2.9 were presented in Table 5.1. The correlation coefficients between the measured and fitted data were always greater than 0.985 (Table 5.1).

***Table 5.1 Model parameters***

| **Soil specimens*** | **Fred. Model ⁺(Eq. 2.8)** | | **MM. Model ⁺⁺(Eq. 2.9)** | | **$R^2$** |
|---|---|---|---|---|---|
| | $b_{sh}$ | $c_{sh}$ | $\beta$ | $wG_{si}$ | |
| JF-Slurry | 0.148 | 44.316 | | | 0.996 |
| JF-SH10 | 0.103 | 6.228 | | | 0.992 |
| JF-SH9 | 0.109 | 6.797 | | | 0.998 |
| JF-SH8 | 0.153 | 3.913 | | | 0.985 |
| JF-SL11 | | | 54.685 | 0.301 | 0.987 |
| JF-SL10 | 0.149 | 5.192 | | | 0.998 |
| JF-SL9 | 0.136 | 7.735 | | | 0.999 |
| JF-SL8 | 0.133 | 4.978 | | | 0.999 |
| TR-Slurry | 0.128 | 8.401 | | | 0.999 |
| TR-SH20 | | | 17.315 | 0.457 | 0.995 |
| TR-SH17 | 0.1357 | 5.689 | | | 0.999 |
| TR-SH15 | 0.137 | 5.294 | | | 0.991 |
| TR-SH14 | 0.142 | 3.472 | | | 0.994 |
| TR-SL20 | | | 17.994 | 0.456 | 0.999 |
| TR-SL17 | | | 14.599 | 0.488 | 0.999 |
| TR-SL15 | | | 11.372 | 0.485 | 0.986 |
| TR-SL14 | | | 13.708 | 0.450 | 0.999 |

⁺ *Fred. Model = Fredlund (2002)'s model*

⁺⁺ *MM. Model = McGarry & Malafant(1987)'s model*

* *JF = JF soil, TR = TR soil, SH = static heavy compaction, SL = static light compaction, No. = initial compaction water content*

## 5.4 Combination of the shrinkage curve and the suction-water content SWCC

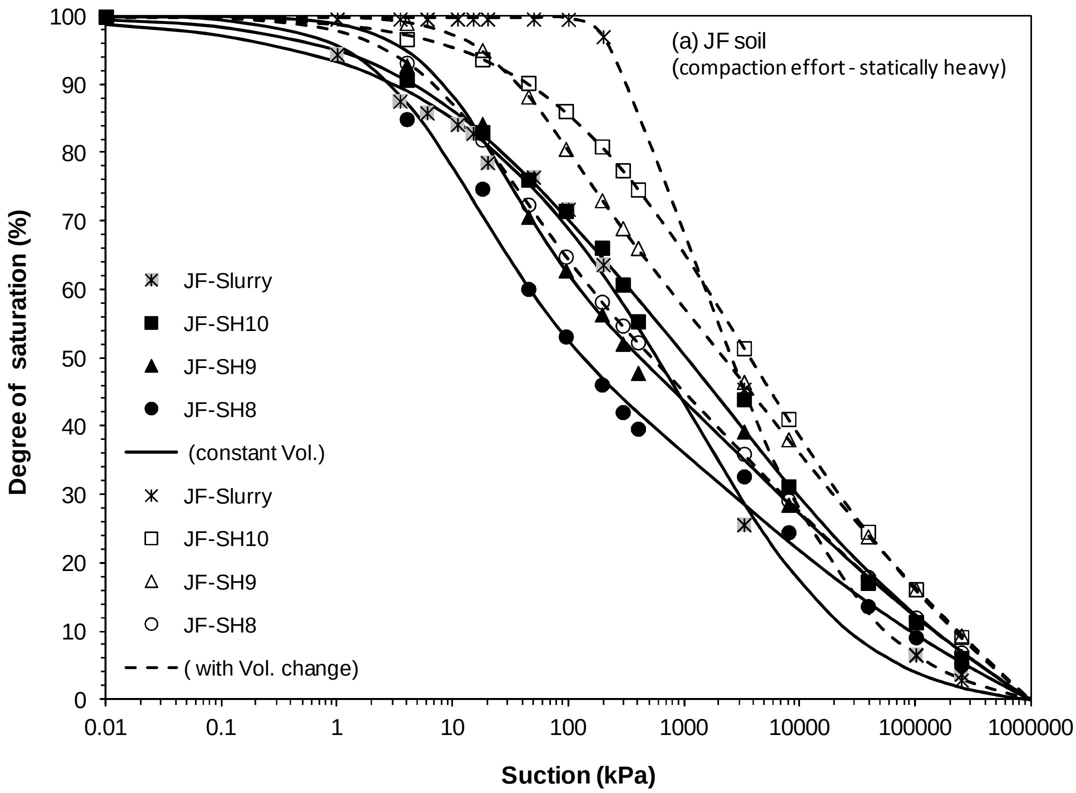
The measured suction-water content SWCC, presented in chapter 4, describe the relationship between gravimetric water content and soil suction and the shrinkage curve results in this chapter provide a relationship between void ratio and water content. By combining the experimental data from the SWCCs and the shrinkage curves it was then possible to establish the suction-void ratio SWCCs and suction-degree of saturation. Firstly, the suction-degree of saturation SWCCs are discussed followed by the suction-void-ratio SWCCs.

### 5.4.1 Suction-degree of saturation SWCCs

The suction-water content SWCCs (see Figs. 4.6 to 4.13) in conjunction with the best-fitted shrinkage curves (Fig. 5.2, Table 5.1) were used to establish the suction-degree of saturation SWCCs. The void ratios from the best-fit shrinkage curves were estimated by considering the water content corresponding to various applied suction from pressure plate tests and desiccators tests. The degree of saturation corresponding to any void ratio was calculated based on the volume-mass relationship. The suction-degree of saturation SWCCs from pressure plate tests and desiccators tests for which the void ratio were calculated based on the Clod test are shown in Figs. 5.4 and 5.5. The suction-degree of saturation SWCCs that were established based on the assumption that there was no volume change (constant *e*) are also shown in Figs. 5.4 and 5.5 for comparison.

Figures 5.4*a* and *b* show the suction-degree of saturation SWCCs for statically heavy and light compacted specimens of JF soil. The open symbols represent the degree of saturation calculated based on the volume change measurements (from Clod test) are found to be quite different from those calculated based on the constant volume of the soil specimen (open symbols). This difference is more considerable for the initially slurried specimens.

Similar differences between the degree of saturation calculated based on the volume change measurements and those calculated based on the constant volume of initially slurried and compacted specimens of TR soil can be observed from Figs. 5.5*a* and *b.* However, the differences between the degree of saturation results calculated in two different ways became more significant. The significant differences between the two methods for the estimation for degree of saturation are due to the large volume changes that occurred as soil suction is increased for TR soil.



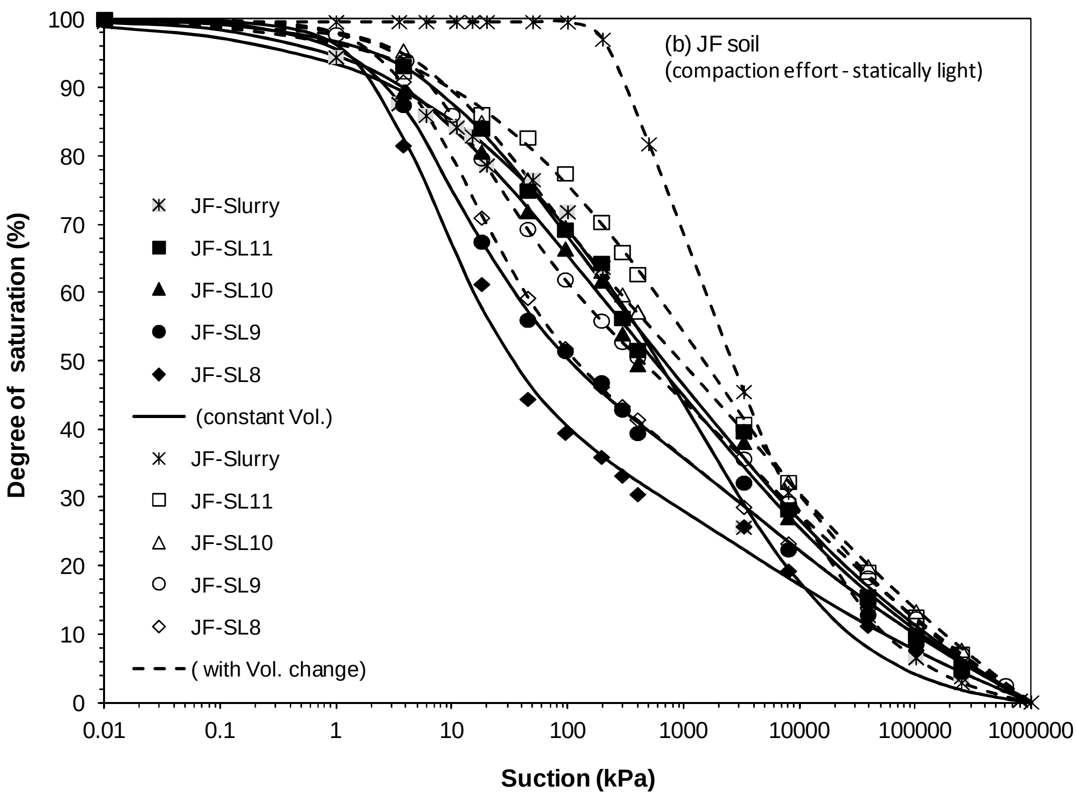
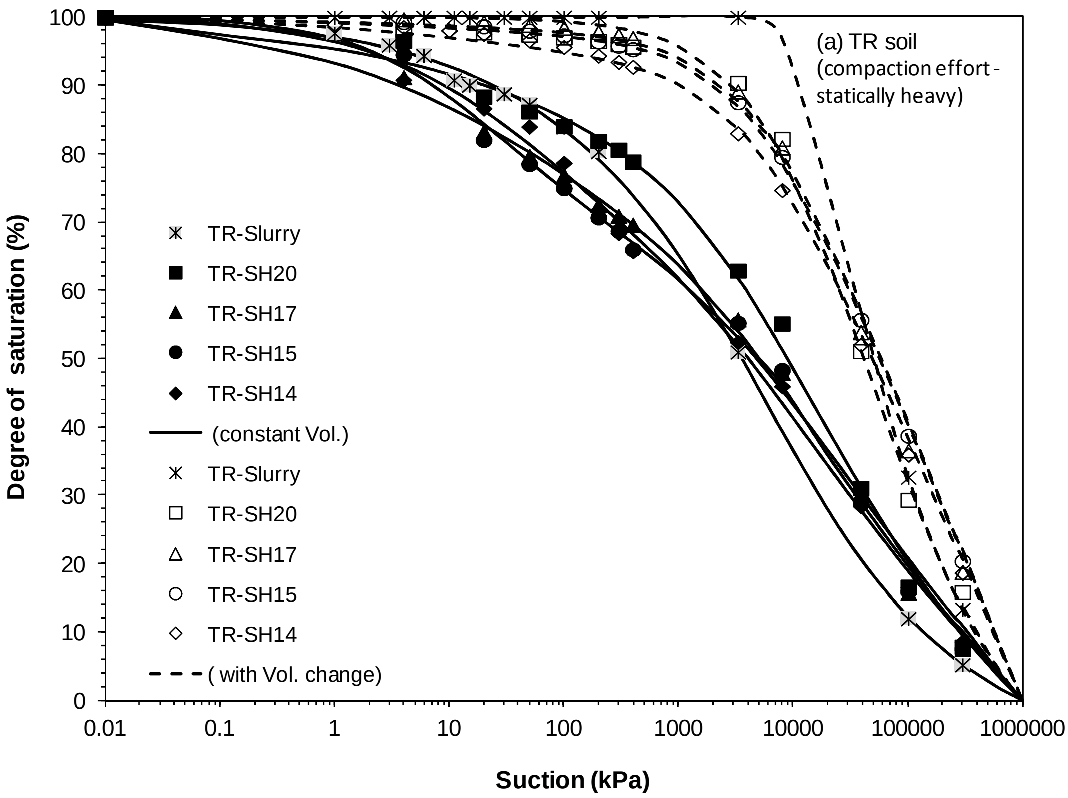




***Fig. 5.4 Suction-degree of saturation SWCCs of JF-soil (a) statically heavy (b) statically light***



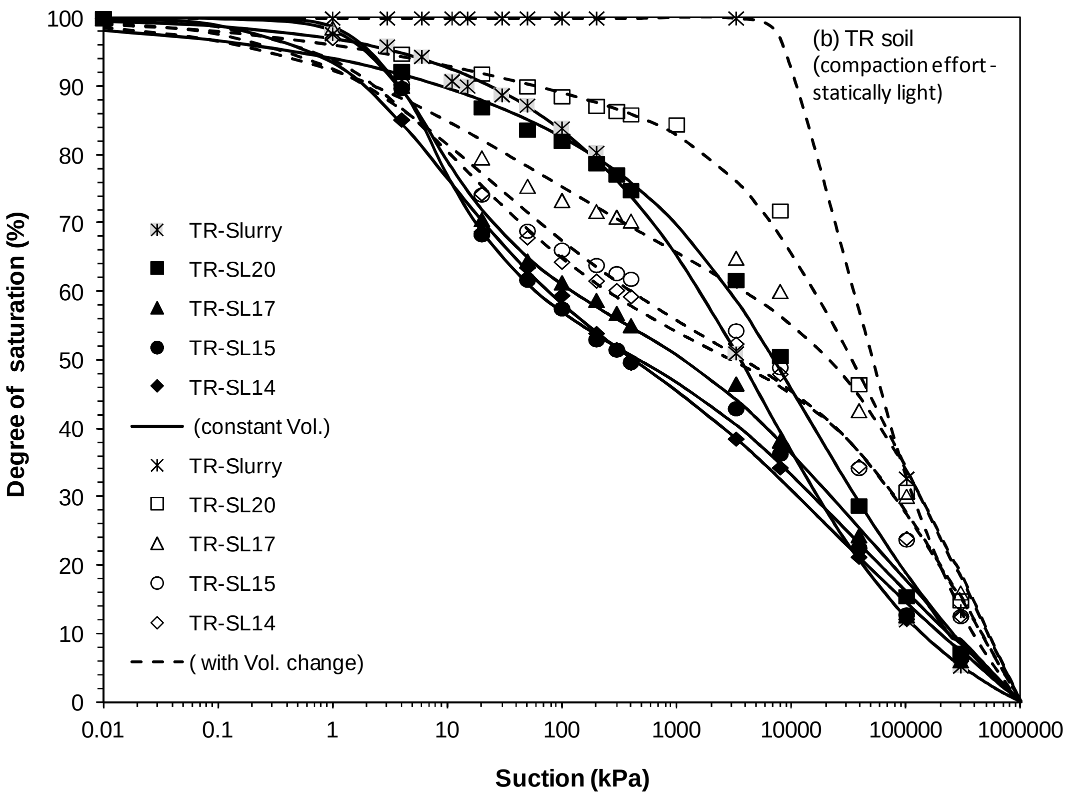




***Fig. 5.5 Suction-degree of saturation SWCCs of TR-soil (a) statically heavy (b) statically light***

### 5.4.2 Suction-void ratio SWCCs

By considering the suction-water content SWCCs obtained from pressure plate and desiccator tests and void ratio-water content relationships determined from Clod test, the suction-void ratio SWCCs of the soil specimens were established. Variations of the void ratio associated to the suction increase for specimens of JF and TR soils are presented in Figs. 5.6 and 5.7. It can be seen from the Figs. 5.6 and 5.7 that for each initial compaction condition, the curve can be divided into three parts. At low suction range (up to about 1 kPa for JF soil and up to about 5 kPa for TR soil), no change in the void ratio was observed. As the suction increased (up to 200 kPa for JF soil and 8000 kPa for TR soil), the void ratio of specimens decreased. These variations in the void ratio ranged from 0.12 to 0.07 for the specimens of JF soil and from 0.3 to 0.2 for the specimens of TR soil. The most significant decrease in void ratio was observed for the initially sluried specimens of both soils. For high suction values, an increase in suction had no influence on the void ratio changes and the void ratio of the specimens remained constant. The ordering of the void ratio SWCCs for both JF and TR soils were found to be concurrent with initial compaction water content and compaction efforts.

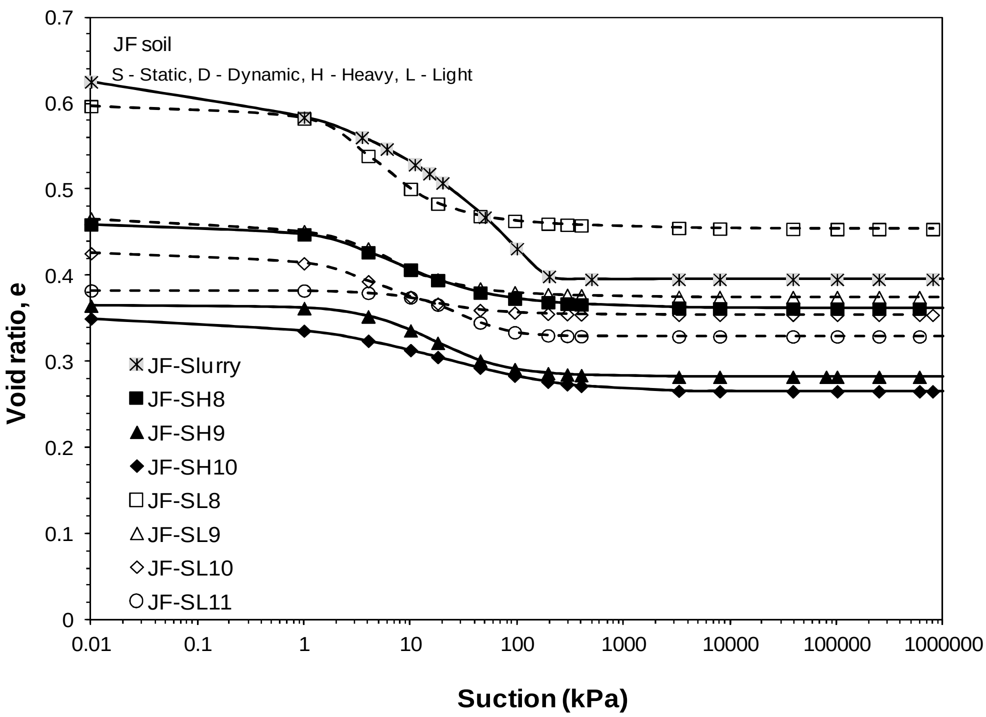



***Fig. 5.6 Suction-void ratio SWCCs for slurried and statically heavy and light compacted JF soil***

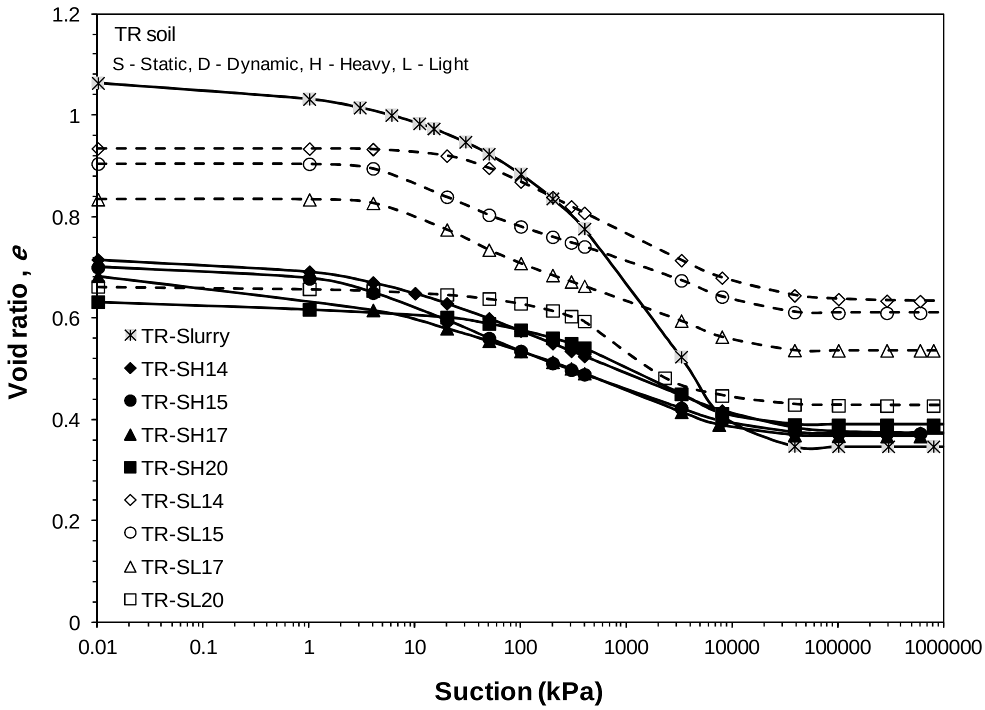



*Fig. 5.7 Suction-void ratio SWCCs for slurried and statically heavy and light compacted TR soil*

## 5.5 Void ratio changes with suction and vertical stress

Limited studies in the literature have compared the suction-void ratio SWCC results with one-dimensional consolidation test results for initially compacted saturated (Fredlund, 1964; Fleureau et al., 1993; Marcial et al., 2002; Tripathy et al., 2010).

Oedometer tests were carried out to establish the vertical pressure-void ratio relationships (section 3.5 - chapter 3). The suction-void ratio SWCCs were established based on the suction-water SWCCs of the soils in conjunction with the Clod test results. The initial water contents of the soil specimens in the oedometer tests were kept similar to that of the specimens tested in the SWCC tests.

A comparison between void ratio changes due to suction (i.e., *s* versus *e*) and due to one-dimensional compression (i.e., *p* versus *e*) for statically compacted specimens of JF and TR soil are presented in Figs. 5.8 and 5.9, respectively. The suction versus $wG_s$ plots (i.e., *s* versus $wG_s$) for JF and TR soils are also included in the Figs. 5.8 and 5.9 for comparison.

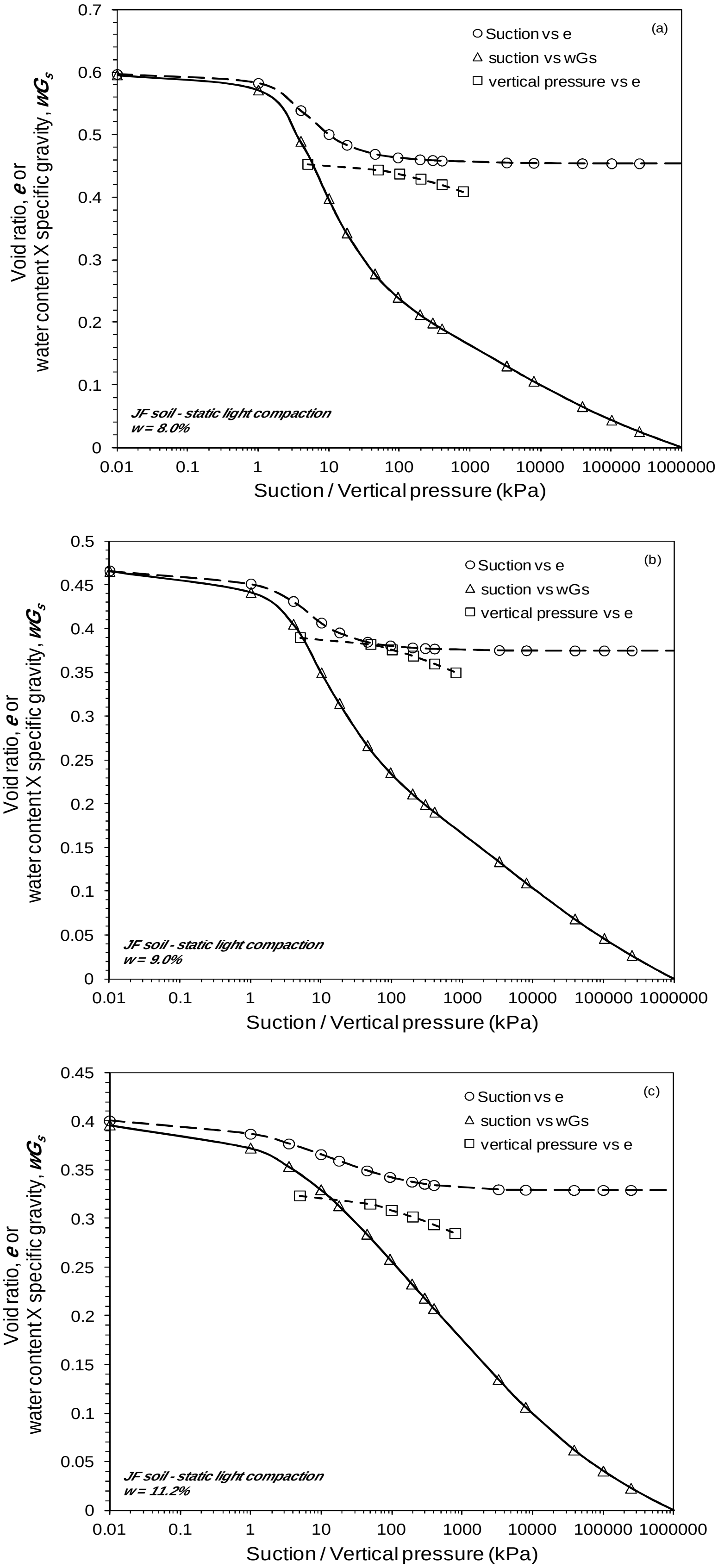



***Fig. 5.8 Influence of suction and vertical pressure on volume change behaviour of JF soil***

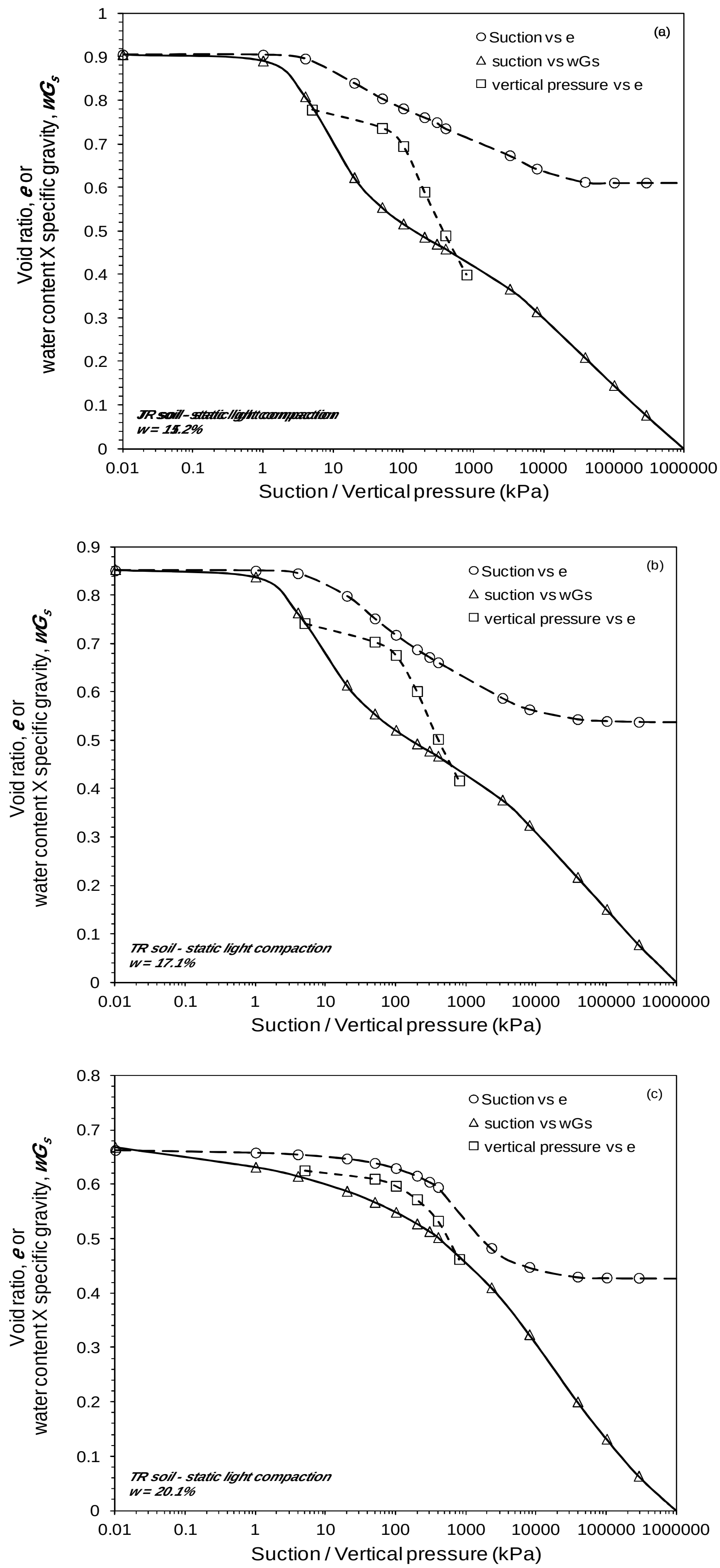



***Fig. 5.9 Influence of suction and vertical pressure on volume change behaviour of TR soil***

It can be seen from Figs. 5.8 and 5.9 that the *s-e* plots remained clearly above that of the $s$-$wG_s$ plots for both soils. Additionally, the *p-e* plot remained above that of the $s$-$wG_s$ plots. An increase in the vertical pressure was more effective in reducing the water content of the soils than due to an increase in suction. The *p-e* plots were found to remain distinctly below that of the *s-e* plots indicating that the volume change due to a vertical pressure increase was more than that due to an increase in suction.

## 5.6 Determination of AEVs and residual suctions

If a soil undergoes insignificant volume change during the drying process, the suction-gravimetric water content and the suction-degree of saturation SWCCs will lead to similar values of AEV and residual suction. However, if the volume change of the soil is significant, the suction-degree of saturation may be used for determination of AEV and residual suction (Fredlund et al., 2011).

A shrinkage curve provides an indication of the AEV of the soil as well as the residual water content. During the drying process a saturated slurried soil follows the 100% saturation line until air begins to enter the largest soil voids at which the shrinkage curve starts to deviate from the 100% saturation line (Marinho, 1994). In some cases the desaturation point may remain close to the plastic limit and can be considered as the air-entry point (Fredlund et al., 2011). The soil continues to dry until it reaches the shrinkage limit at which the volume of voids remains constant. The residual conditions may be correlated with the shrinkage limit of the soil (Fredlund et al., 2012).

The AEVs and the residual suctions of specimens of JF and TR soils were determined from: (*i*) the suction-water content SWCCs (pressure plate and desiccator test results) and (*ii*) the suction-degree of saturation SWCCs established based on the suction-water content SWCCs in conjunction with the best-fit shrinkage curves. The graphical procedures suggested by Vanapalli et al. (1998) were followed for determining the AEVs and the residual suctions. The AEVs of soil specimens thus determined were compared with the suctions corresponding to the shrinkage limits and plastic limits of initially saturated slurried specimens of both soils. The residual suctions were compared with the suctions corresponding to the shrinkage limits of the soils. The AEVs of the soils are presented first followed by the residual suctions.

### 5.6.1 Determination of AEVs

A reduction in the water content during the drying process from the shrinkage tests for compacted specimens of JF soil (both heavy and light compaction efforts) and specimens of TR soil (light compaction effort) showed that desaturation occurred immediately as the drying process commenced (Fig. 5.2). In these cases, the degree of saturation of the specimens decreased from the start of the drying process. However, the commencement of desaturation followed the normal shrinkage phase for the slurried specimens of JF and TR soils and for the specimens of TR soil that were prepared by applying heavy compaction effort. For all cases, the suction-water content SWCCs (chapter 4) together with the corresponding shrinkage curves (Fig. 5.2) enabled establishing the suction-degree of saturation SWCCs (Figs. 5.4 and 5.5).

For better explaining the procedure adopted to determine the AEVs and residual suctions, the suction-water content SWCCs, the shrinkage curves, and the suction-degree of saturation SWCCs for slurried specimens of JF and TR soils are presented in Figs. 5.10, 5.11, and 5.12, respectively. The AEVs and the residual suctions of the specimens are shown in Figs. 5.10 and 5.12. The values of $w_p$, $w_s$, and $w_{AEV}$ of the soils are shown in Fig. 5.11. The suctions corresponding to $w_p$, $w_s$, and $w_{AEV}$ are shown in Figs. 5.10 and 5.12. Table 5.2 presents the suctions corresponding to $w_s$, $w_p$, and $w_{AEV}$ for the initially saturated slurried specimens of both soils and the AEVs determined from the SWCCs.

For JF soil, the AEVs from the suction-water content and suction-degree of saturation SWCCs are 15 and 180 kPa, respectively (Figs. 5.10, 5.12 and Table 5.2). The suctions corresponding to $w_p$, $w_s$, and $w_{AEV}$ are 110, 170, and 140 kPa, respectively. Similarly, for TR soil, the AEVs from the suction-water content and suction-degree of saturation SWCCs are 85 and 6300 kPa, respectively (Figs. 5.10, 5.12 and Table 5.2). The suctions corresponding to $w_p$, $w_s$, and $w_{AEV}$ are 6400, 11500, and 6200 kPa, respectively. Thus, it can be seen that the AEVs determined from the suction-water content SWCCs were distinctly less than that determined from the suction-degree of saturation SWCCs for both soils. The suction corresponding to $w_p$ and $w_{AEV}$ agreed well with the AEVs determined from the suction-degree of saturation SWCCs.

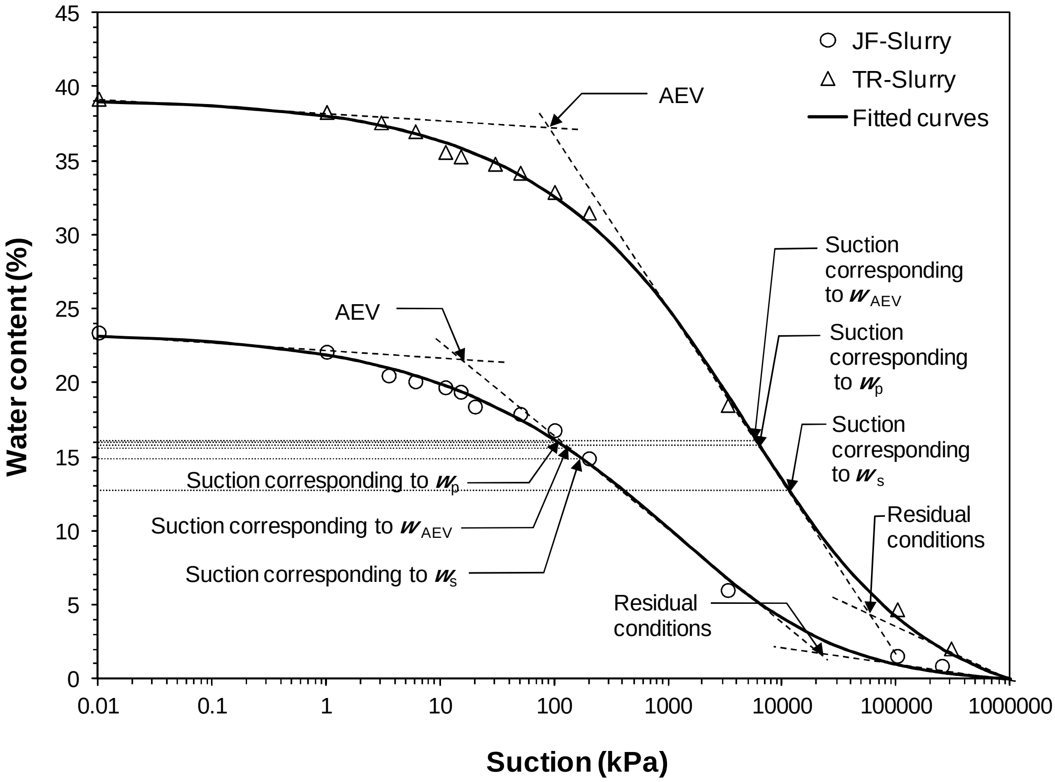



*Fig. 5.10 Suction-water content SWCCs for initially slurried specimens of JF and TR soils*

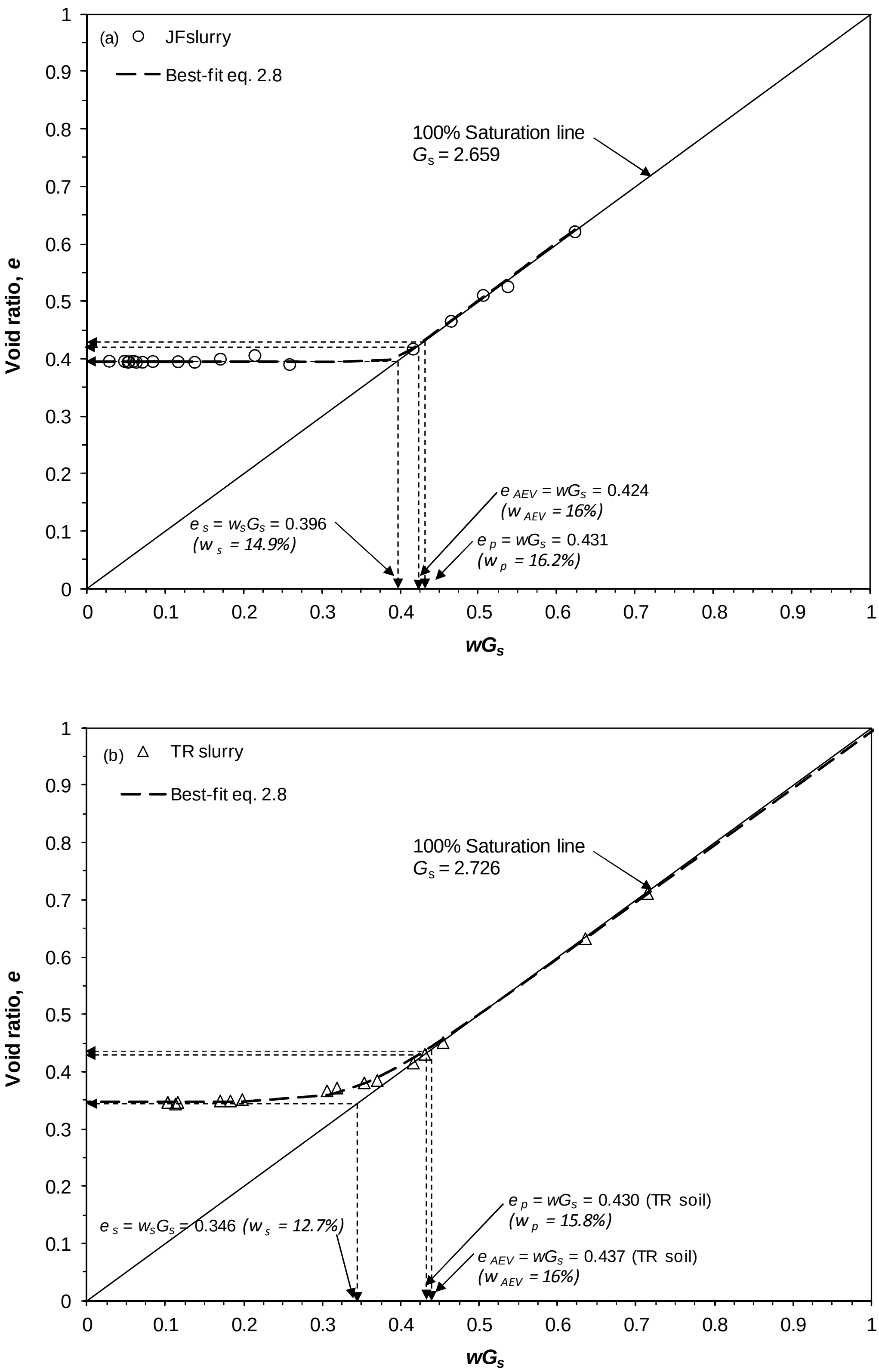



***Fig. 5.11 Shrinkage curves of initially slurried specimens of (a) JF soil and (b) TR soil***

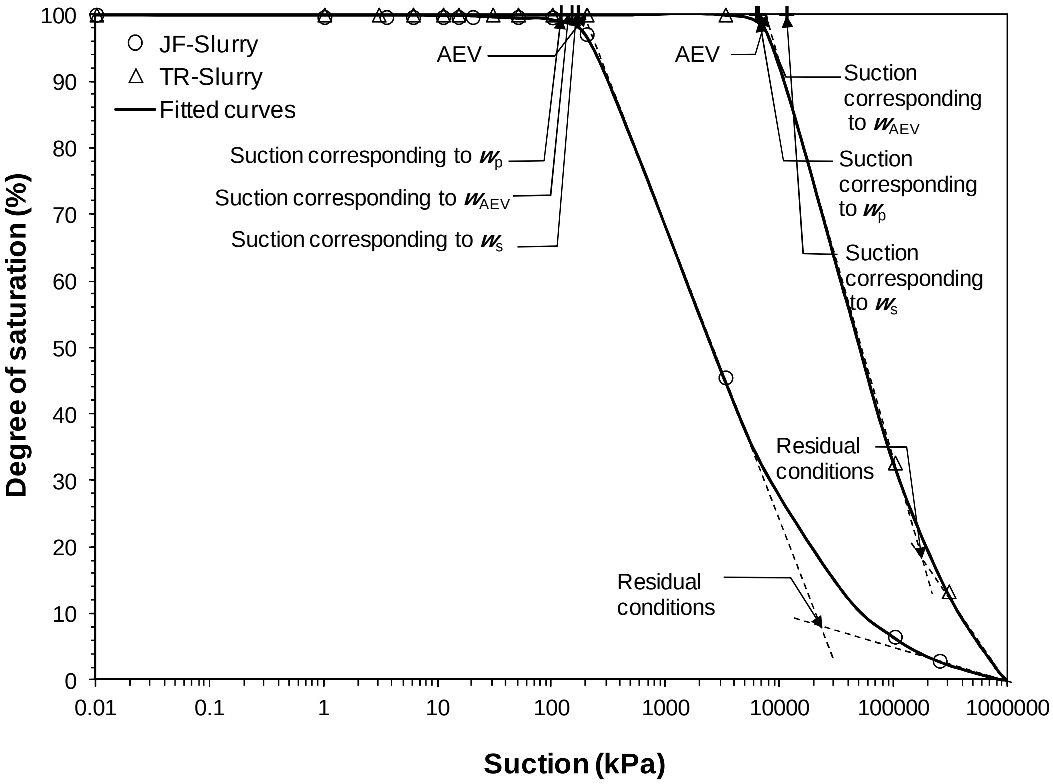



*Fig. 5.12 Suction- degree of saturation SWCCs (based on suction-water content SWCCs and the shrinkage tests) for initially slurried specimens of JF and TR soils*

***Table 5.2 Comparisons of AEVs of JF and TR soils from different approaches***

| Soil specimens* | Suction based on $w_s$ (kPa) | Suction based on $w_p$ (kPa) | Suction based on $w_{AEV}$ (kPa) | AEV** based on suction-water content SWCC (kPa) | AEV*** based on suction-degree of saturation SWCC (kPa) |
|---|---|---|---|---|---|
| JF-Slurry | 170 | 110 | 140 | 15 | 180 |
| JF-SH10 | - | - | - | 4.7 | 43 |
| JF-SH9 | - | - | - | 3.8 | 13 |
| JF-SH8 | - | - | - | 1.7 | 2.5 |
| JF-SL11 | - | - | - | 3.7 | 9.5 |
| JF-SL10 | - | - | - | 1.5 | 4.2 |
| JF-SL9 | - | - | - | 1.4 | 2.6 |
| JF-SL8 | - | - | - | 1.3 | 2.1 |
| TR-Slurry | 11500 | 6400 | 6200 | 85 | 6300 |
| TR-SH20 | - | - | - | 153 | 3200 |
| TR-SH17 | - | - | - | 65 | 2850 |
| TR-SH15 | - | - | - | 31 | 2550 |
| TR-SH14 | - | - | - | 21 | 2350 |
| TR-SL20 | - | - | - | 135 | 1100 |
| TR-SL17 | - | - | - | 2.1 | 750 |
| TR-SL15 | - | - | - | 1.4 | 230 |
| TR-SL14 | - | - | - | 1.1 | 210 |

** JF, TR = JF and TR soils, S = static compaction, H = heavy compaction effort, L = light compaction effort, No. = initial compaction water content*

[+] *$w_s$ = water content shrinkage limit, $w_p$= plastic limit, $w_{AEV}$= water content desaturation point*

*** Based on the suction-water SWCCs of the soils (pressure plate and desiccator test results)*

**** Based on the suction-water SWCCs of the soils (pressure plate and desiccator test results in conjunction with the Clod test results)*

Agreements between the suctions corresponding to $w_{AEV}$ and AEVs from the suction-degree of saturation SWCCs are obvious since the latter were established based on the shrinkage curves of the soils. The suction corresponding to $w_s$ agreed well with the AEVs determined from the suction-degree of saturation SWCC of JF soil, but not in case of TR soil. For the latter case, the difference in the suction corresponding to $w_s$ and the AEV from suction-degree of saturation SWCC is attributed due to significant volume change during the drying process.

For JF soil, the AEVs from the suction-water content and suction-degree of saturation SWCCs are 15 and 180 kPa, respectively (Figs. 5.10, 5.12 and Table 5.2). The suctions corresponding to $w_p$, $w_s$, and $w_{AEV}$ are 110, 170, and 140 kPa, respectively. Similarly, for TR soil, the AEVs from the suction-water content and suction-degree of saturation SWCCs are 85 and 6300 kPa, respectively (Figs. 5.10, 5.12 and Table 5.2). The suctions corresponding to $w_p$, $w_s$, and $w_{AEV}$ are 6400, 11500, and 6200 kPa, respectively. Thus, it can be seen that the AEVs determined from the suction-water content SWCCs were distinctly less than that determined from the suction-degree of saturation SWCCs for both soils. The suction corresponding to $w_p$ and $w_{AEV}$ agreed well with the AEVs determined from the suction-degree of saturation SWCCs. Agreements between the suctions corresponding to $w_{AEV}$ and AEVs from the suction-degree of saturation SWCCs are obvious since the latter were established based on the shrinkage curves of the soils. The suction corresponding to $w_s$ agreed well with the AEVs determined from the suction-degree of saturation SWCC of JF soil, but not in case of TR soil. For the latter case, the difference in the suction corresponding to $w_s$ and the AEV from suction-degree of saturation SWCC is attributed due to significant volume change during the drying process.

Table 5.2 presents the AEVs of compacted soil specimens of both soils based on both suction-water content and suction-degree of saturation SWCCs. Examination of the AEVs for compacted specimens of both soils presented in Table 5.2 clearly showed that the AEVs obtained from the suction-water content SWCCs remained well below AEVs obtained from the suction-degree of saturation SWCCs. Significant differences were noted between the AEVs of compacted specimens from the suction-degree of saturation SWCCs and suctions corresponding to $w_p$ and $w_s$.

### 5.6.2 Determination of residual suctions

Table 5.3 presents the residual conditions of the soils that were determined using the suction-water content SWCCs and the suction-degree of saturation SWCCs. The suctions corresponding to the shrinkage limits of the soils are shown for comparison.

***Table 5.3 Comparisons of residual conditions of JF and TR soils from different approaches***

| Soil specimens* | Suction based on $w_s$ (kPa) | Residual suction** based on suction-water content SWCC (kPa) | Residual suction*** based on suction-degree of saturation SWCC (kPa) |
|---|---|---|---|
| JF-Slurry | 170 | 20000 | 22000 |
| JF-SH10 | - | 31000 | 49000 |
| JF-SH9 | - | 900 | 18000 |
| JF-SH8 | - | 550 | 1700 |
| JF-SL11 | - | 25000 | 35000 |
| JF-SL10 | - | 22000 | 15000 |
| JF-SL9 | - | 165 | 740 |
| JF-SL8 | - | 95 | 200 |
| TR-Slurry | 11500 | 60000 | 170000 |
| TR-SH20 | - | 153 | 3200 |
| TR-SH17 | - | 65 | 2850 |
| TR-SH15 | - | 31 | 2550 |
| TR-SH14 | - | 21 | 2350 |
| TR-SL20 | - | 135 | 1100 |
| TR-SL17 | - | 2.1 | 750 |
| TR-SL15 | - | 1.4 | 230 |
| TR-SL14 | - | 1.1 | 210 |

** JF, TR = JF and TR soils, S = static compaction, H = heavy compaction effort, and L = light compaction effort, No. = initial compaction water content.*

[+] *$w_s$ = water content shrinkage limit*

*** Based on the suction-water SWCCs of the soils (pressure plate and desiccator test results).*

**** Based on the suction-degree of saturation SWCCs of the soils (pressure plate and desiccator test results in conjunction with the Clod test results).*

It can be seen from Table 5.3 that the residual suctions from the suction-degree of saturation SWCCs are much higher than the values obtained from the suction-water content SWCCs, particularly for specimens of TR soil. Disagreements are also noted between the suctions corresponding to the shrinkage limits and the residual suctions from both the suction-degree of saturation SWCCs and the suction-water content SWCCs.

## 5.7 Concluding remarks

The findings from the study presented in chapter 5 concerning the (*i*) determination of the shrinkage curves of the soils, (*ii*) establishing the suction-degree of saturation SWCCs, (*iii*) comparisons of suction-void ratio SWCCs with pressure-void ratio relationships (i.e., consolidation test results), and (*iv*) determination the AEVs and residual suctions of the soils studied, can be summarised as follows:

- In spite of low plasticity characteristics of the soils, a change in matric suction resulted in a reduction in the volume of the soils studied. Therefore, measurements of volume of soils are extremely relevant for establishing the suction-degree of saturation SWCCs.
- The Clod tests were found to be very effective in establishing the entire shrinkage paths for the soils studied. The desaturation points for the soils were determined from the shrinkage paths of the soils.
- The suction-water content SWCCs in conjunction with the Clod test results enabled establishing the suction-degree of saturation SWCCs and the determination of AEVs and residual suctions of the soils.
- Comparison of suction-void ratio SWCCs with pressure-void ratio relationship (i.e., consolidation test results) indicted that the volume change due to a vertical pressure increase was more than that due to an increase in suction.
- The AEVs and residual suctions of the soils determined form suction-water content SWCCs are found to be distinctly lower than the AEVs and residual suctions determined form suction-degree of saturation SWCCs.
- The suctions corresponding to the plastic limits of the soils and the AEVs determined from the suction-degree of saturation SWCCs were found to be very similar. However, the suctions at the shrinkage limits of the soils, the AEVs, and the residual suctions were very poorly correlated.

# CHAPTER 6

# DIRECT MEASURMENT OF SUCTION USING NULL-TYPE AXIS-TRANSLATION TECHNIQUE

## 6.1 Introduction

Compacted soils are used in many civil engineering works, such as roads, embankments, earth dams, backfills, and soil covers. Compacted soils are invariably unsaturated and possess negative pore-water pressure or suction. Matric suction, the difference between the pore-air pressure and the pore-water pressure, is an important stress-state variable of unsaturated soils and is a function of soil structure and soil water content. The measurement of matric suction is a prerequisite for the characterisation of unsaturated soils. Tensiometers, null-type pressure plate device, and high suction probe can be used for direct measurement of matric suctions of soils (Fredlund & Rahardjo, 1993). Tensiometers enable measuring matric suctions of less than about 100 kPa, whereas null-type pressure plate device and high suction probe can be used for measuring matric suctions up to 1500 kPa.

In this chapter, matric suctions of two natural soils from Libya (Jeffara soil (JF) and Terra-rosa soil (TR)) were measured using null-type axis-translation technique. Soil specimens used for suction measurements were prepared at various compaction conditions in which the initial compaction water content, dry density, compaction type, and compaction effort were varied.

## ***CHAPTER 6 – DIRECT MEASURMENT OF SUCTION USING NULL-TYPE AXIS-TRANSLATION TECHNIQUE***

The objective of this chapter were (*i*) to measure matric suction using null-type axis-translation technique, (*ii*) to study the influence of initial compaction conditions on time-matric suction development in null-type device, and (*ii*) to examine the influence of size of the specimens on the measured matric suction.

This chapter divided into several sections which include the experimental programme adopted, and presentation of the test results for both soils. The effects of initial compaction conditions on matric suction of the soils are brought in detail. The concluding remarks are presented towards the end of the chapter.

### 6.2 Experimental programme and specimen preparation

#### 6.2.1 Soil specimen preparation

Dynamically compacted specimens were prepared from both BS-light and BS-heavy compaction samples. Thin walled stainless-steel tubes were used to extrude the compacted specimens from the compaction mould. Samples were taken from the remaining soil to determine the compaction water contents of the specimens. The dry densities of the tested specimens were calculated based on the volume-mass relationships.

Soil specimens were also prepared by statically compacting soil-water mixtures in single lift in a specially fabricated mould (Fig. 3.3). The targeted compaction dry densities and water contents of the statically compacted soil specimens were corresponding to the specimen conditions of the dynamically compacted specimens. Typically, the statically compacted specimens prepared were 12 mm thick and 44 or 80 mm in diameter.

The initial conditions of JF and TR soil specimens are shown in Figs. 6.1*a* and *b*, respectively. In total, 79 JF soil specimens were tested by null-type axis translation device for matric suction measurements (16 specimens for BS-heavy compaction, 18 for BS-light compaction, 15 for static-heavy compaction, 10 for static-intermediate compaction, and 20 for static-light compaction). The degree of saturation of the specimens were between 37% and 90% (Fig. 6.1*a*). Similarly, matric suction measurements were carried out on 45 TR soil specimens (9 specimens for BS-heavy compaction, 13 for BS-light compaction, 11 for static-heavy compaction, and 12 for static-light compaction). The degree of saturation of the specimens varied between within about 48% and 97% (Fig. 6.1*b*).

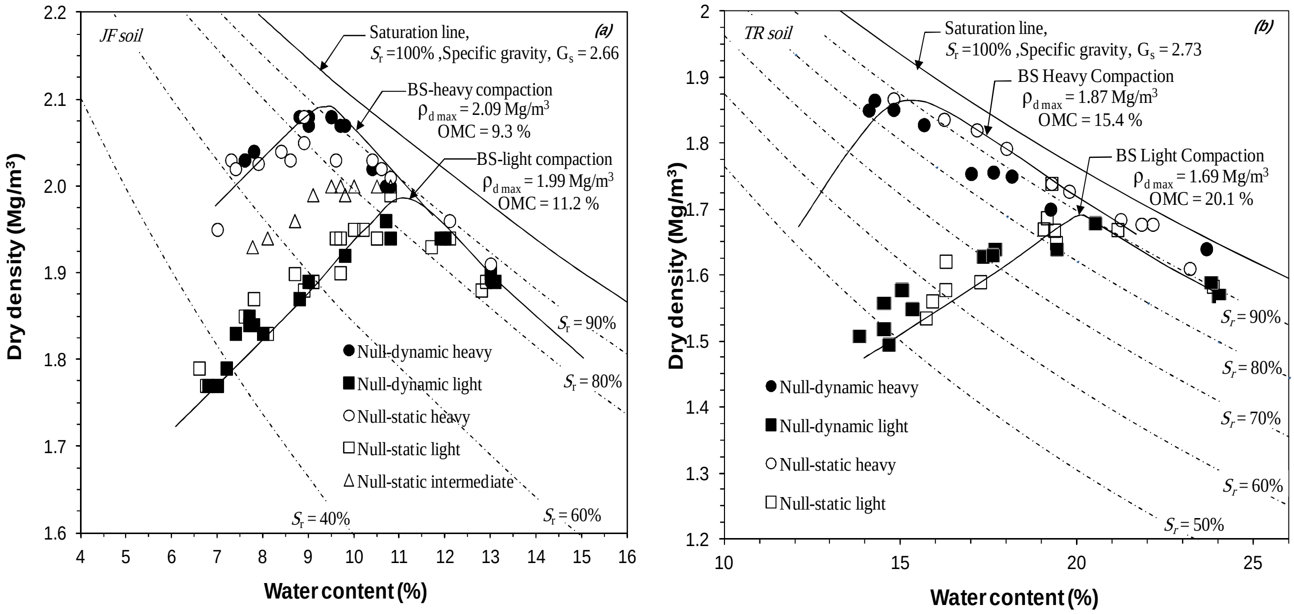



***Fig. 6.1 Compaction characteristics of the soil tested (BS-light and BS-heavy) and placement conditions chosen for (a) JF soil and (b) TR soil***

### 6.2.2 Null-type axis-translation tests

A single wall triaxial cell assembly was used to carry out the null-type axis-translation tests. The main components of the device are presented in section 3.9.1.

The test procedure involved saturation of the ceramic disk with de-aired water and placement of soil specimen to be tested on the ceramic disk. A 1 kg mass was placed on the top of the specimens to ensure a good contact between the specimen and the ceramic disk (Olson & Langfelder, 1965). The apparatus was then quickly assembled (in about 10 seconds) and the air pressure inside the pressure chamber was increased in increments to keep the pore water at atmospheric pressure (zero gauge reading). Equilibrium was achieved when the reading of air pressure was held constant and the pore water pressure showed no change. At equilibrium, the matric suction is the difference between the air pressure applied in the chamber and the recorded pore water pressure in the compartment (zero in all cases). Once the equilibrium was reached, the mass the specimen was measured and the water content was determined by oven drying method.

The final water contents of the specimens were compared with the placement water contents. It was noted in this study that the differences in initial and final water content were less than ± 0.07% in all cases, which was considered to be insignificant.

Laboratory tests involving axis-translation technique are usually carried out by using pressurised air supply. The pressurised air is supplied either by a compressed air plant or a compressed nitrogen gas plant. The air plants usually supply cold and dry air. For example, at the outlets of compressed air plants, the temperature of the air is about 3 to 5°C. The air temperature usually increases in the distribution lines. In order to eliminate the detrimental corrosion effect of water vapour on the plant assembly and distribution lines, the relative humidity of the supplied air from compressed air plants is usually kept close to 0%. In the laboratory, controlled release of compressed air in a closed chamber at a pressure smaller than the maximum designated pressure of the air plant causes an expansion of the supplied air. Additionally, air outflow into the chamber produces a mixture of air and water vapour. Prior to testing, the main sources of water vapour in the pressure chamber are the relative humidity in the laboratory, the water in the saturated ceramic disk, and the water that is used during the saturation of the ceramic disk. During a test, water vapour from soil specimens may contribute to the partial pressure of water vapour within the pressure chamber.

During measurements of matric suction, the relative humidity and the temperature in the pressure chamber is usually not measured. The difference in the relative humidity of soil specimen for which matric suction measurement is carried out and that of the compressed air in the pressure chamber may cause some instability of the system. This may in turn influence the suction equilibrium time (Marinho et al., 2008; Delage et al., 2008).

The air temperature and the relative humidity in the air pressure chamber were monitored during testing of some soil specimens. Statically compacted soil specimens corresponding only light compaction effort were used in this case. The water contents of the soil specimens were such that matric suctions of the soil for both wet and dry conditions were covered. A commercially available relative humidity and temperature transmitter was inserted at the top-lid of the device through a specialised air-tight connection (Fig. 3.3). The transmitter can measure relative humidity and temperature to accuracies of ± 1% and ± 0.5°C, respectively. Prior to use of the transmitter in the null-type device, calibration of the transmitter was carried out with saturated salt solutions. The calibration results indicated that the relative humidity equilibration time of the transmitter was about 40 minutes, whereas the response of the transmitter to temperature changes was about 2 to 3 minutes.

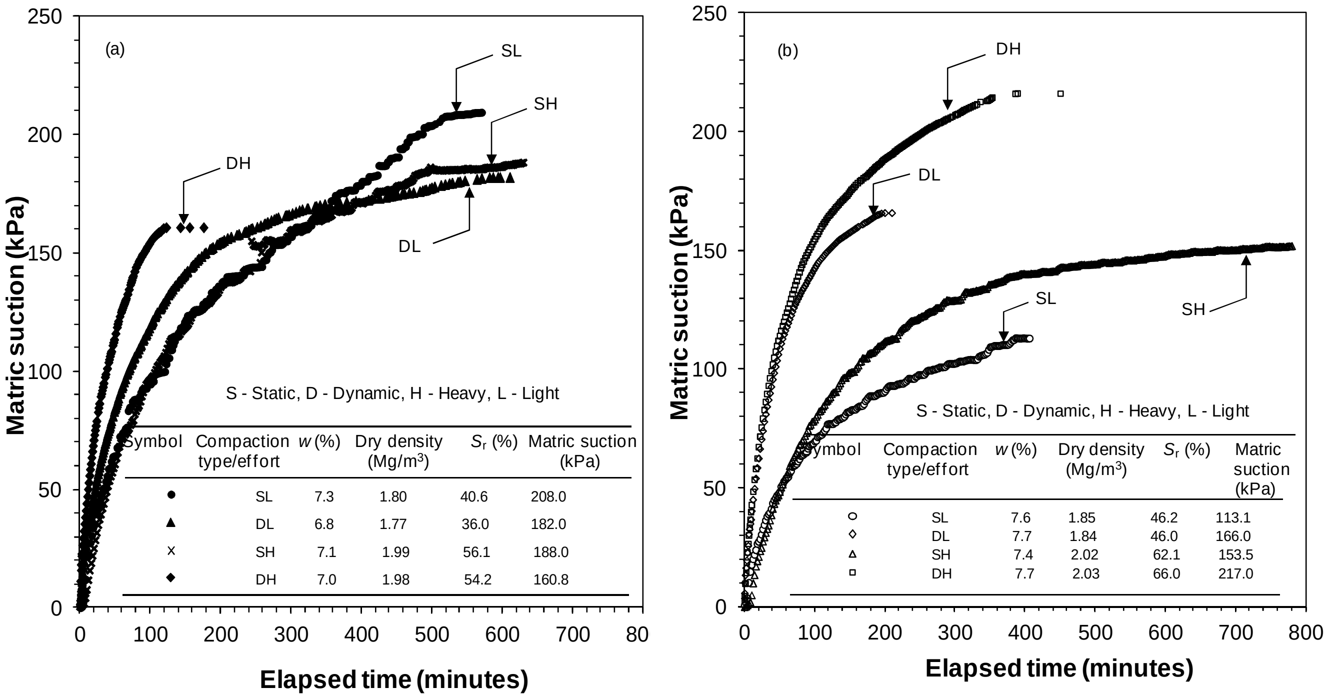
## 6.3 Null-type axis-translation test results

### 6.3.1 Equilibration time

The elapsed time versus matric suction plots for both dynamically (BS-light (DL) and BS-heavy (DH)) and statically compacted specimens (static-light (SL) and static-heavy (SH)) of JF and TR soils are shown Figs. 6.7 and 6.8, respectively. For the sake of brevity, the influence of dry density due to an increase in the compaction effort and the influence of compaction type at six different water content levels for the specimens of JF soil, such as at about 7.1, 7.6, 9.0, 9.7, 10.7 and 12.0% are shown in Fig. 6.7. Similarly, several water content levels for the specimens of TR soil (17.1, 18.2, 19.3, and 23.5%) are shown in Fig. 6.8. Note that the difference between specimen conditions for any compaction effort (heavy or light) is only a slight and the differences remain as due primarily to the compaction type considered (static and dynamic). For example, in Fig. 6.7*a*, for heavy compaction effort, the statically compacted specimen had a water content of 7.1% and dry density of 1.99 Mg/m$^3$, whereas its dynamic counterpart had similar water content and dry density of 7.0% and 1.98 Mg/m$^3$, respectively. In terms of the degree of saturation ($S_r$), the compaction conditions are comparable with some allowance for errors during preparation of the specimens.

Dynamically compacted specimens of JF soil invariably reached equilibrium suctions sooner than their statically compacted counterparts at all water contents considered (Fig. 6.7). However, Figs. 6.8*b* and *c* show that at water contents of about 18.2 and 19.3%, the statically compacted specimens of TR soil reached equilibrium suctions sooner than the dynamically compacted specimens. The statically and dynamically compacted specimens of TR soil compacted at water content of 17.1 and 23.5% attained equilibrium suctions almost at the same time of about 400 and 180 minutes, respectively (Figs. 6.8*a* and *d*).

Additionally, except for the test results at water content of about 7.0% (Fig. 6.7*a*), the measured matric suctions for dynamically compacted specimens of JF soil were generally greater than their statically compacted counterparts. However, Fig. 6.8 shows that the statically compacted specimens of TR soil exhibited higher measured matric suctions as compared to the dynamically compacted specimens of TR soil. The comparison has been made at the same compaction effort (i.e., SL versus DL and SH versus DH).



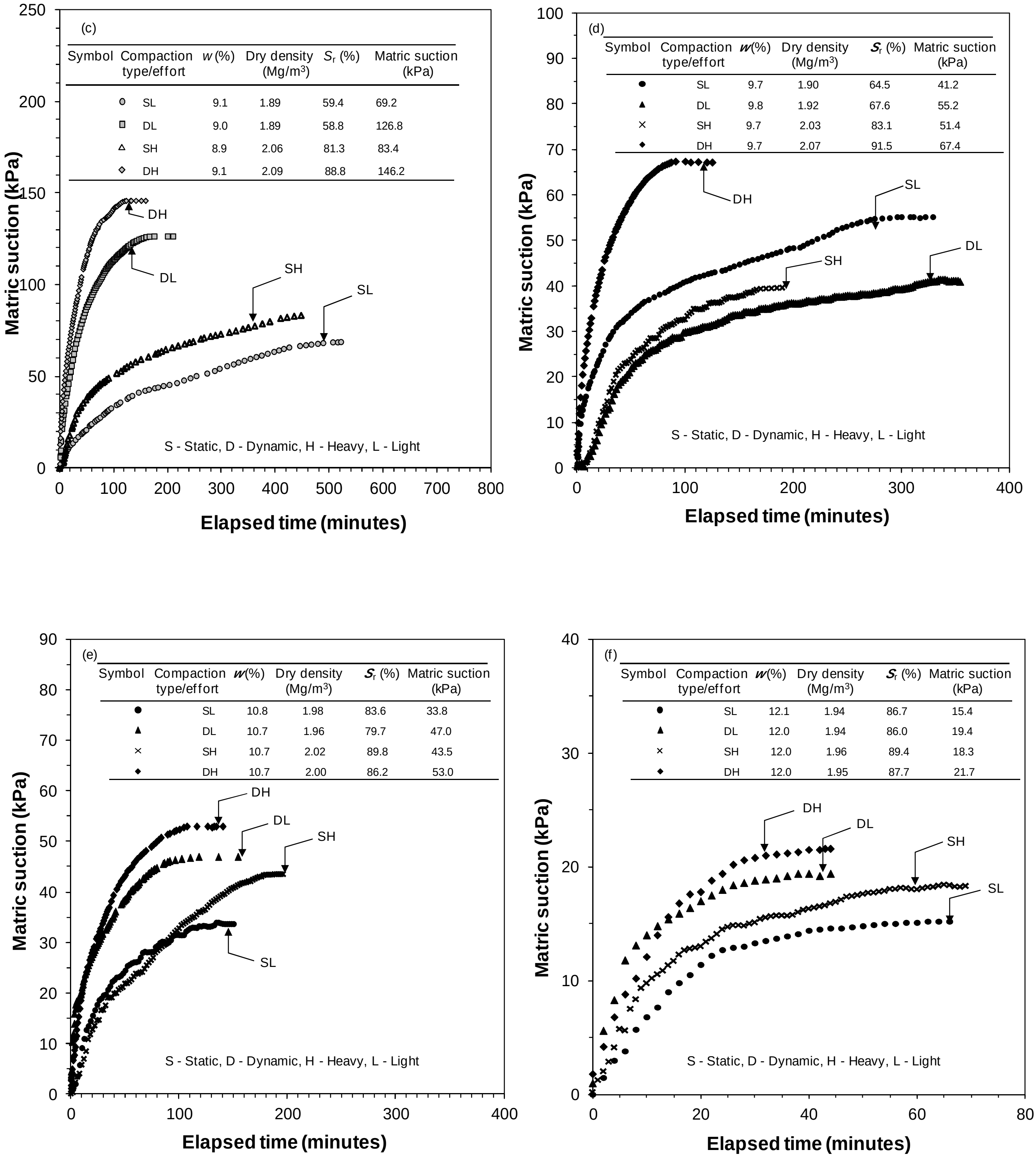



***Fig. 6.7 Time versus matric suction plots of JF soil for average compaction water contents of (a) 7.1%, (b) 7.6%, (c) 9.0%, (d) 9.7%, (e) 10.7%, and (f) 12.0%.***

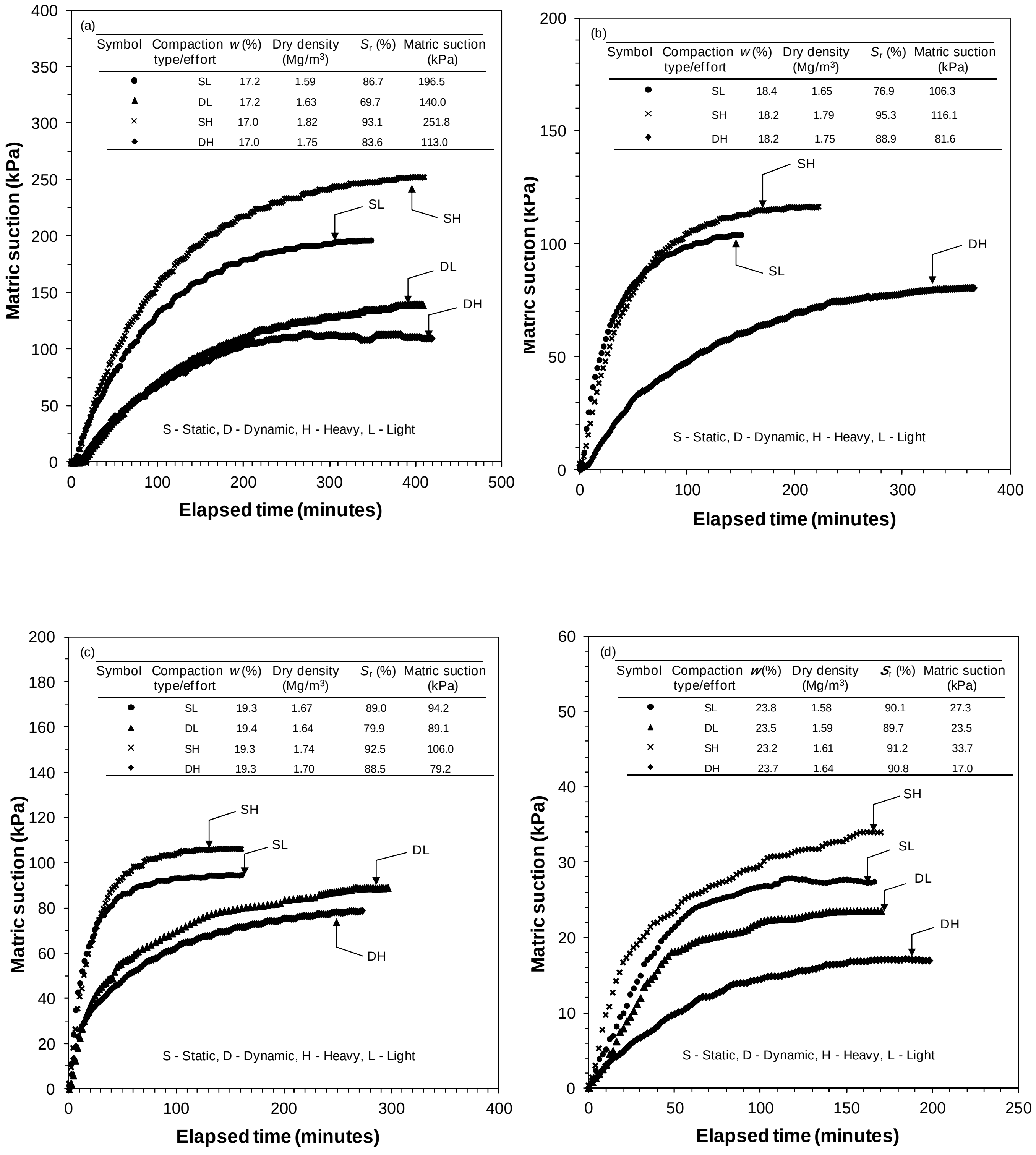



***Fig. 6.8 Time versus matric suction plots of TR soil for average compaction water contents of (a) 17.1%, (b) 18.2%, (c) 19.3%, and (d) 23.5%.***

Some differences were also noted when the compaction type (static and dynamic) was held as a reference and matric suctions were compared on the basis of the difference in the compaction effort (i.e., light and heavy). The differences between matric suctions of JF-SL and JF-SH specimens in Figs. 6.7*a* to 6.7*f* were found to be about 20, 40, 14, 10, 10, and 3 kPa. Similarly, the differences between the measured matric suctions between JF-DL and JF-DH specimens were about 23, 51, 21, 12, 4, and 2.3 kPa in Figs. 6.7*a* to 6.7*f*. For the specimens of TR soil (Figs. 6.8*a* to 6.8*d*), the differences between the measured matric suctions of SL and SH specimens were about 55, 10, 12, 6.5 kPa and those between DL and DH specimens were about 27, 10, and 6.5 kPa.

The relative influence of only the compaction dry density irrespective of compaction type can be noted in Figs. 6.7 and 6.8. At reference water contents of about 7.0, 7.7, 9.0, 9.7, 10.7 and 12.0% for the specimens of JF soil, the difference between the least and highest measured matric suctions were about 47 kPa (Fig. 6.7*a*), 104 kPa (Fig. 6.7*b*), 77 kPa (Fig. 6.7*c*), 26 kPa (Fig. 6.7*d*), 19 kPa (Fig. 6.7*e*) and 6 kPa (Fig. 6.7*f*). Similarly, For the specimens of TR soil the difference between the least and highest measured matric suctions at water contents of about 7.0, 7.7, 9.0, 9.7, 10.7 and 12.0%, were about 139 kPa (Fig. 6.8*a*), 34 kPa (Fig. 6.8*b*), 27 kPa (Fig. 6.8*c*), and 17 kPa (Fig. 6.8*d*). Therefore, it can be seen that the influence of compaction conditions and compaction type increased with an increase in the water content and further decreased.

Considering the test results presented in Figs. 6.7 and 6.8, it was noted that, TR soil had relatively shorter equilibration time as compared to JF soil. This is due to the higher amount of fines in TR soil which result in a better contact between the specimen and the ceramic disk, and lead to a reduction in the required time to reach equilibration. The time required to reach equilibrium suctions in this study varied between 45 to 800 minutes for specimens of JF soil and between 120 to 750 minutes for specimens of TR soil. The time required for suction equilibration was found to be far greater than that reported by Olson & Langfelder (1965), whereas similar equilibration times have been observed by others (Pufahl 1970; Fredlund & Rahardjo, 1993; Tripathy et al., 2005). For any given compaction type and compaction effort, the equilibration time was found to be reduced due to an increase in the degree of saturation for the soil. In other words, the equilibration time was found to increase with an increase in the suction level (Oliveira & Marinho, 2008).

The down-turn of the time-matric suction curves were not noted in the current study as has been experimentally observed by Pufahl (1970) for the cases where air diffusion through ceramic disk was dominant. Padilla et al. (2006) stated that even at applied air pressure close to the air-entry value, the amount of air diffused through saturated ceramic disks with the air-entry value of 500 kPa was quite small (less than about $0.1\times10^{-6}$ $m^3$/day). The compactness of the soil structure associated with fabric and structure of the statically and the dynamically compacted specimens was manifested on the time-matric suction plots.

#### *6.3.1.1 Relative humidity and temperature of the air pressure chamber*

The relative humidity and the temperature in the air pressure chamber were monitored during some tests. The matric suction test results for four statically light compacted specimens of JF and TR soils are presented in Figs. 6.9 and 6.10 along with the compaction conditions of the soil specimens.

Figures 6.9 and 6.10 showed that the temperature in the pressure chamber remained nearly constant throughout the tests (about 22$^{\circ}$C). The measured relative humidity at the start of the tests was about 70%. Further, the relative humidity increased as the tests progressed or as the applied air pressure was increased during the tests. The relative humidity in the chamber was found to be about 80% after about an elapsed time of 30 minutes and further increased to 95% after about two hours of testing. Note that the relative humidity equilibration depends upon response time of the relative humidity transmitter used. Therefore, the relative humidity data shown in Figs. 6.9 and 6.10 correspond to dynamic ambient conditions within the chamber. Both the response time of the transmitter and an increase in the air pressure were manifested on the relative humidity readings. The relative humidity readings after about 180 minutes remained stable and were found to be higher than 95% in all cases.

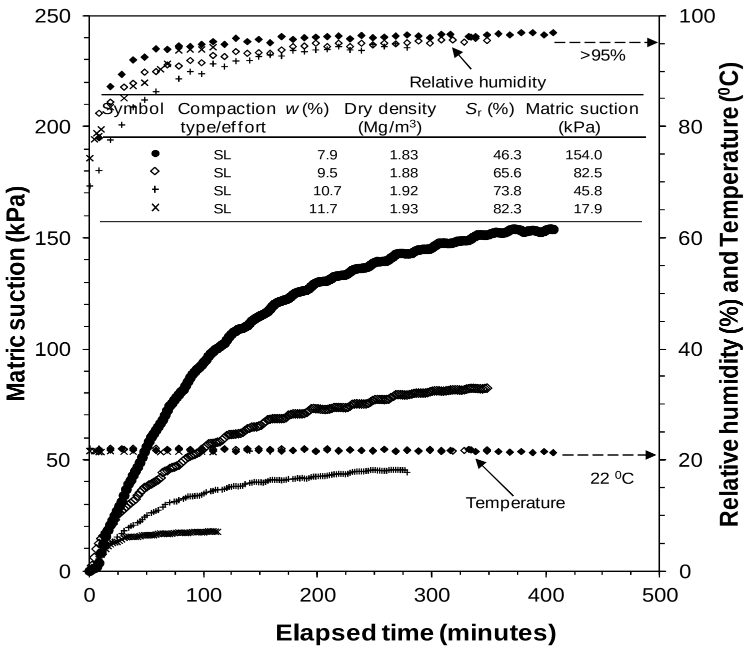



***Fig. 6.9 Relative humidity and temperature of the pressure chamber during null-type tests of light statically compacted JF soil specimens.***

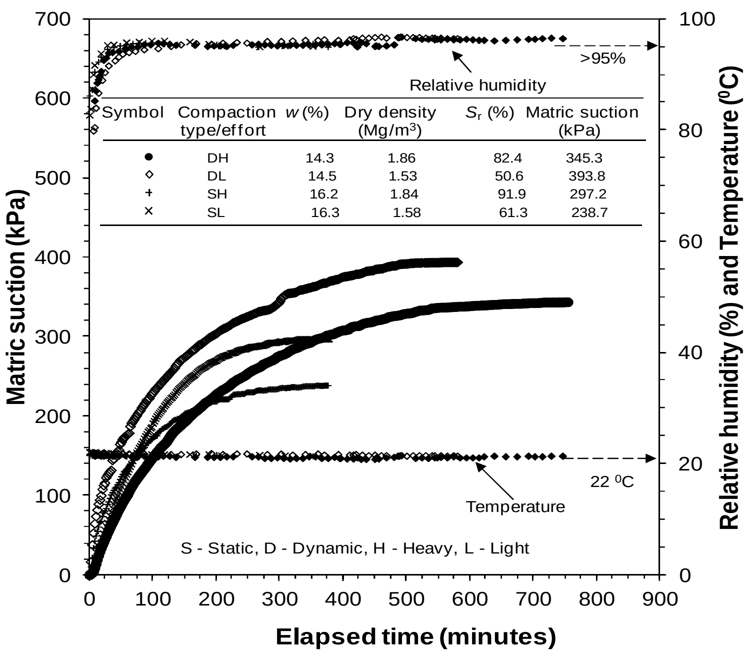



***Fig. 6.10 Relative humidity and temperature of the pressure chamber during null-type tests of compacted TR soil specimens.***

Recalling that an inequality between the relative humidity of soil specimens and the air in the pressure chamber may influence the suction equilibration time (Marinho et al., 2008; Delage et al., 2008), and considering the fact that the water content decrease for the soil specimens tested was insignificant (± 0.07%), it can be stated that drying of soil specimens during the null-type tests may not be held solely responsible for longer suction equilibration time.

### 6.3.2 Influence of compaction conditions on matric suction

The measured matric suction values by null type axis-translation device and the initial conditions for all specimens of JF and TR soils are presented in Tables 6.1 to 6.4. Figures 6.11 to 6.13 show matric suctions of JF and TR soils as influenced by compaction water content, dry density, and degree of saturation. The test results for soil specimens that were tested in order to study the influence of compaction energy and type (i.e., BS-heavy, BS-light, static-heavy, and static-light) are shown in 6.11 to 6.13. The optimum compaction parameter for both light and heavy compaction, such as the OMCs and the corresponding $S_r$ values are shown in the relevant plots.

***Table 6.1 Initial dynamic compaction conditions of JF soil for null-type axis-translation tests***

| No. | Compaction type, effort | Initial compaction conditions | | | | | Matric suction (kPa) |
|---|---|---|---|---|---|---|---|
| | | Specimens notation | Water content (%) | Dry density ($Mg/m^3$) | Void ratio | Degree of saturation (%) | |
| 1 | Dynamic heavy compaction (DH) | JF-DH7.6 | 7.6 | 2.03 | 0.310 | 65.1 | 216.0 |
| 2 | | JF-DH7.6 | 7.6 | 2.03 | 0.310 | 65.1 | 254.0 |
| 3 | | JF-DH7.8 | 7.8 | 2.04 | 0.304 | 68.3 | 178.1 |
| 4 | | JF-DH8.8 | 8.8 | 2.08 | 0.279 | 84.0 | 146.2 |
| 5 | | JF-DH8.9 | 8.9 | 2.08 | 0.279 | 84.9 | 119.0 |
| 6 | | JF-DH9.0 | 9.0 | 2.07 | 0.285 | 84.0 | 126.8 |
| 7 | | JF-DH9.0 | 9.0 | 2.08 | 0.279 | 85.9 | 95.4 |
| 8 | | JF-DH9.0 | 9.0 | 2.08 | 0.279 | 85.9 | 97.8 |
| 9 | | JF-DH9.5 | 9.5 | 2.08 | 0.279 | 90.6 | 100.0 |
| 10 | | JF-DH9.5 | 9.5 | 2.08 | 0.279 | 90.6 | 117.0 |
| 11 | | JF-DH9.7 | 9.7 | 2.07 | 0.285 | 90.5 | 67.4 |
| 12 | | JF-DH9.8 | 9.8 | 2.07 | 0.285 | 91.5 | 67.4 |
| 13 | | JF-DH10.4 | 10.4 | 2.02 | 0.317 | 87.3 | 76.0 |
| 14 | | JF-DH10.7 | 10.7 | 2.00 | 0.330 | 86.3 | 53.0 |
| 15 | | JF-DH10.8 | 10.8 | 2.00 | 0.330 | 87.1 | 55.6 |
| 16 | | JF-DH12.9 | 12.9 | 1.89 | 0.407 | 84.2 | 13.8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 17 | | JF-DL6.8 | 6.8 | 1.77 | 0.503 | 36.0 | 182.0 |
| 18 | | JF-DL7.0 | 7.0 | 1.77 | 0.503 | 37.0 | 206.6 |
| 19 | | JF-DL7.0 | 7.0 | 1.77 | 0.503 | 37.0 | 174.0 |
| 20 | | JF-DL7.2 | 7.2 | 1.79 | 0.486 | 39.4 | 160.8 |
| 21 | | JF-DL7.4 | 7.4 | 1.83 | 0.454 | 43.4 | 200.0 |
| 22 | | JF-DL7.7 | 7.7 | 1.84 | 0.446 | 46.0 | 166.0 |
| 23 | | JF-DL7.7 | 7.7 | 1.85 | 0.438 | 46.8 | 139.0 |
| 24 | Dynamic light compaction (DL) | JF-DL7.8 | 7.8 | 1.84 | 0.446 | 46.6 | 164.0 |
| 25 | | JF-DL8.0 | 8.0 | 1.83 | 0.454 | 46.9 | 115.2 |
| 26 | | JF-DL8.8 | 8.8 | 1.87 | 0.422 | 55.4 | 119.8 |
| 27 | | JF-DL9.0 | 9.0 | 1.89 | 0.407 | 58.8 | 81.8 |
| 28 | | JF-DL9.8 | 9.8 | 1.92 | 0.385 | 67.6 | 55.2 |
| 29 | | JF-DL10.7 | 10.7 | 1.96 | 0.357 | 79.7 | 47.0 |
| 30 | | JF-DL10.8 | 10.8 | 1.94 | 0.371 | 77.4 | 52.0 |
| 31 | | JF-DL11.9 | 11.9 | 1.94 | 0.371 | 85.3 | 24.2 |
| 32 | | JF-DL12.0 | 12.0 | 1.94 | 0.371 | 86.0 | 19.4 |
| 33 | | JF-DL13.0 | 13.0 | 1.90 | 0.400 | 86.5 | 12.2 |
| 34 | | JF-DL13.1 | 13.1 | 1.89 | 0.407 | 85.5 | 7.2 |

***Table 6.2 Initial static compaction conditions of JF soil for null-type axis-translation tests***

| No. | Compaction type, effort | Initial compaction conditions | | | | | Matric suction (kPa) |
|---|---|---|---|---|---|---|---|
| | | Specimens notation | Water content (%) | Dry density ($Mg/m^3$) | Void ratio | Degree of saturation (%) | |
| 35 | | JF-SH7.0 | 7.0 | 1.95 | 0.364 | 51.1 | 243.0 |
| 36 | | JF-SH7.3 | 7.3 | 2.03 | 0.310 | 62.6 | 171.3 |
| 37 | | JF-SH7.4 | 7.4 | 2.02 | 0.317 | 62.1 | 153.5 |
| 38 | | JF-SH7.9 | 7.9 | 2.03 | 0.313 | 67.2 | 107.6 |
| 39 | | JF-SH8.4 | 8.4 | 2.04 | 0.304 | 73.5 | 109.4 |
| 40 | | JF-SH8.6 | 8.6 | 2.03 | 0.310 | 73.7 | 84.5 |
| 41 | | JF-SH8.9 | 8.9 | 2.05 | 0.298 | 79.6 | 83.4 |
| 42 | Static heavy compaction (SH) | JF-SH8.9 | 8.9 | 2.08 | 0.279 | 84.9 | 61.2 |
| 43 | | JF-SH8.7 | 9.7 | 2.03 | 0.310 | 83.1 | 51.4 |
| 44 | | JF-SH10.4 | 10.4 | 2.03 | 0.310 | 89.1 | 39.2 |
| 45 | | JF-SH10.7 | 10.7 | 2.02 | 0.317 | 89.8 | 43.5 |
| 46 | | JF-SH10.8 | 10.8 | 2.01 | 0.323 | 88.8 | 32.4 |
| 47 | | JF-SH12.0 | 12.0 | 1.96 | 0.357 | 89.4 | 18.3 |
| 48 | | JF-SH12.1 | 12.1 | 1.96 | 0.357 | 90.1 | 19.3 |
| 49 | | JF-SH13.0 | 13.0 | 1.91 | 0.393 | 88.1 | 10.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 50 | Static intermediate compaction (SM) | JF-SM7.8 | 7.8 | 1.93 | 0.378 | 54.6 | 154.0 |
| 51 | | JF-SM8.1 | 8.1 | 1.94 | 0.371 | 58.1 | 102.0 |
| 52 | | JF-SM8.7 | 8.7 | 1.96 | 0.357 | 64.8 | 87.0 |
| 53 | | JF-SM9.1 | 9.1 | 1.99 | 0.337 | 71.9 | 108.5 |
| 54 | | JF-SM9.5 | 9.5 | 2.00 | 0.330 | 76.6 | 84.6 |
| 55 | | JF-SM9.7 | 9.7 | 2.00 | 0.330 | 78.2 | 62.8 |
| 56 | | JF-SM9.8 | 9.8 | 1.99 | 0.337 | 77.4 | 81.2 |
| 57 | | JF-SM10.0 | 10.0 | 2.00 | 0.330 | 80.6 | 61.0 |
| 58 | | JF-SM10.5 | 10.5 | 2.00 | 0.330 | 84.6 | 32.4 |
| 59 | | JF-SM10.7 | 10.7 | 1.92 | 0.385 | 73.9 | 45.8 |
| 60 | Static light compaction (SL) | JF-SL6.6 | 6.6 | 1.79 | 0.486 | 36.1 | 220.0 |
| 61 | | JF-SL6.8 | 6.8 | 1.78 | 0.494 | 36.6 | 166.2 |
| 62 | | JF-SL7.6 | 7.6 | 1.85 | 0.438 | 46.2 | 113.1 |
| 63 | | JF-SL7.8 | 7.8 | 1.84 | 0.446 | 46.6 | 125.4 |
| 64 | | JF-SL8.1 | 8.1 | 1.83 | 0.454 | 47.5 | 90.3 |
| 65 | | JF-SL8.7 | 8.7 | 1.90 | 0.401 | 57.8 | 74.2 |
| 66 | | JF-SL8.9 | 8.9 | 1.88 | 0.415 | 57.1 | 66.3 |
| 67 | | JF-SL9.1 | 9.1 | 1.89 | 0.407 | 59.4 | 53.0 |
| 68 | | JF-SL9.1 | 9.1 | 1.89 | 0.407 | 59.4 | 69.2 |
| 69 | | JF-SL9.6 | 9.6 | 1.94 | 0.371 | 68.8 | 32.8 |
| 70 | | JF-SL9.7 | 9.7 | 1.92 | 0.385 | 67.0 | 41.4 |
| 71 | | JF-SL9.7 | 9.7 | 1.94 | 0.371 | 69.5 | 33.6 |
| 72 | | JF-SL10.0 | 10.0 | 1.95 | 0.364 | 73.1 | 27.0 |
| 73 | | JF-SL10.2 | 10.2 | 1.95 | 0.364 | 74.5 | 26.2 |
| 74 | | JF-SL10.8 | 10.8 | 1.95 | 0.364 | 78.9 | 28.2 |
| 75 | | JF-SL10.8 | 10.8 | 1.98 | 0.343 | 83.7 | 33.7 |
| 76 | | JF-SL11.7 | 11.7 | 1.93 | 0.378 | 82.3 | 17.9 |
| 77 | | JF-SL12.1 | 12.1 | 1.94 | 0.371 | 86.7 | 15.4 |
| 78 | | JF-SL12.8 | 12.8 | 1.88 | 0.415 | 82.1 | 12.2 |
| 79 | | JF-SL12.9 | 12.9 | 1.89 | 0.407 | 84.2 | 13.8 |

***Table 6.3 Initial dynamic compaction conditions of TR soil for Null-type axis-translation tests***

| No. | Compaction type, effort | Initial compaction conditions | | | | | | Matric suction (kPa) |
|---|---|---|---|---|---|---|---|---|
| | | Specimens notation | Water content (%) | Dry density (Mg/m$^3$) | Void ratio | Degree of saturation (%) | | |
| 1 | Dynamic heavy compaction (DH) | TR-DH14.2 | 14.2 | 1.85 | 0.474 | 81.8 | | 362.0 |
| 2 | | TR-DH14.3 | 14.3 | 1.87 | 0.462 | 84.2 | | 345.3 |
| 3 | | TR-DH15.0 | 15.0 | 1.85 | 0.473 | 86.5 | | 257.8 |
| 4 | | TR-DH15.7 | 15.7 | 1.83 | 0.491 | 86.9 | | 231.7 |
| 5 | | TR-DH17.0 | 17.0 | 1.75 | 0.554 | 83.6 | | 113.0 |
| 6 | | TR-DH17.6 | 17.6 | 1.76 | 0.552 | 87.0 | | 92.8 |
| 7 | | TR-DH18.2 | 18.2 | 1.75 | 0.558 | 89.0 | | 81.6 |
| 8 | | TR-DH19.3 | 19.3 | 1.70 | 0.604 | 87.2 | | 79.0 |
| 9 | | TR-DH23.7 | 23.7 | 1.64 | 0.662 | 97.4 | | 17.0 |
| 10 | Dynamic light compaction (DL) | TR-DL13.7 | 13.7 | 1.51 | 0.805 | 46.4 | | 488.0 |
| 11 | | TR-DL14.5 | 14.5 | 1.56 | 0.747 | 52.9 | | 356.2 |
| 12 | | TR-DL14.5 | 14.5 | 1.53 | 0.782 | 50.6 | | 393.8 |
| 13 | | TR-DL14.7 | 14.7 | 1.50 | 0.822 | 48.6 | | 359.0 |
| 14 | | TR-DL15.0 | 15.0 | 1.58 | 0.725 | 56.4 | | 281.9 |
| 15 | | TR-DL15.3 | 15.3 | 1.55 | 0.759 | 55.0 | | 298.3 |
| 16 | | TR-DL17.2 | 17.2 | 1.63 | 0.672 | 69.7 | | 140.9 |
| 17 | | TR-DL17.6 | 17.6 | 1.63 | 0.670 | 71.6 | | 106.9 |
| 18 | | TR-DL17.7 | 17.7 | 1.64 | 0.662 | 72.7 | | 105.7 |
| 19 | | TR-DL19.4 | 19.4 | 1.64 | 0.662 | 79.9 | | 89.0 |
| 20 | | TR-DL20.5 | 20.5 | 1.68 | 0.623 | 89.8 | | 44.0 |
| 21 | | TR-DL23.5 | 23.5 | 1.59 | 0.714 | 89.7 | | 23.5 |
| 22 | | TR-DL24.0 | 24.0 | 1.57 | 0.736 | 88.9 | | 14.3 |

***Table 6.4 Initial static compaction conditions of TR soil for Null-type axis-translation tests***

| No. | Compaction type, effort | Initial compaction conditions | | | | | Matric suction (kPa) |
|---|---|---|---|---|---|---|---|
| | | Specimens notation | Water content (%) | Dry density ($Mg/m^3$) | Void ratio | Degree of saturation (%) | |
| 23 | Static heavy compaction (SH) | TR-SH14.8 | 14.8 | 1.87 | 0.46 | 87.7 | 435.9 |
| 24 | | TR-SH16.2 | 16.2 | 1.84 | 0.48 | 91.9 | 297.2 |
| 25 | | TR-SH17.0 | 17.0 | 1.82 | 0.50 | 93.1 | 252.1 |
| 26 | | TR-SH17.9 | 17.9 | 1.78 | 0.53 | 91.8 | 166.6 |
| 27 | | TR-SH18.2 | 18.2 | 1.79 | 0.52 | 95.2 | 116.0 |
| 28 | | TR-SH19.3 | 19.3 | 1.74 | 0.57 | 92.6 | 106.0 |
| 29 | | TR-SH19.8 | 19.8 | 1.73 | 0.58 | 93.2 | 77.6 |
| 30 | | TR-SH21.2 | 21.2 | 1.68 | 0.62 | 93.6 | 55.4 |
| 31 | | TR-SH21.8 | 21.8 | 1.68 | 0.63 | 95.1 | 29.3 |
| 32 | | TR-SH22.2 | 22.2 | 1.68 | 0.63 | 96.5 | 24.1 |
| 33 | | TR-SH23.2 | 23.2 | 1.61 | 0.69 | 91.2 | 33.7 |
| 34 | Static heavy compaction (SL) | TR-SL15.7 | 15.7 | 1.54 | 0.78 | 55.2 | 303.2 |
| 35 | | TR-SL15.9 | 15.9 | 1.56 | 0.75 | 58.1 | 258.3 |
| 36 | | TR-SL16.3 | 16.3 | 1.62 | 0.68 | 65.1 | 235.4 |
| 37 | | TR-SL16.3 | 16.3 | 1.58 | 0.73 | 61.3 | 238.7 |
| 38 | | TR-SL17.2 | 17.2 | 1.59 | 0.71 | 65.6 | 196.5 |
| 39 | | TR-SL18.4 | 18.4 | 1.65 | 0.65 | 76.9 | 106.0 |
| 40 | | TR-SL19.0 | 19.0 | 1.67 | 0.63 | 81.9 | 116.5 |
| 41 | | TR-SL19.2 | 19.2 | 1.69 | 0.62 | 85.0 | 94.3 |
| 42 | | TR-SL19.3 | 19.3 | 1.65 | 0.65 | 80.6 | 94.7 |
| 43 | | TR-SL19.4 | 19.4 | 1.67 | 0.63 | 83.4 | 87.5 |
| 44 | | TR-SL21.2 | 21.2 | 1.67 | 0.63 | 91.0 | 48.3 |
| 45 | | TR-SL23.9 | 23.9 | 1.58 | 0.72 | 90.1 | 16.0 |

#### *6.3.2.1 Water content versus matric suction relationship*

In spite of some scatter in the test data due to the test results of some soil specimens out of 79 specimens of JF soil and 45 specimens of TR soil tested in total, particularly for the compaction conditions intermediately between BS-heavy and BS-light JF soil compaction curves, in general, the trends were distinct. An increase in the water content caused a decrease matric suction of the soil specimens (Figs. 6.11). The measured matric suctions were found to be not very sensitive to compaction effort for any given compaction type; however, the type of compaction influenced the measured suctions, particularly between the water contents of about 7.5 to 11% and between 14 to 19% for specimens of JF and TR soils, respectively.

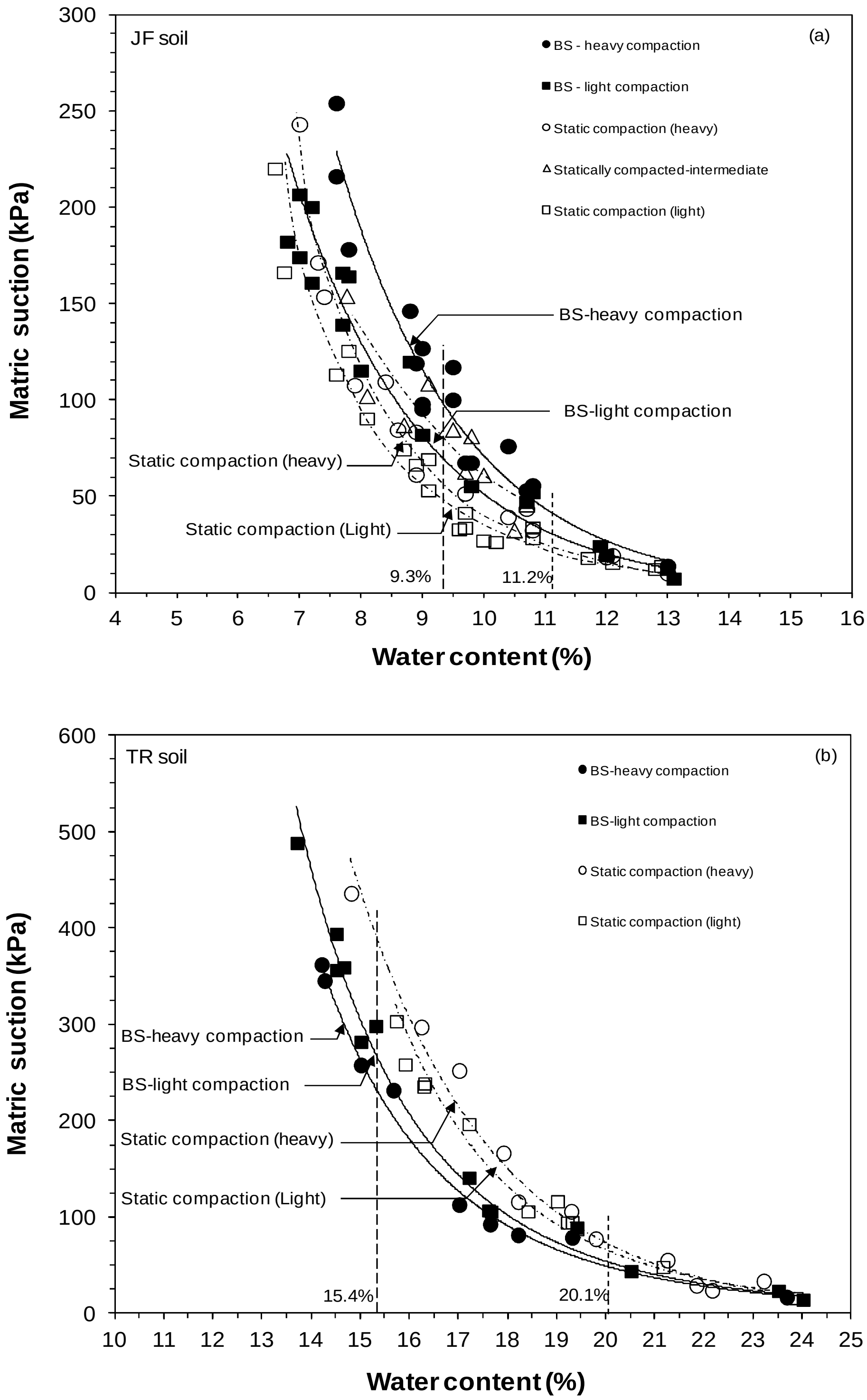



***Fig. 6.11 Water content versus matric suction plot for the (a) JF soil specimens and (b) TR soil specimens tested in this study.***

For both soils, the test results for dry of optimum water contents show a sharp increase in suction with a slight decrease in the water content. For instance, an increase in matric suction was about 25% for decrease in the water content of about 0.2% for specimens JF-DL7.0 and JF-DL7.2 (Table 6.1), and for specimens JF-SL6.6 and JF-SL6.8. Similarly, a difference in the matric suction was 112 kPa between specimens TR-DL14.5 and TR-DL15.0. Suctions of the specimens of TR soil were distinctly higher than those of specimens of JF soil.

*6.3.2.1.1 Effect of specimen size*

In order to investigate the influence of specimen size on the measured matric suction, a number of additional tests on larger diameter specimens (80 mm) were carried out. Only statically compacted specimens from both soils were used in this phase of the investigation.

Water content versus suction tests results for both soils for heavy and light compaction efforts are presented in Figs. 6.12*a* and *b*. It can be seen from the test results shown in Figs. 6.12*a* that an increase in the diameter of specimens of JF soil had a negligible effect on the measured matric suctions for both compaction efforts. However, statically compacted specimens of TR soil with light compaction effort showed an increase in the measured matric suctions as the diameter of the specimens increased, particularly for dry of optimum specimens. The measured matric suction increased from 196.5 to 276.6 kPa for the specimen of TR soil compacted at water content of 17.2%, whereas for the specimen compacted at water content of 15.8%, the measured matric suction increased by about 45%. It appears from the test results that the impact of size of the specimens on matric suction depends on the soil type and initial compaction water content.

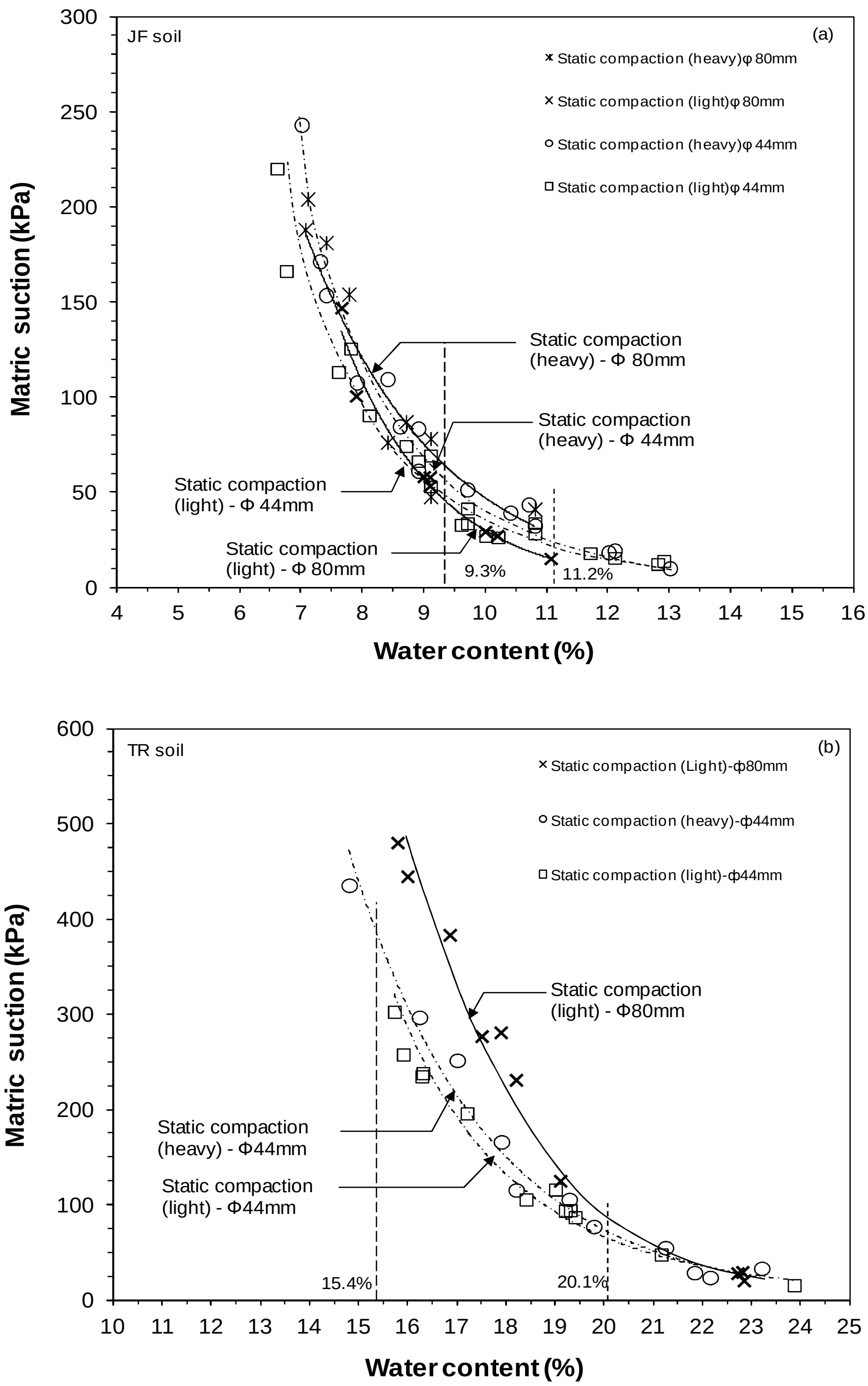



***Fig. 6.12 Influence of size of specimens on matric suction***

***(a) JF soil and (b) TR soil***

### *6.3.2.2 Degree of saturation-matric suction relationship*

The combined influence of an increase in the water content and variation of the dry density due to compaction was found to be manifested on the degree of saturation versus suction plots (Figs. 6.13*a* and *b*). Considering that the chosen specimen conditions on the wet-side of OMCs were between the degree of saturation of about 85 and 95% and that such a variation in the degree of saturation has only a minor influence on the fabric and structure of the soil, the trend curves were drawn for specimens tested under various compaction type and effort in Figs. 6.13*a* and *b*. The test results clearly indicated that at any degree of saturation, matric suction of the both soils increased with an increase in the compaction effort. For the specimens of JF and TR soils that were prepared by applying heavy compaction energy (both statically and dynamically compacted specimens), a decrease in the matric suction was found to be abrupt between the degree of saturation of 85 and 95%. On the other hand, matric suction decrease was gradual with an increase in the degree of saturation for soil specimens that were prepared by applying light compaction energy.

For very wet soil specimens (i.e., on the wet-side of OMC), the measured matric suctions varied between 10 to 25 kPa, and between 16 to 34 kPa for JF and TR soil specimens, respectively. On the other hand, for very dry soil specimens matric suction remained between 174 to 243 kPa, and between 345 to 488 kPa for JF and TR soil specimens, respectively.

In general, Figs. 6.7 to 6.13 showed that specimens prepared using dynamic and static compaction methods resulted in a different soil structure or fabric of the compacted specimens. This difference in soil fabric and structure was reflected both in the time-suction plots and on the measured matric suctions.

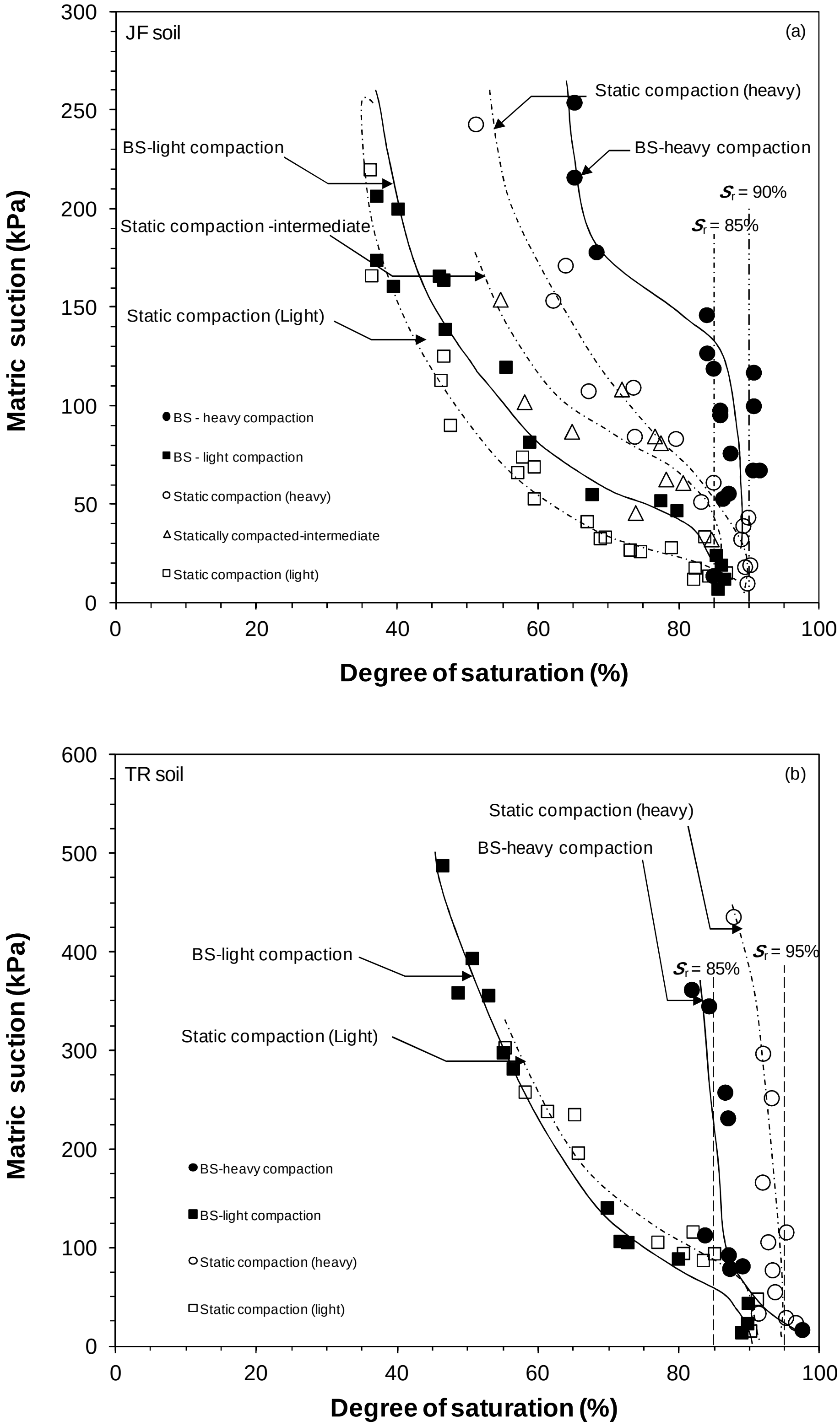



***Fig. 6.13 Degree of saturation versus matric suction plot for (a) JF soil specimens and (b) TR soil specimens tested in this study.***

### *6.3.2.3 Influence of compaction density on matric suction*

To study the influence of initial dry density on matric suction, the test results of soil specimens compacted at similar compaction water content and dry density values ranging between 1.65 to 20.8 Mg/m$^3$ for JF soil and 1.5 to 1.83 Mg/m$^3$ for TR soil are shown in Figs. 6.14 and 6.15. The void ratios versus matric suction plot for each soil are shown in Figs. 6.14 and 6.15.

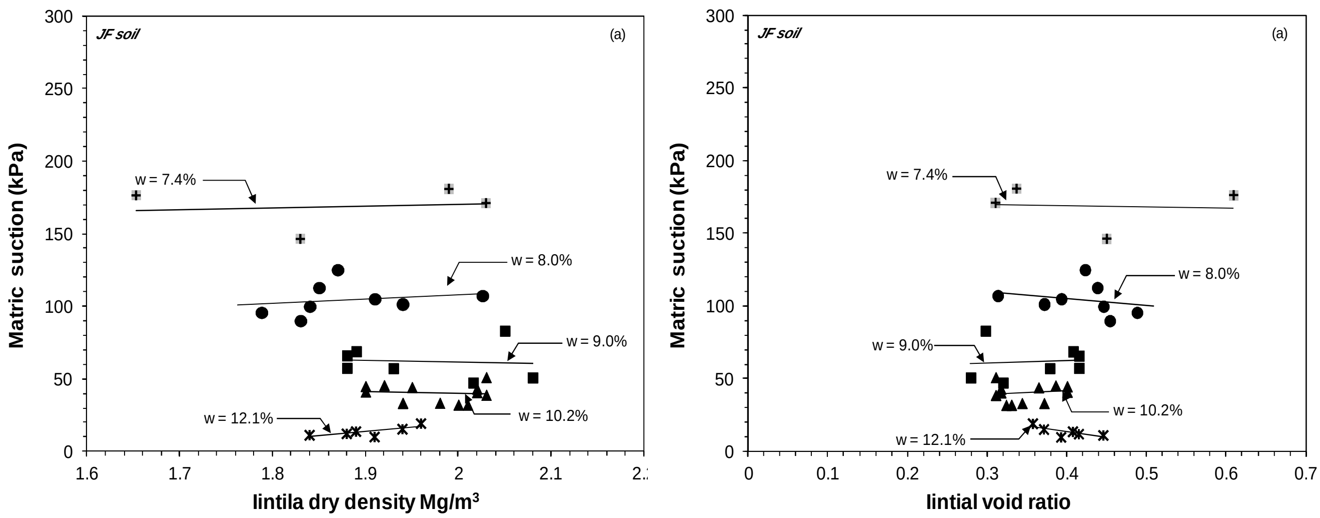



*Fig. 6.14 Influence of compaction density on matric suction for JF soil.*

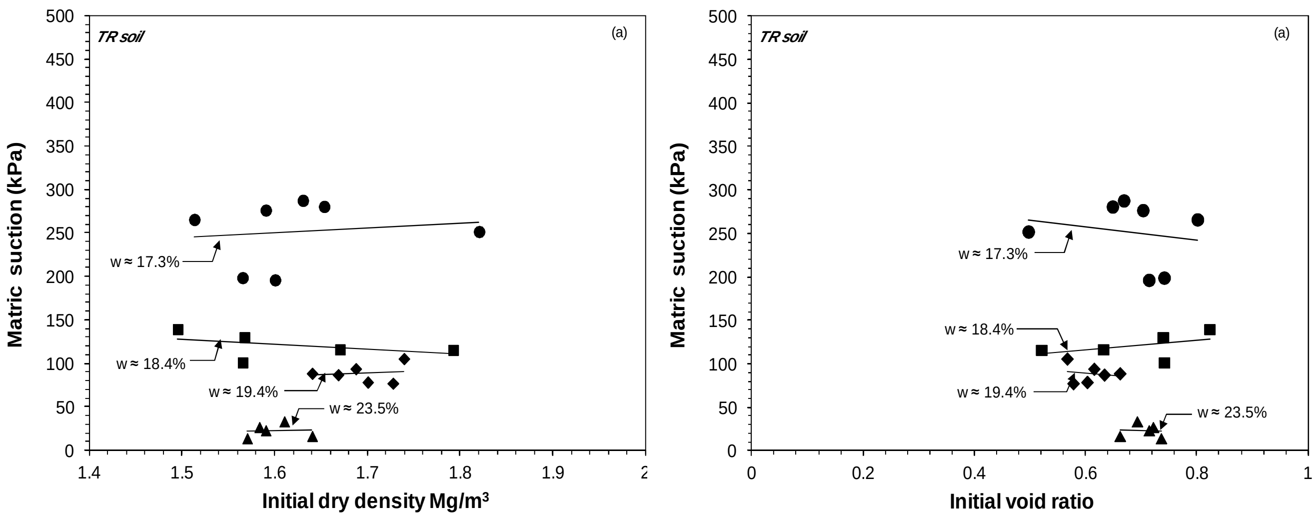



*Fig. 6.15 Influence of compaction density on matric suction for TR soil.*

The results presented in Figs.6.14 and 6.15 showed that the dry density may have a slight influence on suction depending on the water content level. This could be due to a combined effect of the void size and water mass within the soils. However, the changes in suction due to the differences in the dry density are relatively small. The test results indicated that the matric suction is mainly a function of the compaction water content with some minor effects of the dry density and the compaction techniques for the soils tested in this study.

## 6.4 Concluding remarks

Suction measurements were carried out on both soils using null-type axis-translation technique. The influences of initial compaction conditions, soil type, compaction type, compaction effort, and specimen size on suction were brought out. The test results clearly revealed the following:

- The equilibration time in null-type tests was found to be dependent upon the initial compaction conditions of the soil. Longer equilibrium times were observed for dry of optimum specimens as compared to wet of optimum specimens for both soils (JF and TR).
- Monitoring the relative humidity and the temperature in the air pressure chamber during the null-type tests indicated that drying of soil specimens may not be held solely responsible for longer suction equilibration time.
- In general, the measured suctions were found to be dependent on the water content, with some influence of dry density and compaction method. The influence of dry density on suction was found to be dependent upon the water content level.
- Soil with higher percentage of clay fractions (TR soil) tends to give higher soil suction values than less percentage of clay fractions (JF soil).

# CHAPTER 7

# VERIFICATION OF CONTINUITY IN WATER PHASE IN NULL-TYPE AXIS-TRANSLATION TEST

## 7.1 Introduction

The axis-translation approach is one of the laboratory techniques used to measure/control matric suction of soils. The measurement of matric suction using the axis-translation technique is limited by the air entry value of the ceramic disk used. Continuity of the air phase within the soil specimen is crucial in order to obtain reliable results. Similarly, continuity between the water in the soil specimen, the water in the ceramic disk, and the water in the compartment below the ceramic disk is necessary in order to correctly establish the matric suction.

The scientific basis of the axis-translation technique is that since both the pore fluid and the soil solids can be assumed incompressible, under undrained condition and for any applied air pressure increase within the pores of unsaturated soil systems that possess sufficient continuity of the air phase, there will be a corresponding increase of the pore-water pressure (Hilf, 1956; Fredlund & Rahardjo, 1993). Therefore, the difference between the applied air pressure and the pore-water pressure (i.e., matric suction) remains constant regardless of the translation of both the pore-air and pore-water pressures.

## ***CHAPTER 7 – VERIFICATION OF CONTINUITY IN WATER PHASE IN NULL-TYPE AXIS-TRANSLATION TEST***

It is generally assumed that the pre-requisite conditions (i.e., continuity in water and air phase) persist during axis-translation tests. However, very limited studies have devoted to provide any evidence of water phase continuity during the tests.

The combined influence of the presence of the diffused air in the water compartment, the expansion of the water compartment, and the compressibility of the air-water mixture can be studied by monitoring the pore-water pressure change due to an increase in the chamber air pressure at the end of suction measurement. The main objective of this chapter was to study in detail continuity in the water phase between soil specimens, the water in the ceramic disk, and the water in the compartment during null-type axis-translation tests via a series of laboratory tests using the null-type device.

The coefficient of permeability of the ceramic disk in null-type device is first presented followed by the test results from the water phase continuity tests, additional tests to verify the water phase continuity without soil specimens, and the test results with various interfaces. The concluding remarks are presented towards the end of the chapter.

### 7.2 Permeability of high air-entry ceramic disk

The saturated coefficient of permeability of the ceramic disk was measured and compared with the manufacturer value to ensure saturation. After the saturation process, the pressure chamber was assembled and filled with distilled and de-aired water until the surface of the ceramic disk was inundated. The inflow valve was closed and the water flow volume was measured by an advanced pressure/volume controllers. Four different pressures were chosen to create different hydraulic heads. The thickness and the diameter of the high-air entry ceramic disk was 7.59 mm and 80.21 mm, respectively. The permeability of the disk was calculated using Darcy's law (Darcy, 1856) given with the following equation:

$$k \quad = \frac{Vw}{At}\frac{h}{H} \qquad \text{(Eq. 7.1)}$$

where, *k* is the permeability of the ceramic disk in *m/s*, *Vw* is the water volume discharge in $m^3$, *A* is the cross sectional area of the ceramic disk in $m^2$, *t* is the time in *s*, *h* is the thickness of the ceramic disk in *m* and *H* is the hydraulic head in *m*.

Table 7.1 shows the applied water pressures, the applied hydraulic gradients, the outflow rates obtained, and the corresponding saturated coefficients of permeability of the 5-bar ceramic disk. The average saturated coefficient permeability of the disk used was found to be $3.88 \times 10^{-10}$ m/s. A difference was noted between the saturated coefficient permeability specified by the manufacturer ($1.21 \times 10^{-9}$ m/s) and the measured values in this study. The saturated coefficient permeability of the ceramic disk in this study was found to be similar to the value reported by Leong et al. (2004) for ceramic disks with the air-entry value of 500 kPa ($1.68 \times 10^{-10}$ m/s).

***Table 7.1 Coefficient of permeability of the ceramic disk (approximate porosity = 31 %)***

| Applied water pressure, kPa (1) | Applied hydraulic gradient (2) | Flow rate[a], $\times 10^{-6}$ $m^3/s$ (3) | Saturated coefficient of permeability, m/s (4) |
|---|---|---|---|
| 100 | 1346 | 0.0028 | $4.01 \times 10^{-10}$ |
| 200 | 2688 | 0.0052 | $3.87 \times 10^{-10}$ |
| 300 | 4033 | 0.0078 | $3.85 \times 10^{-10}$ |
| 400 | 5375 | 0.0103 | $3.84 \times 10^{-10}$ |
| 500 | 6716 | 0.0129 | $3.83 \times 10^{-10}$ |

[a] average of ten time intervals.

## 7.3 Water phase continuity verification tests

All specimens of JF soil selected for the verification tests were statically compacted to various dry densities and water contents. On the other hand, both dynamically and statically compacted specimens of TR soil were used for the verification tests. Additionally, in order to investigate the water phase continuity in more detail, two different sizes of soil specimens (44 mm and 80 mm dia.) were tested.

The degree of saturation of soil specimens tested under this testing program varied between 30 to 96%. Matric suctions of the soil specimens were first measured using the null-type axis-translation device. Further, the chamber pressure was increased monotonically until the total air pressure was about 400 kPa. For each increment of air pressure, the corresponding increase in the water pressure below the ciermaic disk was measured. In all cases, for each increment of air pressure, the air pressure was held constant for 30 mins. Additionally, in some cases a longer time was allowed at each applied chamber pressure in order to study the response of the water pressure transducer.

Figure 7.1 shows typical test results of specimens of JF soil for applied chamber air pressures versus water pressures measured in the water compartment below the ceramic disk. The test results for three specimens are shown that had equilibrium matric suctions of 29.0, 51.4, and 188.8 kPa. The compaction conditions of the specimens are shown in Fig. 7.1. The ratio between the changes in the water pressure for any applied air pressure increment (i.e., $\Delta u_w/\Delta u_a$, where $\Delta u_w$ = change in the water pressure and $\Delta u_a$ = change in the air pressure) for all chamber air pressure increments are shown in Fig. 7.1. The elapsed times prior to increasing the chamber air pressure for each pressure increment are shown within brackets. For example in Fig. 7.1, the chamber air pressure was held constant at predetermined values for about 30 minutes for the initial two pressure increments and the pore water pressures were measured. For ideal conditions, where the chamber air pressure increase will directly get reflected on the water pressure increase, a line of equality (shown as a dotted line in Fig. 7.1) making an angle $45^{\circ}$ to the horizontal can be obtained (Hilf, 1956; Olson & Langfelder, 1965). In other words, if continuity in the water phase exists for soil specimens, this would in turn yield lines parallel to the line of equality.

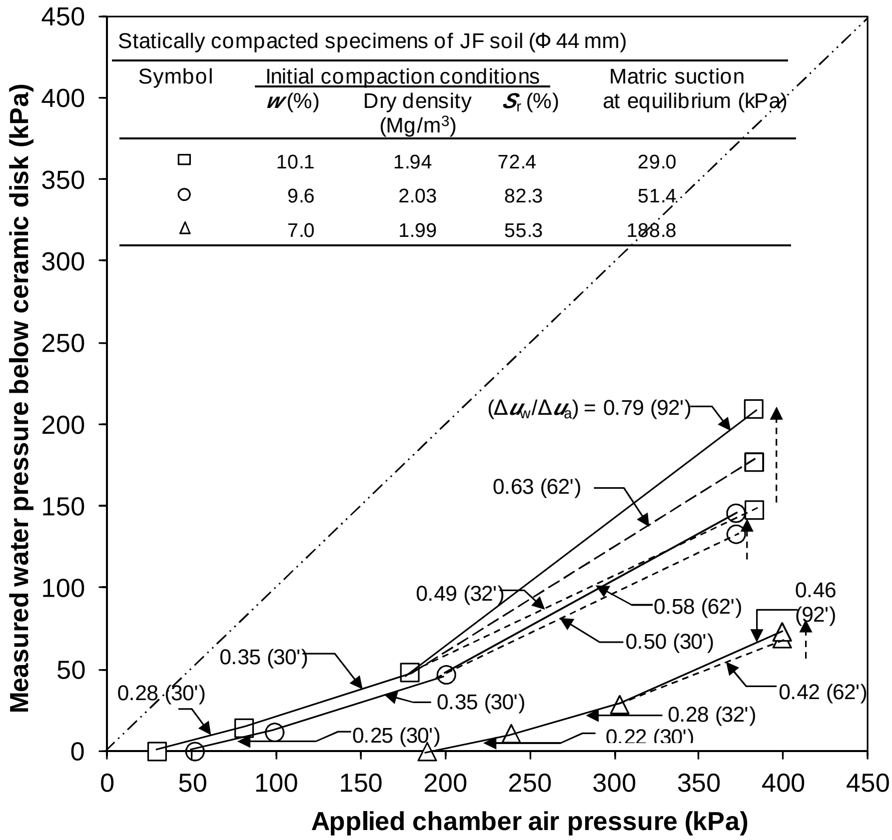



***Fig. 7.1 Time effect on pore water pressure transducer response for JF soil.***

Differences were noted between the measured water pressures for any increase in the chamber air pressure for all cases shown in Fig. 7.1 and for all other specimens tested under this testing program. This in turn affected the $\Delta u_w/\Delta u_a$ values. In Fig. 7.1, the ratio, $\Delta u_w/\Delta u_a$, was found to be the least for all cases during the first increment of the applied air pressure (i.e., about 0.25), whereas it increased during the successive air pressure increments. Additionally, it was noted that the time allowed at each air pressure steps improved the value of $\Delta u_w/\Delta u_a$. The values of $\Delta u_w/\Delta u_a$ for the last incremental applied chamber air pressures at elapsed times about 60 and 90 mins are shown in Fig. 7.1. The results showed that for the specimen that had matric suction of 29 kPa, the ratio increased from 0.49 for an elapsed time of 32 mins to 0.79 for a cumulative elapsed time of 92 mins. On the other hand, for the other two specimens in Fig. 7.1, an increase in the water pressure with an increase in the elapsed time was less (i.e., 0.50 to 0.58 for specimen with matric suction of 51.4 kPa and 0.42 to 0.46 for specimen with matric suction of 188.8 kPa).

The degree saturation versus $\Delta u_w/\Delta u_a$ results are plotted for all the specimens tested for both soil in Figs. 7.2*a* and 7.2*b*. The test results for specimens with diameter 44 mm and 80 mm are presented in Figs 7.2*a* and 7.2*b*. The test results are for a predetermined allocated time of 30 minutes at each air pressure increment steps. Since $\Delta u_w/\Delta u_a$ was found to vary due to the magnitude of the applied chamber pressure, an average $\Delta u_w/\Delta u_a$ value was obtained for all applied chamber pressure steps by best-fitting the data with linear relationships. In most cases, the coefficient of regression was 0.85 and higher. The test results shown in Figs. 7.2*a* and 7.2*b* clearly indicated that although equilibrium was attained during the measurement of matric suction; however, the water phase continuity was lacking for all the specimens tested. $\Delta u_w/\Delta u_a$ was found to increase with an increase in the degree of saturation. For JF soil specimens, the maximum value of $\Delta u_w/\Delta u_a$ was 0.97 (water content = 13.0%, dry density = 1.92 $Mg/m^3$, and matric suction = 10.0 kPa), whereas the least value obtained was 0.30 (water content = 7.6%, dry density = 1.85 $Mg/m^3$, and matric suction = 113.1 kPa). Similarly, the maximum value of $\Delta u_w/\Delta u_a$ for TR soil specimens was 0.97 (water content = 24.0%, dry density = 1.57 $Mg/m^3$, and matric suction = 14.3 kPa), whereas the least value obtained was 0.34 (water content = 15.9 %, dry density = 1.56 $Mg/m^3$, and matric suction = 258.3 kPa).

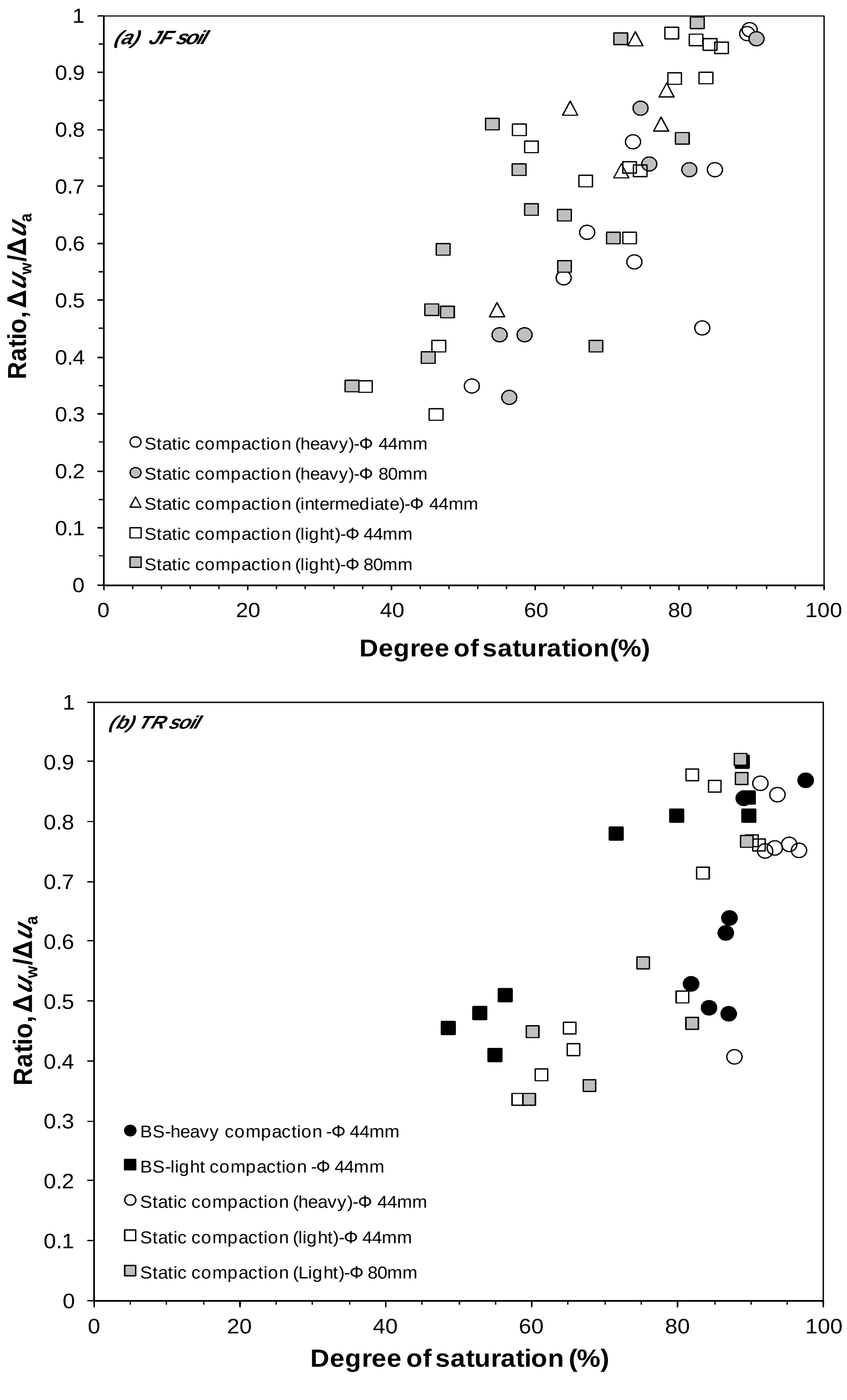
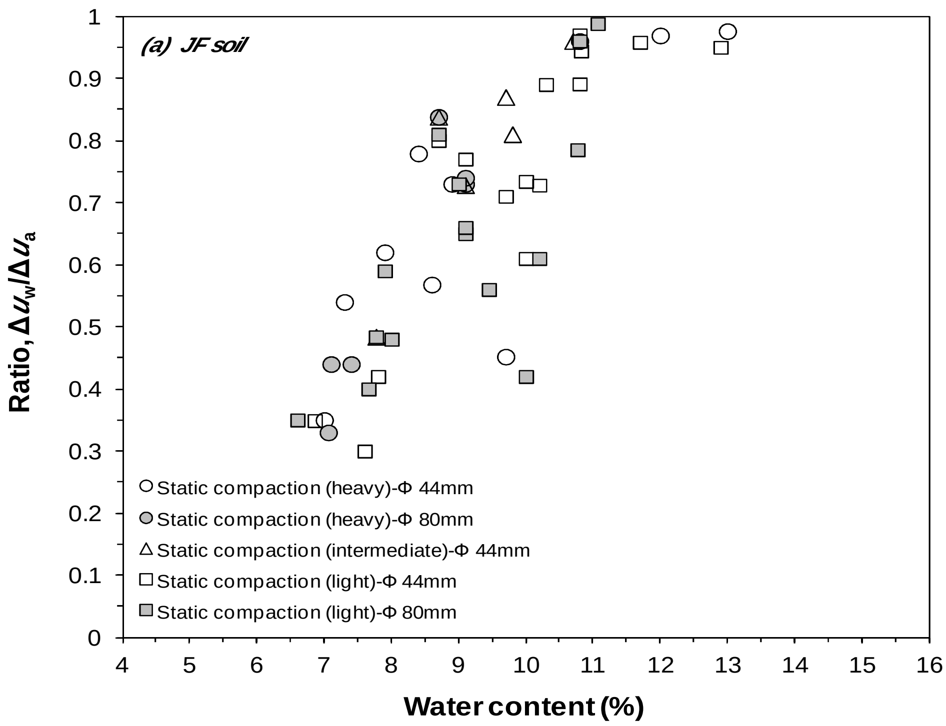



***Fig. 7.2 Influence of degree of saturation on the ratio, $\Delta u_w/\Delta u_a$ for (a) JF soil and (b) TR soil.***

# ***CHAPTER 7 – VERIFICATION OF CONTINUITY IN WATER PHASE IN NULL-TYPE AXIS-TRANSLATION TEST***

A pressure difference between the air and water phases is associated with the existence of a curved air-water interface with its concave side facing towards the phase that possesses a higher pressure (Lu & Likos, 2004). If drainage from the water compartment is allowed during tests involving the axis-translation technique and the chamber air pressure is increased (viz., pressure plate tests), an initially flat water surface in the saturated pores of the disk becomes curved due to retreat of the air-water interface inwards from the surface of the disk (Soilmoisture Equipment Corporation 2011). On the other hand, if drainage from the water compartment is not permitted, the air-water interface may retreat into the pores of the disk only under some specific conditions, such as due to expansion of the water compartment and compression of air-water mixture following an increase in the water pressure, and evaporation of water from the surface of the ceramic disk. Considering that air diffusion rate in case of ceramic disks with the air-entry value of 500 kPa is small (Padilla et al., 2006), the test results presented in Figs. 7.2 indicated that the water pressure increase did not comply to an increase in the chamber air pressure primarily on account of the existence of curved air-water interfaces in the pores of the ceramic disk. Therefore, a pressure drop across the ceramic disk was compensated by surface tension at the ceramic-air-water interface. An increase in the values of $\Delta u_w/\Delta u_a$ due to an increase in the chamber air pressure and elapsed time (Fig. 7.1) is attributed to the flow of soil pore water into the pores of the ceramic disk that in turn partially reduced the surface tension effect.

Figures 7.3*a* and 7.3*b* show the water content versus $\Delta u_w/\Delta u_a$ plot for the specimens of JF and TR soils. The results clearly indicated that an increase in the degree of saturation due to an increase in the water content created a better continuity in the water phase between the water in the soil specimens, the water in the ceramic disk, and the water in the compartment. The test results presented in Figs. 7.2 and 7.3 also indicate a slight improvement in the water phase continuity as the diameter of the specimens increased from 44 mm to 80 mm.



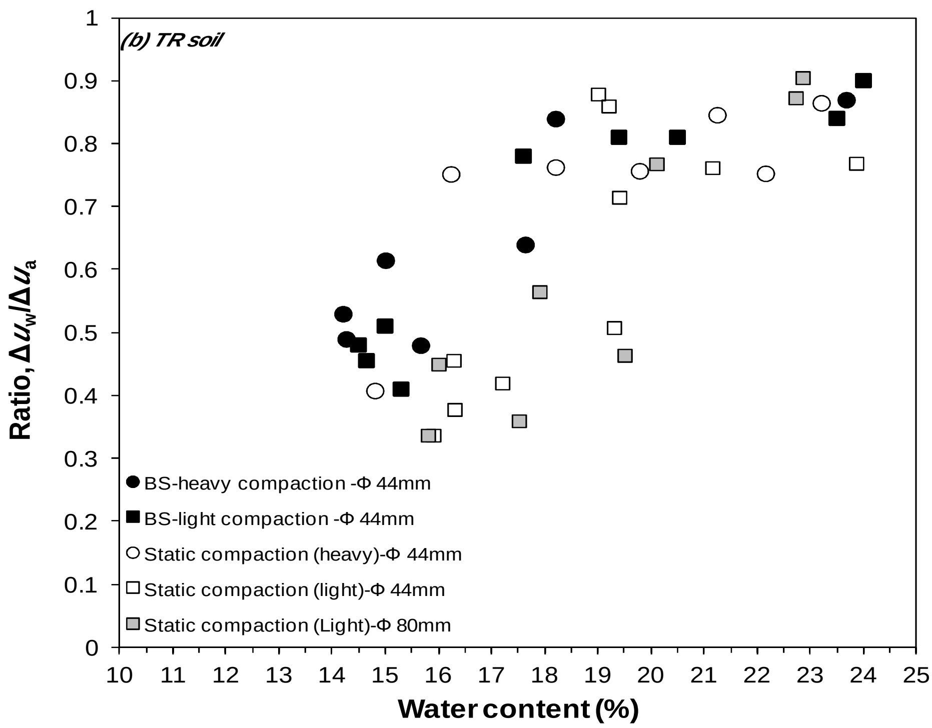




***Fig. 7.3 Influence of water content on the ratio, $\Delta u_w/\Delta u_a$ for (a) JF soil and (b) TR soil***

## 7.4 Additional tests

In an attempt to improve continuity in the water phase during null-type axis-translation tests, a more detailed investigation was undertaken in which a number of additional tests were carried out. Under this testing program, tests were carried out without any soil specimens and with soil specimens on the ceramic disk. For the former, the chamber air pressure was increased on the saturated ceramic disk for the conditions with and without any water being present above the ceramic disk. Additionally, a test was performed by placing a wet filter paper (Whatman Grade 5) on the ceramic disk and further the chamber air pressure was increased. The test results are shown in Fig. 7.4.

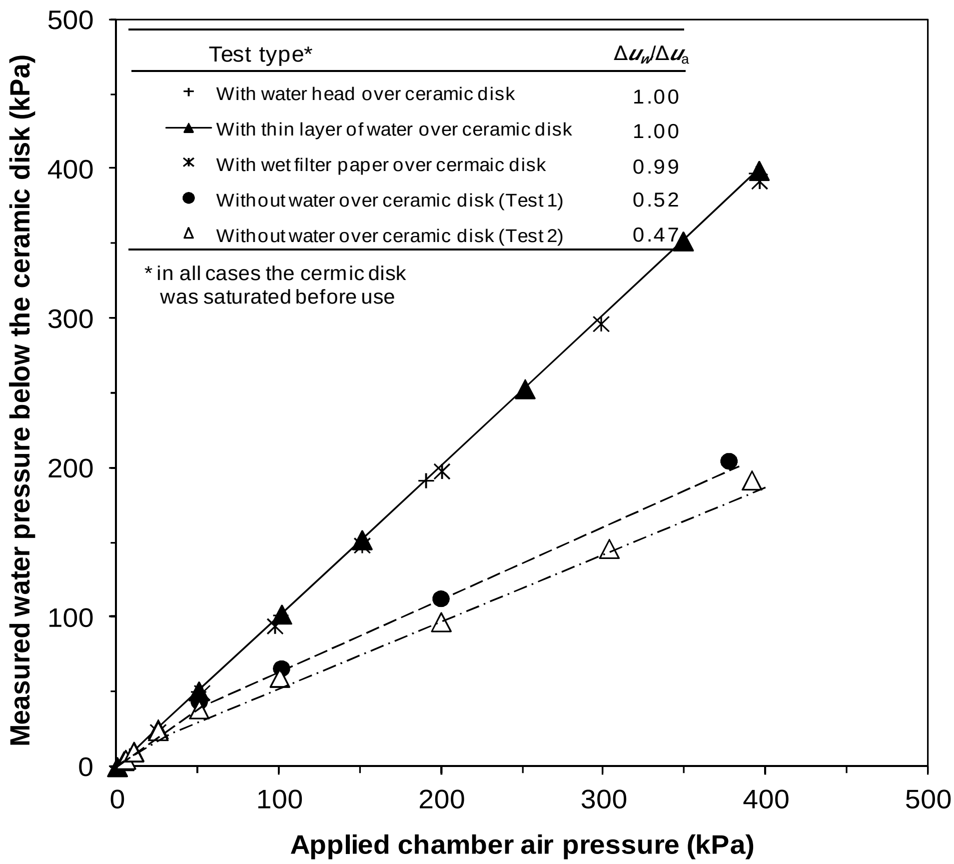



***Fig. 7.4 Influence of air pressure increase on water pressure below saturated ceramic disk for various conditions (without soil specimen)***

Referring to Fig. 7.4, for the cases with a water head over the ceramic disk, a thin film of water over the ceramic disk, and with a wet filter paper on the ceramic disk, the value of $\Delta u_w/\Delta u_a$ was found to be 1.0. On the other hand, for the tests without any water over the ceramic disk, $\Delta u_w/\Delta u_a$ was found to be 1.0 up to an applied chamber air pressure of about 50 kPa, whereas the ratio decreased at higher applied chamber air pressures. A reduction of $\Delta u_w/\Delta u_a$ at higher applied chamber air pressures is attributed to the expansion of the water compartment that enabled the flow of water from the ceramic disk into the water compartment causing the air-water interface to retreat inwards from the surface of the ceramic disk. The test results indicated that if an adequate quantity of water is available on the surface of the ceramic disk (a wet filter paper over the ceramic disk is adequate in this case) that has a tendency to flow into the water compartment under the application of chamber air pressure, the water compartment expansion effect can be overcome. Therefore, the water phase continuity during an actual test can be improved.

### 7.4.1 Tests with various interfaces

Discontinuity in the water phase can be overcome by considering a thin clay-water paste, such as kaolinite, between the soil specimen and the saturated ceramic disk (Guan & Fredlund, 1997). Measurements of matric suction of compacted soil specimens using a high suction probe with various interfaces are reported by Oliveira & Marinho (2008).

Matric suctions of statically compacted specimens of JF and TR soils corresponding to two compaction conditions were measured with three different interfaces between the soil specimens and the saturated ceramic disk, such as (*i*) a wet filter paper (Whatman Grade 5, thickness = 250 µm), (*ii*) slurry prepared from the tested soils, and (*iii*) slurried kaolinite. The water content of the slurries prepared from the soils and Speswhite kaolin (liquid limit = 56%) were equal to their corresponding liquid limits. The filter paper was wetted after placing it on the ceramic disk. Soon after the completion of the measurement of matric suction, the soil specimens were subjected to an increasing chamber air pressure and the corresponding water pressures in the water compartment were measured.

The time-suction plots of for both statically compacted specimens (static-light (SL) and static-heavy (SH)) of JF and TR soils are presented Figs. 7.5 and 7.6, respectively. The initial compaction conditions of the soil specimens used, the interface type, the measured matric suctions, the average values of $\Delta u_w/\Delta u_a$ for 30 minutes elapsed time allocated for each incremental applied chamber pressure, and $\Delta u_w/\Delta u_a$ values for the last incremental chamber air pressures are shown in Figs. 7.7*a* and *b and* Figs. 7.8*a and b*.

Figures 7.5 and 7.6 showed that the specimens of JF and TR soils compacted at higher compaction water content ( 9.1 and 19.3%) and tested with or without interfaces, attained equilibrium suctions sooner than the specimens compacted at lower compaction water content (7.1 and 17.9%), respectively. On the other hand, it can be seen clearly that at any compaction conditions, the specimens of JF and TR soils that were tested without interfaces reached equilibrium suctions later than the specimens that tested with interfaces at all water contents considered (Figs. 7.5 and 7.6).

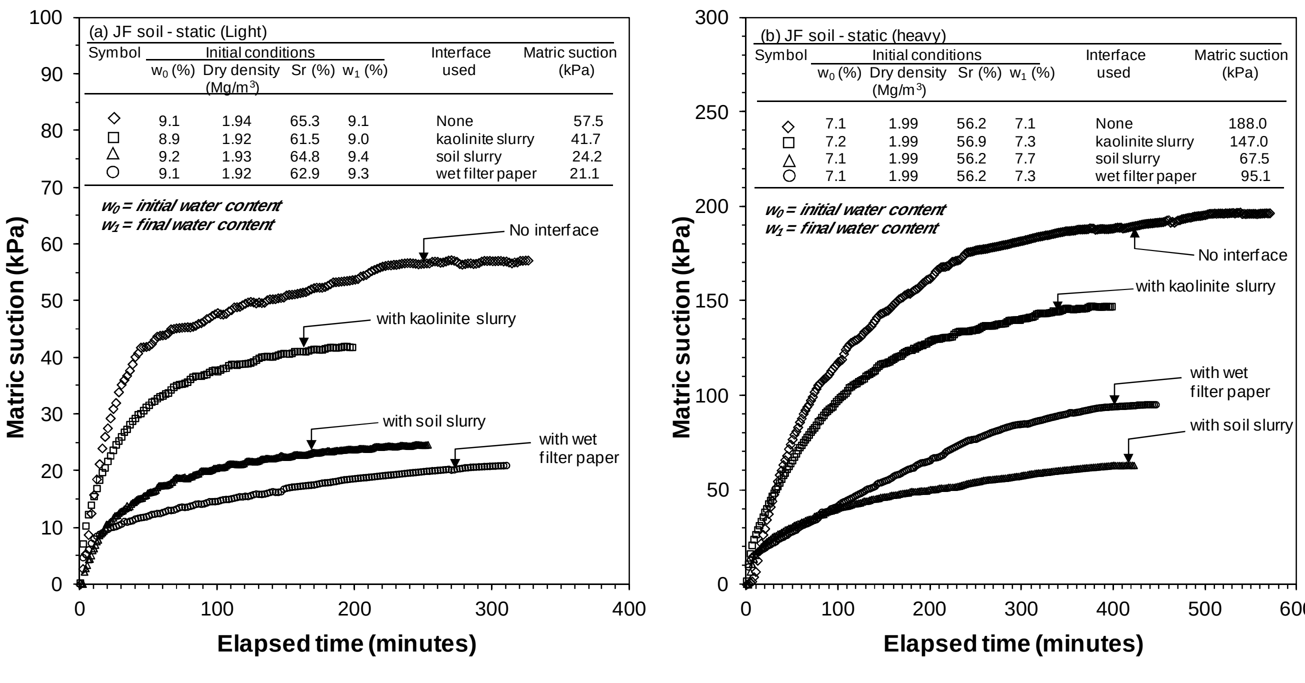



***Fig. 7.5 Time versus matric suction plots of JF soil for average compaction water contents of (a) 9.1%, and (b) 7.1%.***

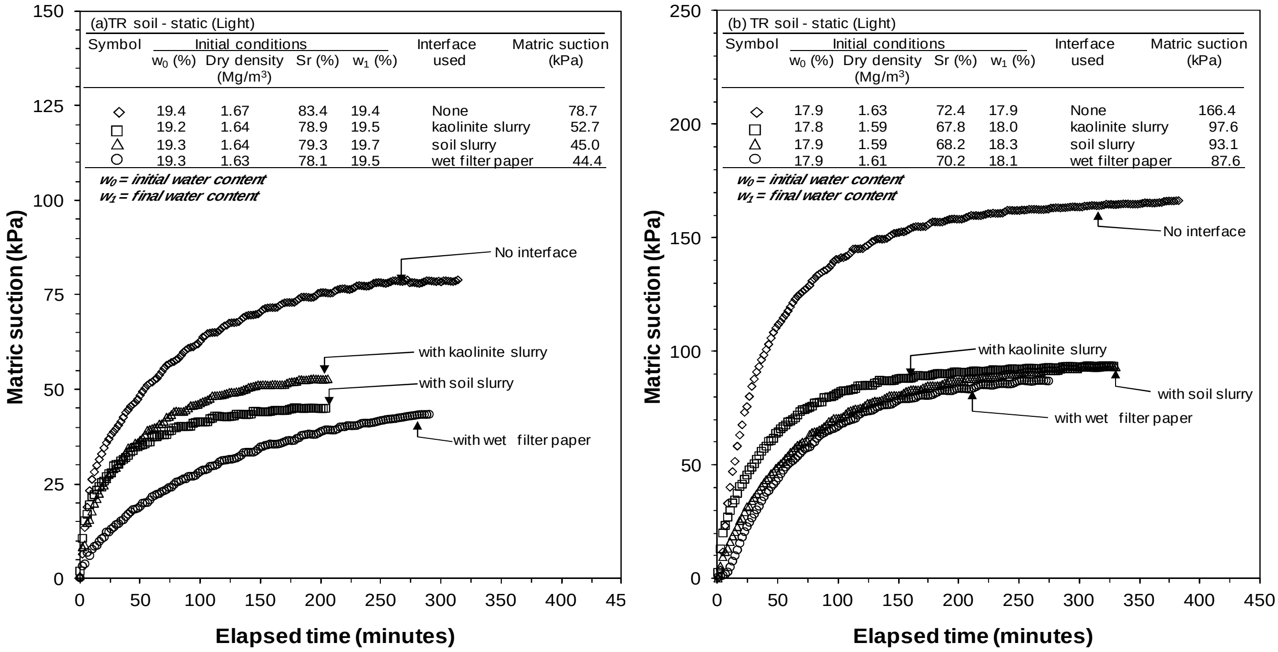



***Fig. 7.6 Time versus matric suction plots of TR soil for average compaction water contents of (a) 19.3%, and (b) 17.9%.***

Matric suction measurements of statically compacted specimens of JF and TR soils corresponding to two compaction conditions were carried out with and without the interfaces. The tests results along with the measured water pressures corresponding to an increase in the chamber air pressure after completion of the matric suction measurements are presented in Figs. 7.7 and 7.8.

The test results presented in Figs. 7.7 and 7.8 showed that the measured matric suctions of both soils with and without the interfaces differed significantly. For the specimen of JF soil that was tested at the compaction water content of 9.1% (Fig. 7.7*a*), matric suction reduced by about 35 kPa with a wet filter paper as the interface. Similarly, for the soil specimen tested at the compaction water content of 7.1% (Fig. 7.7*b*), a reduction in matric suction with the soil slurry as the interface was about 120 kPa. The average decrease on the measured matric suction were about 31 and 74 kPa with all the interfaces used for the specimens of TR soil that were tested at compaction water contents of 19.3 and 17.9 %, respectively (Fig. 7.8*a* and *b*).

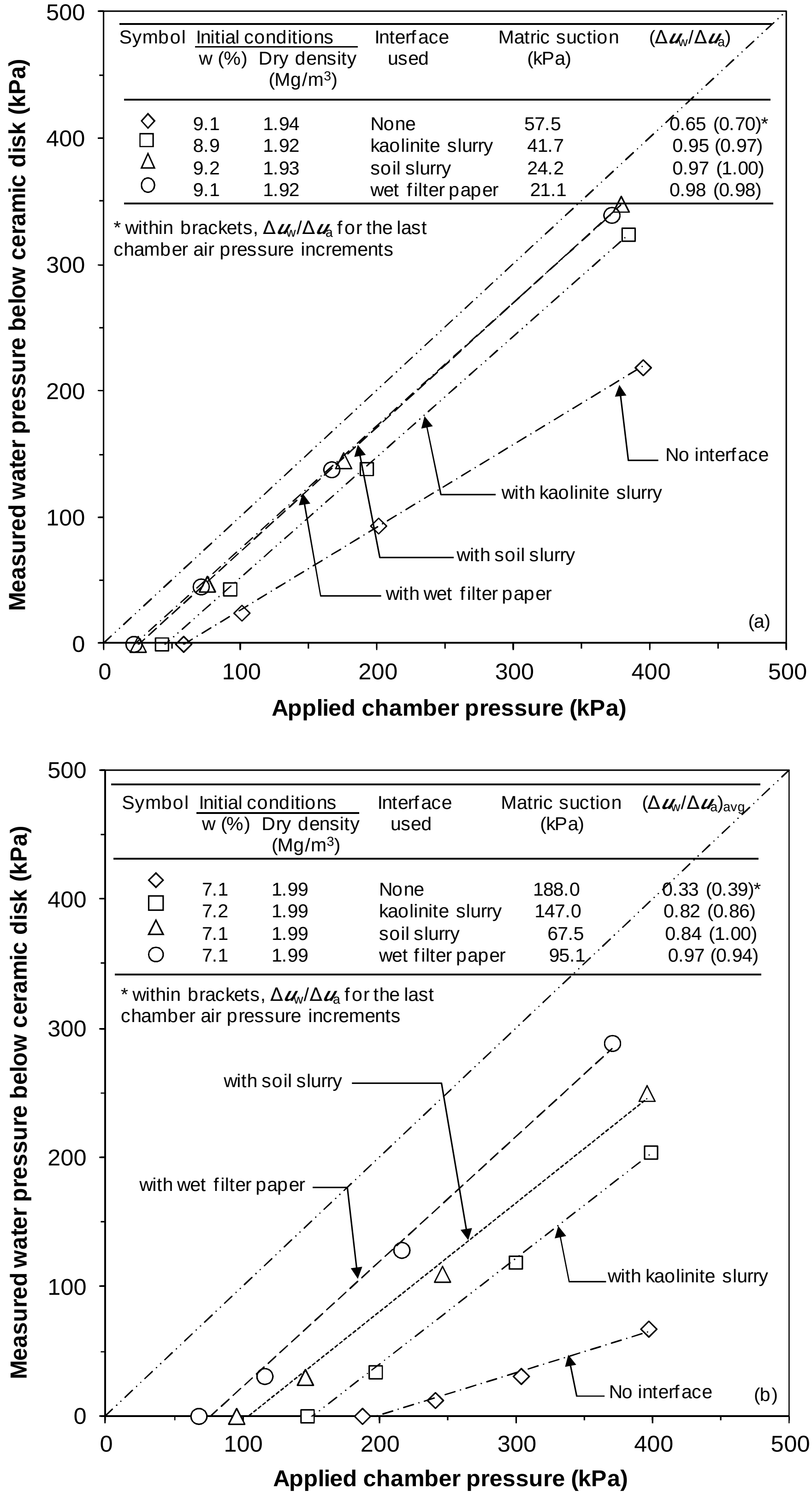
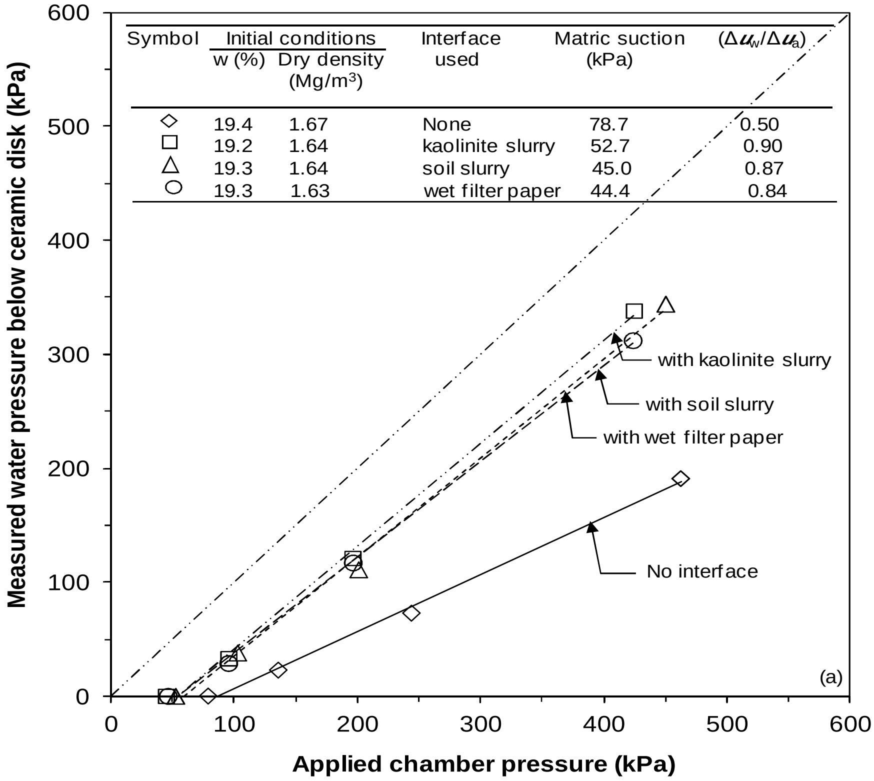



***Fig. 7.7 Influence of air pressure increase on water pressure below saturated ceramic disk with various interfaces for two compaction conditions of JF soil specimens***



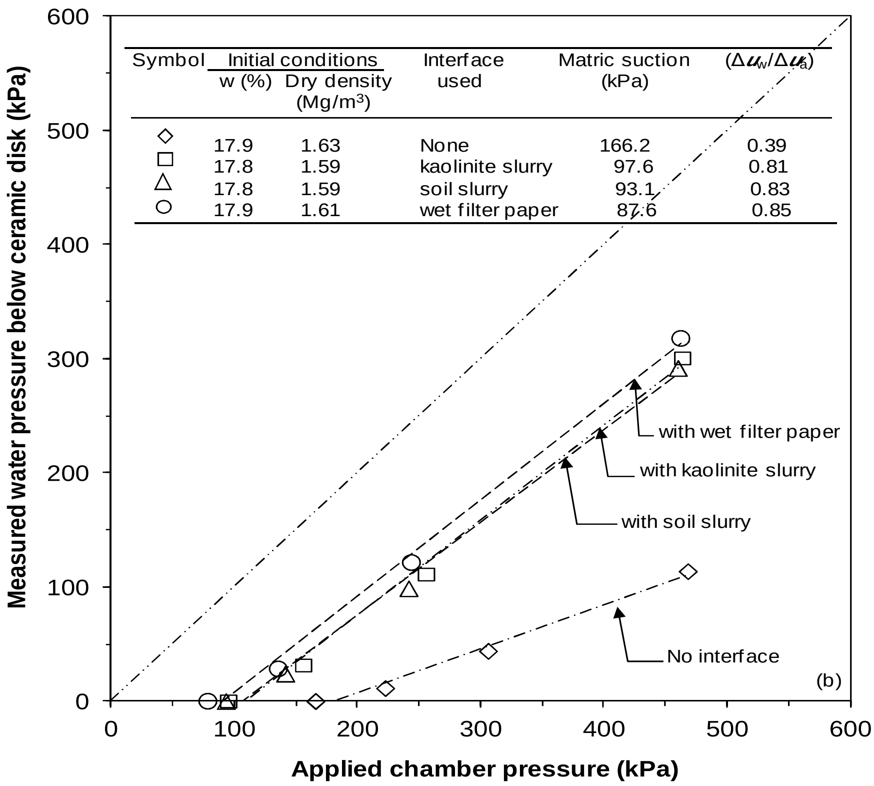




***Fig. 7.8 Influence of air pressure increase on water pressure below saturated ceramic disk with various interfaces for two compaction conditions of TR soil specimens***

An increase in $\Delta u_w/\Delta u_a$ due to the use of various interfaces was distinct indicating that the interfaces used created better continuity in the water phase. On the other hand, the interfaces used possibly altered the initial conditions of the soil specimens to some extent. Continuity in the water phase was better for the specimens of JF soil compacted at water content of 9.1% than that of the specimens compacted at 7.1%. However, for both the specimens of TR soil (Figs. 7.8*a* and *b*), the continuity in the water phase improved by about 45%.

Flow of water in soils occurs primarily due to the hydraulic head gradient and not due to the matric suction gradient (Fredlund & Rahardjo, 1993). It is anticipated that continuity in the water phase between the interfaces and the ceramic disk was soon established due to the gravitational flow of water immediately after the interfaces were placed on the ceramic disk. Further, as soon as a soil specimen is placed in contact with the saturated interface materials, the driving potential for the flow of water from the interfaces to the unsaturated soil specimens is due to the difference in the water pressures of both that in turn created the continuity in the water phase. The flow of water into the soil specimen induced suction in the interfaces that was manifested on the water pressure transducer readings. The volume of water flowing into the soil specimens depends upon the desorption behaviour of the interface material under any applied air pressure. Smaller applied suctions can have significant influence on the materials that have lesser water holding capacity. Therefore, it is hypothesized that a relatively greater amount of water expelled into the soil specimens when the interfaces used were a wet filter paper and the slurries prepared from the soils than that occurred for slurried Speswhite kaolin.

For the case with JF soil specimens compacted at water content of about 9.1% (Fig. 7.7*a*), $\Delta u_w/\Delta u_a$ values for all the interfaces used remained close to 1.0 indicating reasonable continuity in the water phase in the measuring system. On the other hand, for the specimens of JF soil with compaction water content of 7.1% (Fig. 7.7*b*), the average value of $\Delta u_w/\Delta u_a$ for the entire range of the applied chamber air pressure decreased for the interfaces in the order of a wet filter paper (0.97), soil slurry (0.84), and the slurry prepared from Speswhite kolin (0.82). Similarly, the tests results of specimens of TR soil indicated the same order of the interfaces as the specimens of JF soil. The values of $\Delta u_w/\Delta u_a$ for TR soil specimens compacted at water content of 17.9% were 0.90, 0.87, and 0.84 (see Fig. 7.8*a*). However, for TR soil specimens compacted at water content of 19.3%, the values of $\Delta u_w/\Delta u_a$ increased for the interfaces in the order of a wet filter paper (0.85), soil slurry (0.83), and the slurry prepared from Speswhite kolin (0.81) (see Fig. 7.8*b*)..

The measured matric suctions remained concurrent with $\Delta u_w/\Delta u_a$ values for both JF and TR soils specimens (e.g., 95.1, 67.5, and 147, kPa (Fig. 7.7*b*), and 87.5, 93.1, and 95.6, kPa (Fig. 7.8*b*) for interfaces as a wet filter paper, soil slurry, and slurried Speswhite kaolin, respectively) indicating that higher the value of $\Delta u_w/\Delta u_a$, greater is the reduction in matric suction of the soil specimen. An increase in $\Delta u_w/\Delta u_a$ and the corresponding decrease in the measured matric suctions of soil specimens are directly linked to the volume of water expelled from the interfaces into the soil specimens and into the water compartment in order to compensate the expansion of the water compartment.

The test results presented in Figs. 7.1 to 7.8 indicated that discontinuity in the water phase in null-type axis-translation tests was manifested on $\Delta u_w/\Delta u_a$ values that in turn depends upon the compaction conditions and matric suction of the soil (or the applied chamber air pressure). With regard to suitability of the interface materials, it appears that using kaolinite slurry a decrease in matric suction can be up to about 40% (depends on compaction conditions and soil type) with reasonable continuity in the water phase. For other interface types, a greater reduction in matric suction may be expected.

## 7.4 Concluding remarks

Continuity in the water phase between soil specimens, the water in the ceramic disk, and the water in the compartment during null-type axis-translation tests were studied in this chapter. Measurements of the coefficient of permeability of the ceramic disk in null-type device, water phase continuity tests, verification of the water phase continuity without soil specimens, and tests with various interfaces (wet filter paper, soil slurry, and slurried kaolinite) were carried out.

Based on the findings of this study, it can be concluded that:

- Very high RHs (> 95%) and ambient temperature within the air pressure chamber were measured during the direct measurements of suctions of compacted soil specimens using the null-type device.
- Evaporation of water from soil specimens and from the ceramic disk did not significantly contribute to longer suction equilibration time. This based on insignificant differences between the water contents of the specimens before and after the tests, and similar suctions for specimens that either covered partially or fully the ceramic disk during tests that were found.
- An increase in the chamber air pressure soon after the null-type tests were completed clearly indicated that the water phase continuity between the water in the soil specimens and the water in the ceramic disk was lacking in all cases. The measured water pressures in the water compartment were found to be less than the applied chamber air pressures.
- A pressure drop across the ceramic disk can be attributed to the existence of curved air-water interfaces in the pores of the ceramic disk and therefore, the surface tension effect partially resisted the applied air pressures.
- The test results showed that soil specimens with higher water contents created better continuity in the water phase.
- The water phase continuity could be improved by considering various interfaces. However, it was noted that the interfaces used reduced the matric suctions of the soil specimens tested.

- Depending upon soil type and initial compaction conditions, the matric suction reduced by about 30, 60, and 55% with interfaces as slurried kaolinite, slurry prepared from the soils, and a wet filter paper.

# CHAPTER 8

# INDIRECT MEASURMENTS OF SUCTION USING FILTER PAPER AND CHILLED-MIRROR TECHNIQUES

## 8.1 Introduction

Soil suction is an essential property for studying the behaviour of unsaturated soils. Soil suction is the negative pressure within the pores between soil particles and it is a function of many soil properties such as soil structure and soil water content. Suction can be measured indirectly in which another parameter, such as relative humidity, resistivity, conductivity and water content is measured and related to the suction through a calibration with known values of suction (Ridley & Wray, 1995).

In this chapter, matric and total suction measurements were conducted using filter paper method. Measurements of total suction were also carried out using chilled-mirror dew-point device. The suction measurements were performed on soil specimens prepared from the two chosen soils (Jaffara soil, JF and Terra-rosa soil, TR) and at different compaction conditions.

The objectives of this chapter were (*i*) to evaluate the filter paper method for total and matric suction measurements in term of calibration curve and equilibrium time, (*ii*) to measure matric suctions of the soils using filter paper method, (*iii*) to measure total suctions of the soils using chilled-mirror device and non-contact filter paper method, and (*iv*) to study the influence of initial compaction conditions of the soils on matric and total suctions.

This chapter begins with presenting the experimental programme adopted, followed by the test results obtained for both soils from various suction measurement techniques. The effects of initial compaction conditions on total and matric suctions are discussed in detail. Towards the end of the chapter, the concluding remarks are presented.

## 8.2 Experimental program and specimen preparation

### 8.2.1 Soil specimen preparation

For suction measurements by filter paper method and chilled-mirror device, only statically compacted specimens of JF and TR soils were used. Soil specimens were prepared by compaction soil-water mixtures to desired dry densities and water contents in specially fabricated mould using heavy and light compaction efforts. The initial compaction conditions of the statically compacted specimens were corresponding to the specimen conditions of the dynamically compacted specimens (BS- heavy and BS-light). Additionally, soil-water mixtures with different initial water contents were tested to study the effect of initial dry density. The dry densities and the water contents for the statically compacted specimens of JF and TR soils are shown in Figs. 8.1*a* and *b*, respectively.

The number of specimens that were used for measuring total and matric suctions by filter paper method was 13 for JF soil (7 for static-heavy compaction and 6 for static-light compaction) and 12 for TR soil (6 for static-heavy compaction and 6 for static-light compaction). For total suction measurements using chilled-mirror device, 44 specimens of JF soil and 42 specimens of TR soil were prepared (Figs. 8.1*a* and *b*). Total suction measurements were also carried out on un-compacted (loose) specimen by using non-contact filter paper method and the chilled-mirror device to study the effect of density on total suction.

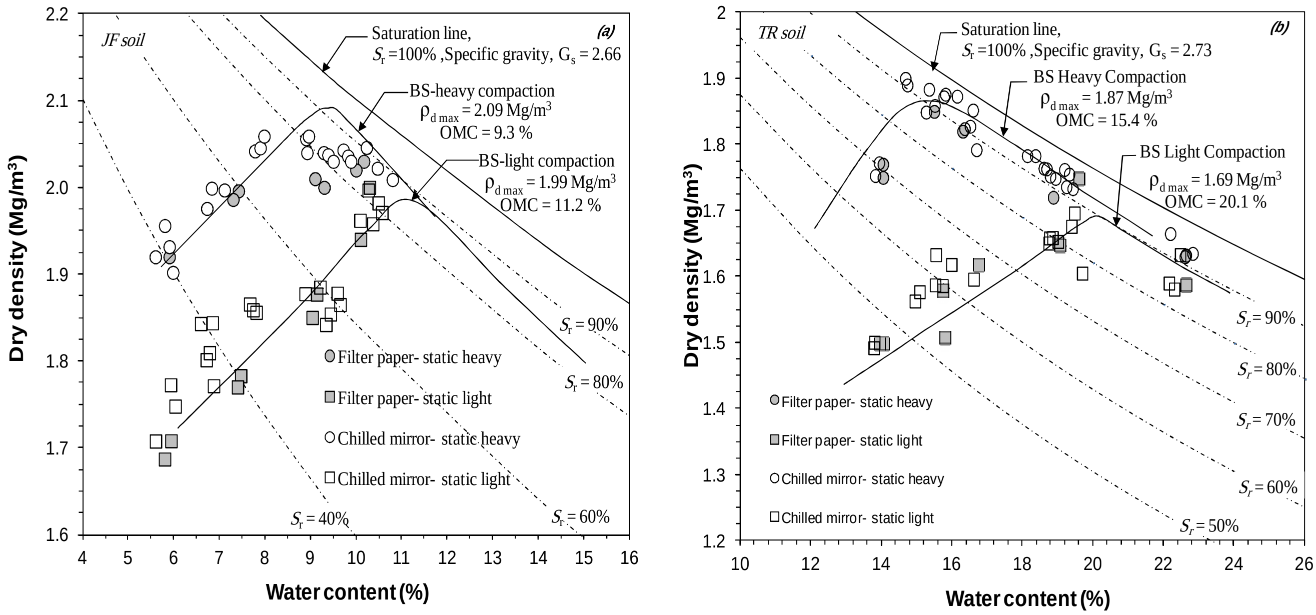



***Fig. 8.1 B.S compaction tests and initial specimens conditions of (a) JF soil and (b) TR soil, for filter paper and chilled-mirror tests***

## 8.2.2 Experimental methods

Contact and non contact filter paper tests were carried out for measuring matric and total suctions of JF and TR soils, whereas chilled-mirror device was used to measure total suctions of both soils.

### *8.2.2.1 Filter paper tests*

The principle of the filter paper method is to measure suction indirectly by relating the water absorbed by specified filter papers with suction by means of calibration curves. The total suction is measured when water transfer is by vapour movement and the matric suction is measured when water transfer is by liquid movement (Gardner, 1937; Bulut, et al., 2001, Leong, et al., 2002)

For the measurement of matric suction an oven dry Whatman 42 filter paper was sandwiched between two protective Whatman 42 filter papers and placed in direct contact between two halves of soil specimens (section 3.9.2 - chapter 3). The two halves of soil specimens, with filter papers in between, were taped together with electrical tape and put in glass jars. For total suction measurements, one Whatman 42 filter paper was placed above the soil specimens where PVC rings were used to separate the soil specimens and the filter papers (section 3.9.2 - chapter 3). The soil specimens were put in a tightly sealed glass jar and placed in an insulated chest to reduce temperature fluctuations for a period of two weeks. After the equalisation period, the water contents of the filter papers were determined. The calibration curve established in this study was used to determine soil suctions of the two soils used.

#### *8.2.2.2 Filter paper calibration curve*

Despite several calibration curves for the Whatman No. 42 filter paper are available in the literature, it is recommended to establish a calibration curve for each study involving different filter paper lots (Deka et al., 1995). Several factors, such as suction source used in calibration, quality of filter paper, hysteresis, and equilibration time, may have influenced the different calibration curves found in the literature (Leong et al., 2002).

In this study, calibration tests for the Whatman No. 42 filter paper was conducted to establish contact filter paper (or matric suction) and non-contact (or total suction) filter paper calibration curves. Additionally, the influences of suction source, hysteresis, quality of filter paper, and equilibration time on calibration curves were examined. The detailed testing procedure for establishing calibration curves is described in Section 3.9.2.2.

*8.2.2.2.1 Suction sources*

In this study, calibration tests for the Whatman No. 42 filter paper was conducted using pressure plate apparatus for contact filter paper (or matric suction) and using sodium chloride (NaCl) salt solutions for non-contact (or total suction) filter paper.

The drying and wetting test results of Whatman No. 42 filter papers are presented in Fig. 8.2. The best fit contact and non contact calibration curves for initially dry and initially wet Whatman No. 42 filter paper, as obtained in this study (Fig. 8.2), are shown in Fig. 8.3. The calibration curves of initially dry filter papers reported in ASTM D5298-10 and by Leong et al. (2002) together with the results from the current study are presented in Fig. 8.4. Similarly, the calibration curves of initially wet filter papers from the present study are presented along with the calibration tests results reported by Ridley (1995) and Harrison & Blight (1998) in Fig. 8.5.

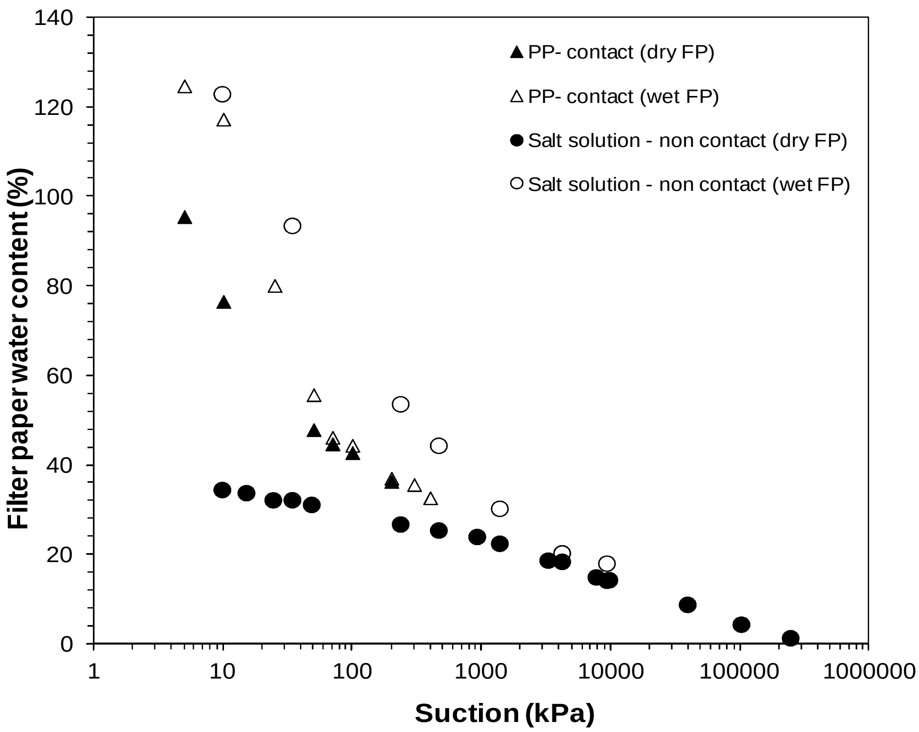



***Fig. 8.2 Drying and wetting suction–water content characteristic of filter papers***

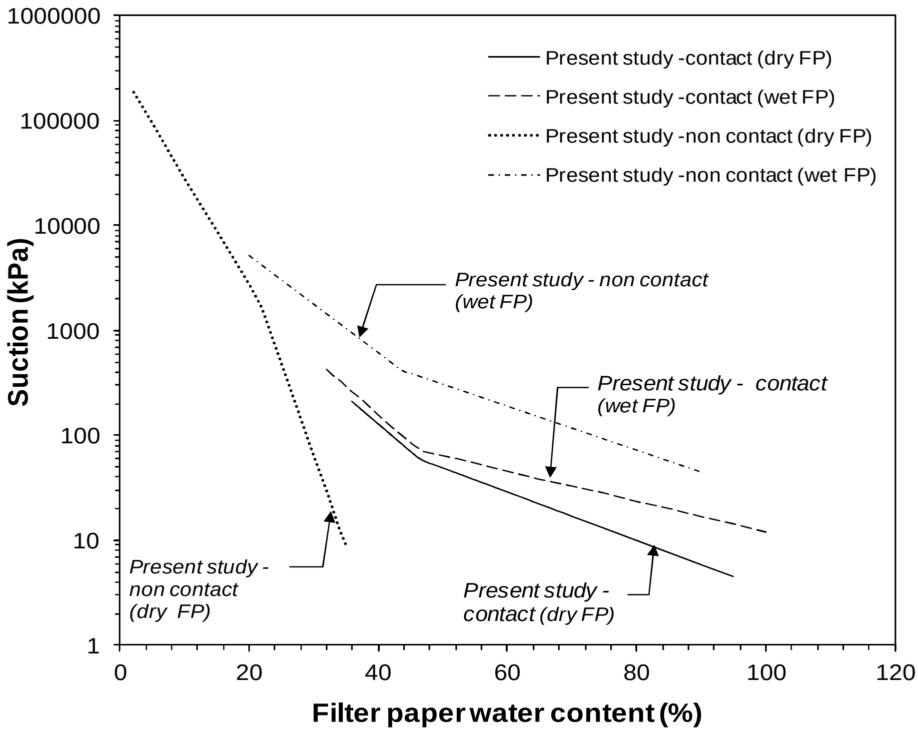



***Fig. 8.3 Contact and non contact calibration curves of Whatman No. 42 filter papers (in this study)***

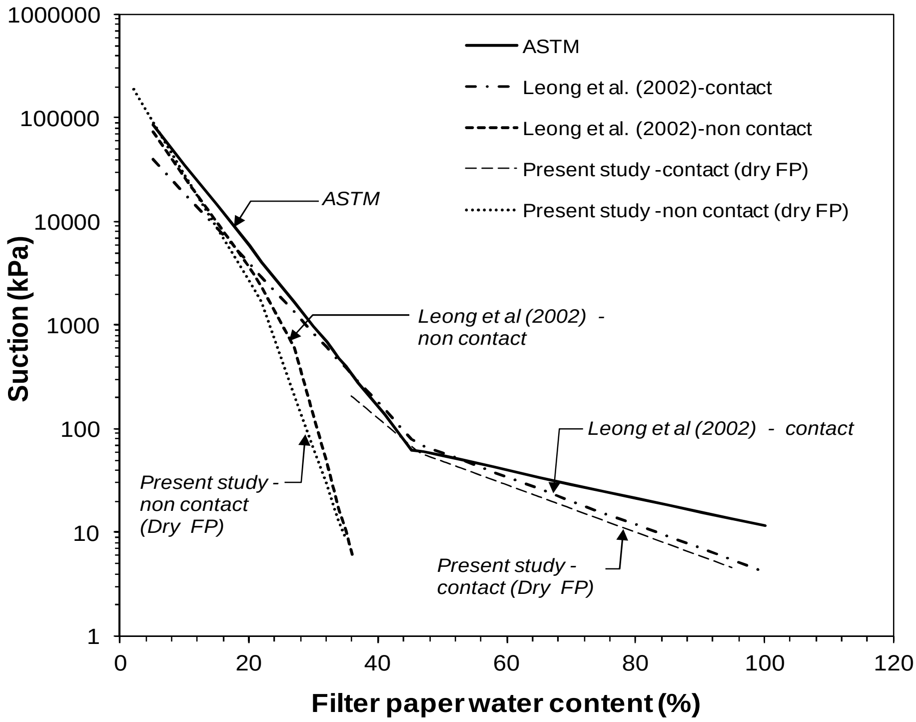



***Fig. 8.4 Contact and non contact calibration curves of initially dry***

***Whatman No. 42 filter papers***

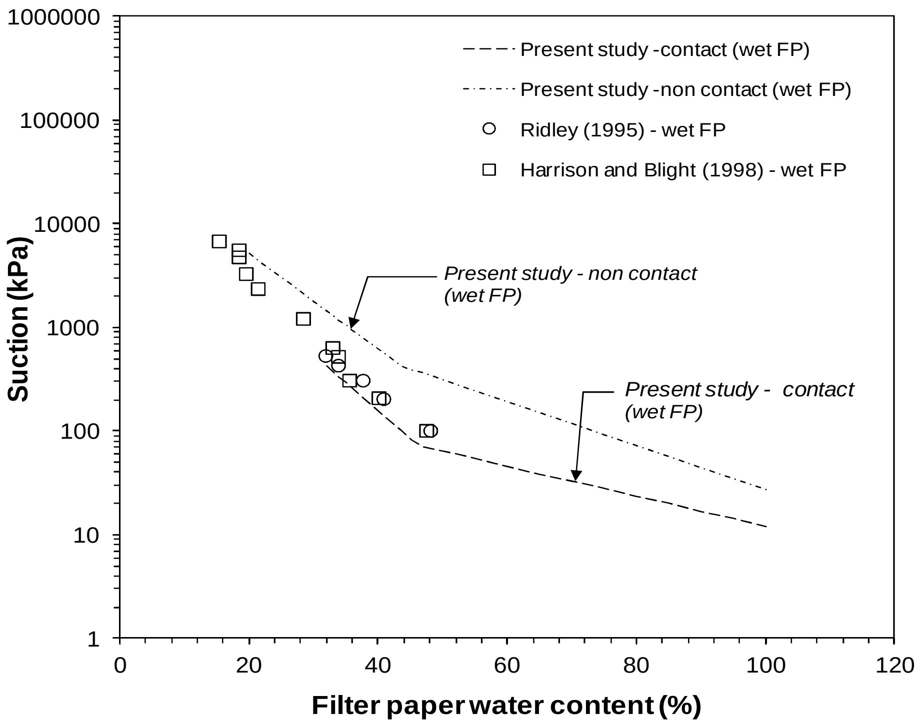



***Fig. 8.5 Contact and non contact calibration curves of initially wet***

***Whatman No. 42 filter papers***

It can be seen from Fig. 8.2 and 8.3 that, the relationships between filter papers water content and suction are bilinear for both contact and non contact calibration curves. Also, the calibration curves determined from present study are different for contact and non contact filter papers. The sensitivity change of the filter paper water content occurred at a water content of about 23% and about 54% for non contact and contact calibration curves, respectively (Fig. 8.3). For suction greater that 1000 kPa, the total and matric suction tests results seem to converge (Figs. 8.2 and 8.3). This observation is consistent with the findings from other studies (Houston, et al., 1994; Bulut, et al., 2001; Leong, et al., 2002) (Fig. 8.4). However, other studies (Marinho, 2004, Stenke et al., 2006) pointed out that only one calibration curve for total and matric suction can be obtained if longer equilibration time is allowed especially at lower imposed levels of suction. It should be noted that, two weeks was allowed for equilibrium time in this study.

*8.2.2.2.2 Hysteresis in drying and wetting calibration curves of filter papers*

Figure 8.3 showed that hysteresis exists between the wetting and drying calibration curves. The calibration curve for initially dry filter paper is different from that of the initially wet filter paper. Ridley (1995) and Harrison & Blight (1998) have shown that the filter papers for both drying and wetting paths exhibit hysteretic behaviour. Leong et al. (202) stated that insufficient equilibration time will lead to larger hysteresis in the wetting and drying responses of the filter paper. As any other porous medium, the hysteresis is expected for filter paper during drying and wetting processes and this was distinctly manifested in Fig. 8.2.

*8.2.2.2.3 Calibration tests of different batches of filter papers*

In order to examine the use of different batches of filter paper, an independent non-contact calibration tests for three separate batches of Whatman No. 42 filter paper were performed. The tests were conducted on initially dry filter paper suspending above salt solutions (non-contact method) and on initially wet filter paper placing them in contact with the pressure plate (contact method). The test results shown in Fig. 8.6 indicate an insignificant variation between different calibration curves on different batches for either contact or non-contact tests.

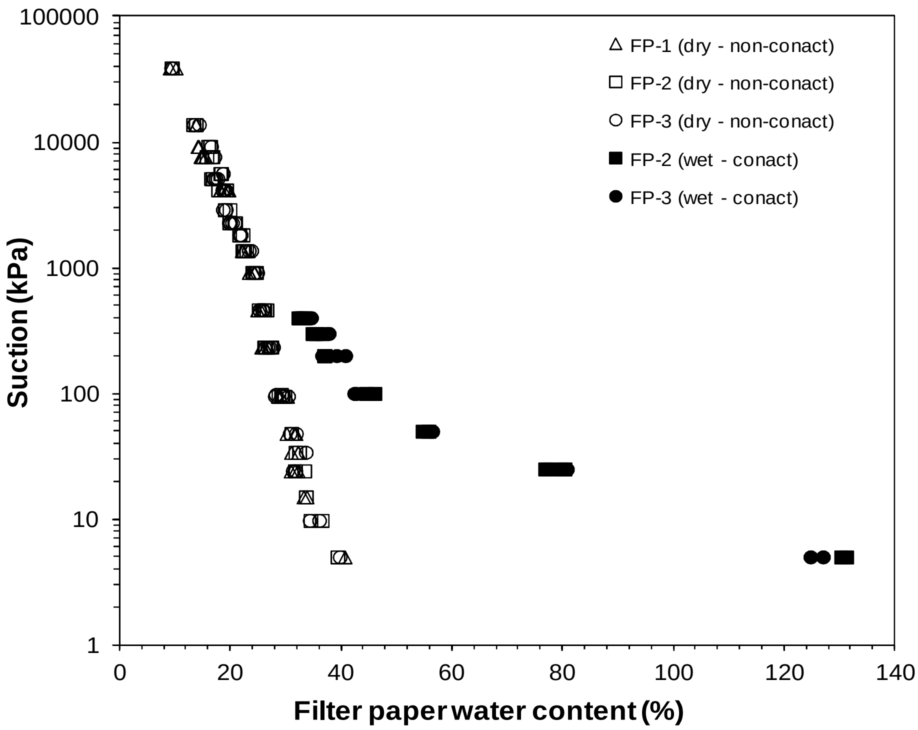



***Fig. 8.6 Calibration tests for different batches of Whatman No. 42 filter paper***

*8.2.2.2.4 Filter paper suction equilibrium period*

ASTM D5298-10 recommends a minimum equilibration time of seven days for measuring suction using the filter paper method. However, various researchers have used different equilibration times. This indicates that the equilibration time depends upon the suction source, measured suction type, material type, water content of soil specimen, and number of filter papers used. To examine the effect of equilibration time on contact calibration curve, initially dry filter papers were suspended above salt solutions in closed jars and for different equilibrium periods (3, 7, 14, 30 and 60 days).

The equilibration times determined for the non-contact filter paper with various imposed suction are presented in Fig. 8.7. The test results presented in Fig. 8.7 indicated that the equilibrium time is dependent upon the imposed suction level. Three different categories of equilibrium conditions can be distinguished based on the test results. For suction level below 100 kPa, the equilibrium was not reached even after 60 days, indicating that more time was needed for water content equalisation. At intermediate suction levels (100 to 500 kPa), the filter paper were equilibrated at about 14 days. The extension in equilibrium time beyond 3 days did not significantly influence the suction for higher level of imposed suction (≥1000 kPa) and therefore three days was sufficient to achieve equilibrium.

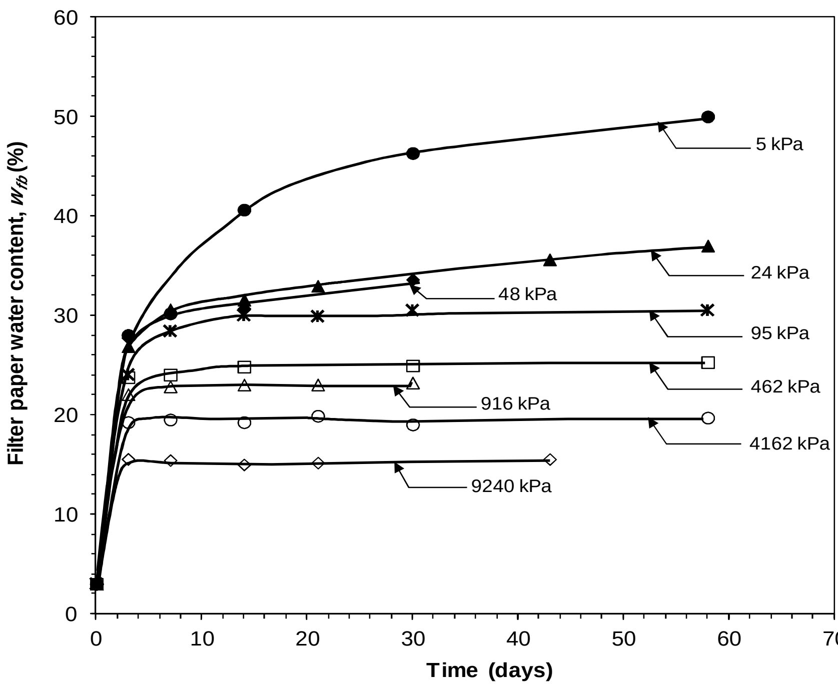



***Fig. 8.7 Filter paper water content versus equilibrium time at different imposed suction levels***

*8.2.2.2.5 Contact and non contact calibration equations in this study*

It is recommended that the calibration curve used for computing suction should relate to whether the filter paper is being wetted or dried. Al-Khafaf & Hanks (1974), Sibley & Williams (1990) and Swarbrick (1995) suggested that soil suction measurements should be performed in the same way as the filter paper being calibrated. In this study, the suction measurements were performed using initially dry filter papers (ASTM D 5298-10) and the time required to establish equilibrium was chosen to be two weeks. Therefore, equations 8.1*a* and *b* and 8.2*a* and *b* which represent the matric and total suction (contact and non contact) calibration curves for initially dry Whatman No. 42 filter paper, respectively, were used in this study to calculate the suctions of soil specimens.

For matric suction:

$$<54\% \quad \log \Psi = 4.4093 - 0.056\, w_{fp} \qquad \textit{(Eq. 8.1a)}$$

$$\geq 54\% \quad \log \Psi = 2.6081 - 0.0203\, w_{fp} \qquad \textit{(Eq. 8.1b)}$$

For total suction:

$$<23\% \quad \log \Psi = 5.4798 - 0.1027\, w_{fp} \qquad \textit{(Eq. 8.2a)}$$

$$\geq 23\% \quad \log \Psi = 7.0059 - 0.1734\, w_{fp} \qquad \textit{(Eq. 8.2b)}$$

where, $\Psi$ is suction and $w_{fp}$ is the filter paper water content.

#### *8.2.2.3 Chilled-mirror dew point tests*

The working principle of the chilled-mirror dew point device is based on the thermodynamic relationship between relative humidity, temperature and total soil suction according to Kelvin's equation. The device computes the relative humidity from the difference between the dew-point temperature of the air above the soil specimen in the closed chamber and the temperature of the soil specimen. The value of the total suction is then calculated using Kelvin's equation (Eq.3.3) by software within the device and displayed on an LCD panel in MPa unit along with the specimen temperature.

Statically compacted specimens and soil-water mixtures with different initial water contents of JF and TR soils were placed in a stainless steel container of approximately 37 mm diameter and 6 mm thick. The temperature of the soil specimen was controlled by using the thermal plate before placing it in the device. The total suction measuring time was usually about 7 to 15 minutes.

*8.2.2.3.1 Verification of chilled-mirror device*

Prior to use of the chilled-mirror dew point (WP4C) device, calibration of the chilled-mirror device was carried out with saturated salt solutions with 0.5 M KCl solution provided by the manufacturer, which should yield a suction of 2.19 ± 0.05 MPa, at 20$^{o}$C. In addition, suction values of different sodium chloride (NaCl) salt solutions with known osmotic suctions were measured using the chilled-mirror device in order to ensure the reliability of the calibration. Figure 8.8 shows the calculated suction values versus the measured values using the WP4C device. Good agreements were observed between the suctions of NaCl salt solutions and the measured suction values.

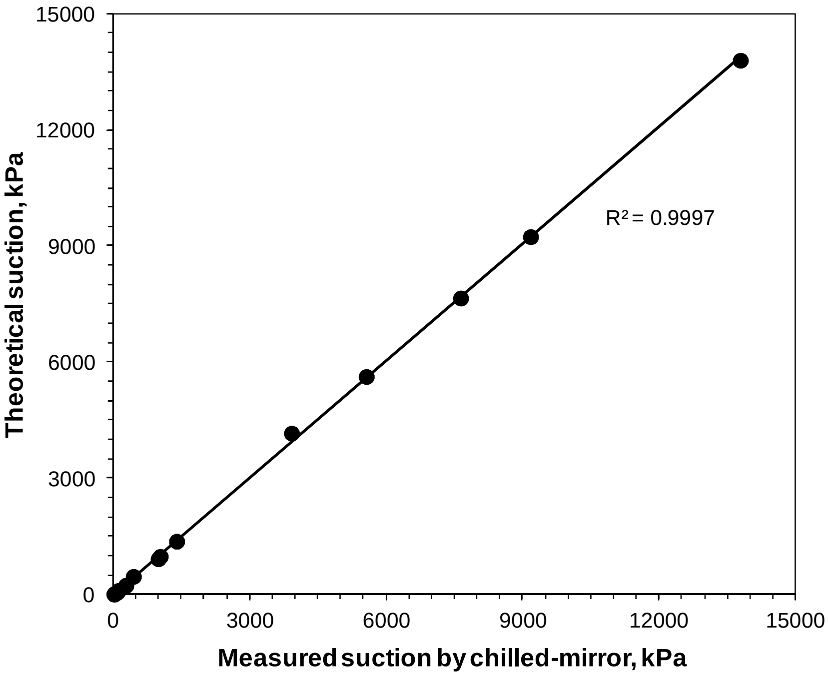



***Fig. 8.8 Calculated suctions and measured suctions by chilled-mirror dew-point device for solutions of NaCl***

## 8.3 Presentation of test results and discussion

### 8.3.1 Filter paper test results

Total and matric suction measurements of JF and TR soils were carried out using filter paper method. The measurements were performed on compacted statically soil specimens subjected to heavy and light compaction efforts. Several tests were also performed in which on un-compacted (soil-water mixture) specimens were considered in order to study the density effect on suction. Equations 8.1 and 8.2 were used to compute matric and total suction values from the filter paper water content calibration curves. The initial conditions of the soil specimens along with the tests results are presented in Tables 8.1 to 8.4.

***Table 8.1 Initial compaction conditions and matric suctions of JF soil (contact filter paper tests)***

| No. | Compaction type and effort | Initial compaction conditions | | | | Matric suction (kPa) |
|---|---|---|---|---|---|---|
| | | Water content (%) | Dry density ($Mg/m^3$) | Void ratio | Degree of saturation (%) | |
| 1 | Static heavy compaction (SH) | 10.28 | 2.02 | 0.317 | 86.3 | 37.2 |
| 2 | | 9.81 | 2.03 | 0.310 | 84.1 | 213.8 |
| 3 | | 9.17 | 2.04 | 0.304 | 80.3 | 418.9 |
| 4 | | 9.21 | 2.06 | 0.291 | 84.0 | 342.4 |
| 5 | | 7.29 | 1.99 | 0.337 | 57.7 | 681.1 |
| 6 | | 5.96 | 1.92 | 0.385 | 41.4 | 913.7 |
| 7 | | 6.00 | 1.93 | 0.378 | 42.2 | 847.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | | 10.34 | 2.00 | 0.330 | 83.3 | 29.9 |
| 9 | | 10.06 | 1.96 | 0.357 | 74.9 | 144.1 |
| 10 | Static light compaction (SL) | 8.90 | 1.82 | 0.462 | 51.3 | 438.5 |
| 11 | | 7.42 | 1.78 | 0.494 | 39.8 | 578.9 |
| 12 | | 7.47 | 1.77 | 0.503 | 39.5 | 589.2 |
| 13 | | 5.92 | 1.69 | 0.574 | 27.4 | 868.0 |

***Table 8.2 Initial compaction conditions and total suctions of JF soil (non contact filter paper tests)***

| No. | Compaction type and effort | Initial compaction conditions | | | | Total suction (kPa) |
|---|---|---|---|---|---|---|
| | | Water content (%) | Dry density (Mg/m$^3$) | Void ratio | Degree of saturation (%) | |
| 1 | Static heavy compaction (SH) | 10.17 | 2.02 | 0.317 | 85.4 | 148.5 |
| 2 | | 10.28 | 2.03 | 0.310 | 88.1 | 123.9 |
| 3 | | 9.17 | 2.04 | 0.304 | 80.3 | 312.3 |
| 4 | | 9.48 | 2.05 | 0.298 | 84.7 | 239.7 |
| 5 | | 7.42 | 1.99 | 0.337 | 58.6 | 600.1 |
| 6 | | 7.31 | 2.00 | 0.333 | 58.5 | 743.0 |
| 7 | | 6.00 | 1.92 | 0.385 | 41.4 | 1535.8 |
| 8 | Static light compaction (SL) | 10.34 | 2.00 | 0.330 | 83.3 | 80.8 |
| 9 | | 10.21 | 1.94 | 0.371 | 73.2 | 111.9 |
| 10 | | 9.25 | 1.88 | 0.415 | 59.3 | 224.3 |
| 11 | | 9.14 | 1.85 | 0.438 | 55.5 | 352.7 |
| 12 | | 7.47 | 1.78 | 0.494 | 40.2 | 648.2 |
| 13 | | 7.40 | 1.77 | 0.503 | 39.1 | 707.1 |
| 14 | | 5.92 | 1.69 | 0.57 | 27.44 | 1652.30 |

| | | | |
|---|---|---|---|
| 15 | Uncompacted (soil - water mixture) | 11.36 | 10.0 |
| 16 | | 9.30 | 170.5 |
| 17 | | 8.30 | 403.2 |
| 18 | | 8.00 | 530.5 |
| 19 | | 7.60 | 727.2 |
| 20 | | 6.31 | 1548.7 |
| 21 | | 6.20 | 1646.4 |
| 22 | | 3.78 | 11985.0 |
| 23 | | 2.15 | 39985.6 |
| 24 | | 2.08 | 39955.6 |

***Table 8.3 Initial compaction conditions and matric suctions of TR soil (contact filter paper tests)***

| No. | Compaction type and effort | Initial compaction conditions | | | | Matric suction (kPa) |
|---|---|---|---|---|---|---|
| | | Water content (%) | Dry density (Mg/m$^3$) | Void ratio | Degree of saturation (%) | |
| 1 | Static heavy compaction (SH) | 10.28 | 2.02 | 0.317 | 86.3 | 37.2 |
| 2 | | 9.81 | 2.03 | 0.310 | 84.1 | 213.8 |
| 3 | | 9.17 | 2.04 | 0.304 | 80.3 | 418.9 |
| 4 | | 9.21 | 2.06 | 0.291 | 84.0 | 342.4 |
| 5 | | 7.29 | 1.99 | 0.337 | 57.7 | 681.1 |
| 6 | | 5.96 | 1.92 | 0.385 | 41.4 | 913.7 |
| 7 | | 6.00 | 1.93 | 0.378 | 42.2 | 847.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | | 10.34 | 2.00 | 0.330 | 83.3 | 29.9 |
| 9 | | 10.06 | 1.96 | 0.357 | 74.9 | 144.1 |
| 10 | Static light compaction (SL) | 8.90 | 1.82 | 0.462 | 51.3 | 438.5 |
| 11 | | 7.42 | 1.78 | 0.494 | 39.8 | 578.9 |
| 12 | | 7.47 | 1.77 | 0.503 | 39.5 | 589.2 |
| 13 | | 5.92 | 1.69 | 0.574 | 27.4 | 868.0 |

***Table 8.4 Initial compaction conditions and total suctions of TR soil (non contact filter paper tests)***

| No. | Compaction type and effort | Initial compaction conditions | | | | Total suction (kPa) |
|---|---|---|---|---|---|---|
| | | Water content (%) | Dry density (Mg/m$^3$) | Void ratio | Degree of saturation (%) | |
| 1 | Static heavy compaction (SH) | 10.17 | 2.02 | 0.317 | 85.4 | 148.5 |
| 2 | | 10.28 | 2.03 | 0.310 | 88.1 | 123.9 |
| 3 | | 9.17 | 2.04 | 0.304 | 80.3 | 312.3 |
| 4 | | 9.48 | 2.05 | 0.298 | 84.7 | 239.7 |
| 5 | | 7.42 | 1.99 | 0.337 | 58.6 | 600.1 |
| 6 | | 7.31 | 2.00 | 0.333 | 58.5 | 743.0 |
| 7 | | 6.00 | 1.92 | 0.385 | 41.4 | 1535.8 |
| 8 | Static light compaction (SL) | 10.34 | 2.00 | 0.330 | 83.3 | 80.8 |
| 9 | | 10.21 | 1.94 | 0.371 | 73.2 | 111.9 |
| 10 | | 9.25 | 1.88 | 0.415 | 59.3 | 224.3 |
| 11 | | 9.14 | 1.85 | 0.438 | 55.5 | 352.7 |
| 12 | | 7.47 | 1.78 | 0.494 | 40.2 | 648.2 |
| 13 | | 7.40 | 1.77 | 0.503 | 39.1 | 707.1 |
| 14 | | 5.92 | 1.69 | 0.57 | 27.44 | 1652.30 |

| | | | |
|---|---|---|---|
| 15 | Uncompacted (soil - water mixture) | 11.36 | 10.0 |
| 16 | | 9.30 | 170.5 |
| 17 | | 8.30 | 403.2 |
| 18 | | 8.00 | 530.5 |
| 19 | | 7.60 | 727.2 |
| 20 | | 6.31 | 1548.7 |
| 21 | | 6.20 | 1646.4 |
| 22 | | 3.78 | 11985.0 |
| 23 | | 2.15 | 39985.6 |
| 24 | | 2.08 | 39955.6 |

### *8.3.1.1 Water content versus suction*

The test results of water content versus matric and total suctions for compacted specimens of JF and TR soils obtained by the filter paper method are presented in Figs. 8.9*a* and *b* (normal scale) and Figs. 8.10*a* and *b* (log-scale). Total suction measurements of uncompacted specimens were also included in Figs. 8.9 and 8.10.

The test results of the specimens of JF and TR soils show that total and matric suctions decreased with an increase in the initial water content. Except for the test results at water content of about 6.0% (Figs. 8.9*a* and 8.10*a*), the measured total and matric suction for the specimens of JF soil were found to be similar. The difference between total and matric suctions at low water content may be attributed due to the lack of contact between the filter paper and the soil specimens. For the specimens of TR soil (Figs. 8.9*b* and 8.10*b*), the measured total suctions were generally greater than the measured matric suctions. The difference between total and matric suction values for JF soil varied between 65 kPa for wet specimens to 400 kPa for dry specimens (Figs. 8.9*a* and 8.10*a*). The differences between total and matric suctions of TR soil are attributed due to the osmotic suction. The differences between total and matric suction values of TR soil varied between 86 kPa for wet specimens to 680 kPa for dry specimens (Figs. 8.9*b* and 8.10*b*). Figures 8.9 and 8.10 showed that compaction efforts had no measurable effect on the total suction values for both soils.

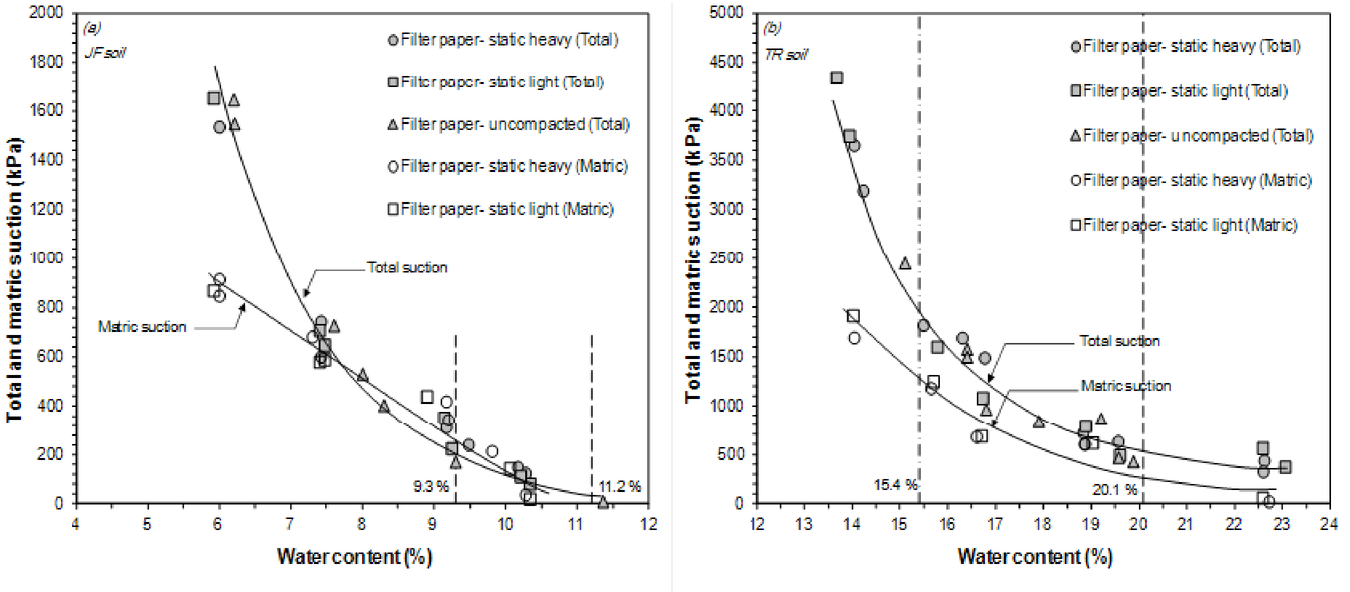



***Fig. 8.9 Water content versus total and matric suctions (normal scale) plot for (a) JF soil specimens and (b) TR soil specimens, tested using filter paper method***

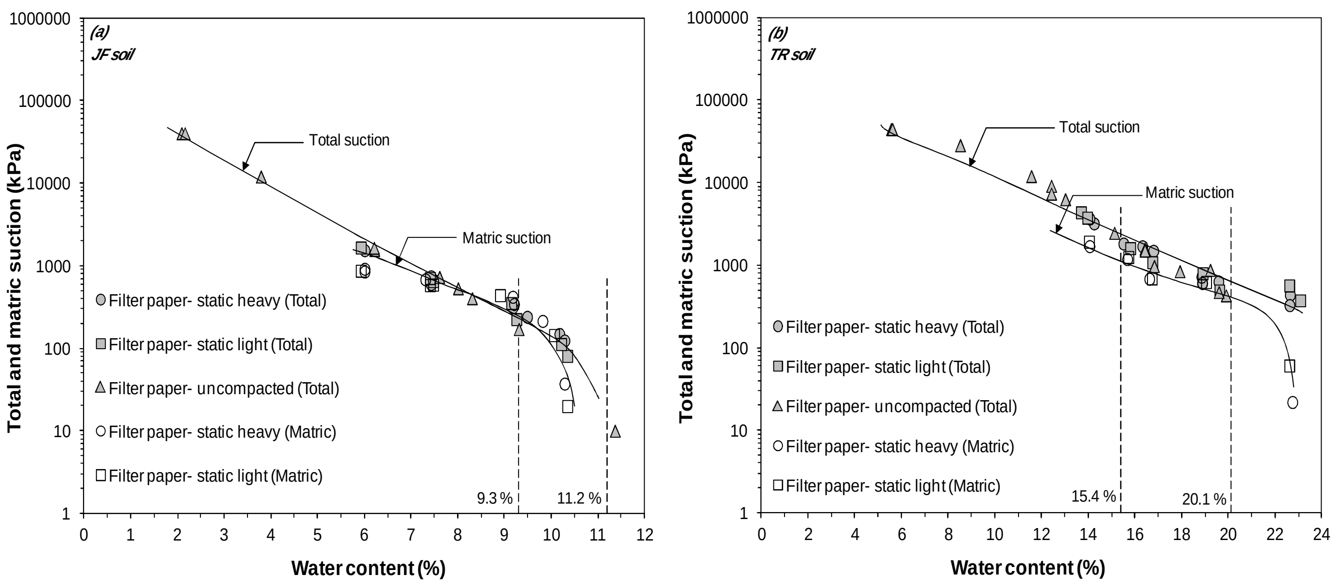



***Fig. 8.10 Water content versus total and matric suctions (Log-scale) plot for (a) JF soil specimens and (b) TR soil specimens, tested using filter paper method***

Figures 8.10*a* and *b* showed that the total suction versus water content results for the both soils follow the same single curve. The measured total suction varied between 0.01 to 40 MPa corresponding to change in water contents from 11.4 to 2.1% for JF soil. For the specimens of TR soil, the total suction was found to vary between 0.37 to 44.4 MPa for a range of water content between 23.0 to 5.5%.

#### *8.3.1.2 Degree of saturation versus suction*

The test results of soil suction with respect to the degree of saturation for JF and TR soil specimens are presented in Figs. 8.11*a* and *b.* Figures 8.11*a* and *b* showed that as the compaction effort increases, the total and matric suctions of the both soils increased. The degree of saturation versus suction curves for statically heavy compacted specimens remained above the statically light compacted specimens curves. In general, it can be seen that the total and matric suction decreased with an increase in the degree of saturation for both soils.

The degree of saturation versus suction curves for both soils compacted with different compaction efforts show a non-uniqueness relationship. However, the water content versus suction curves for both soils was found to be unique. Similar behaviour was observed by Agus (2005) for sand-bentonite mixture.

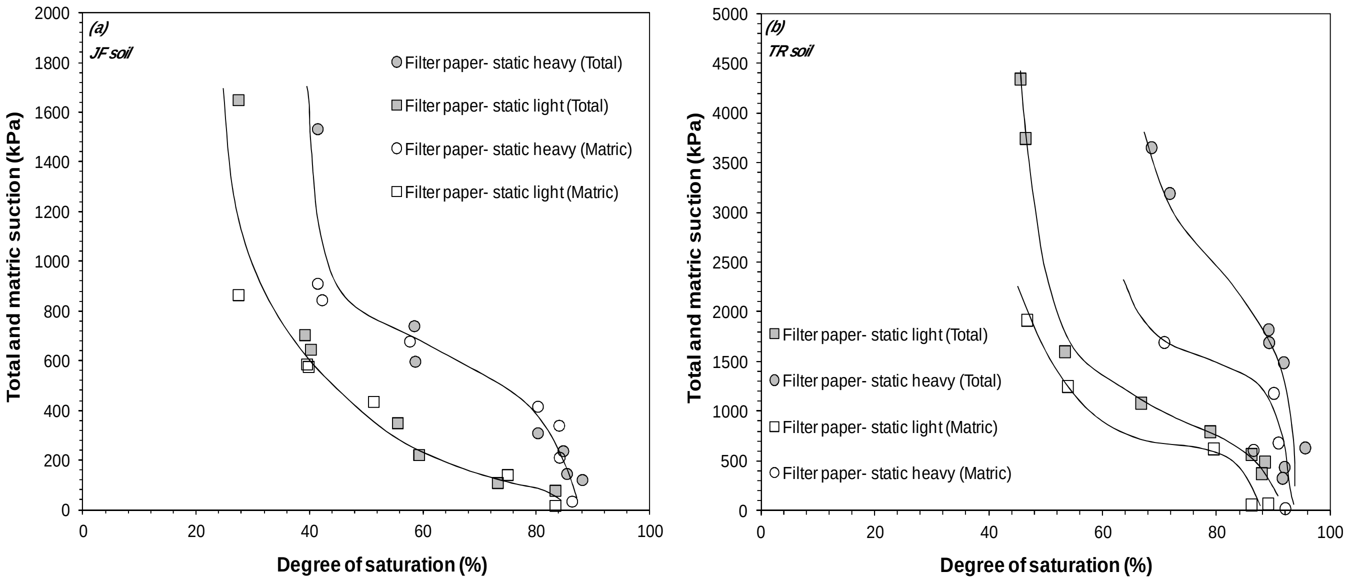



***Fig. 8.11 Degree of saturation versus total and matric suction plot for (a) JF soil specimens and (b) TR soil specimens tested using filter paper method***

### 8.3.2 Chilled-Mirror dew-point test results

Chilled-mirror dew-point device (WP4C) was used to measure total suctions of statically compacted specimens and soil-water mixtures of JF and TR soils. The influence of compaction water content, degree of saturation, and compaction efforts on total suction was studied.

#### *8.3.2.1 Water content versus total suction*

Figures Figs. 8.12*a* and *b* (normal scale) and Figs. 8.13*a* and *b* (log-scale) present the water content versus total suction relationship of JF and TR soils obtained using the chilled-mirror device. The tests results indicated that the total suction results of the statically heavy compacted specimens are essentially the same as those of the statically light compacted specimens. For both soils, the water contents versus total suctions plots show a unique relationship with no significant influence of compaction density.

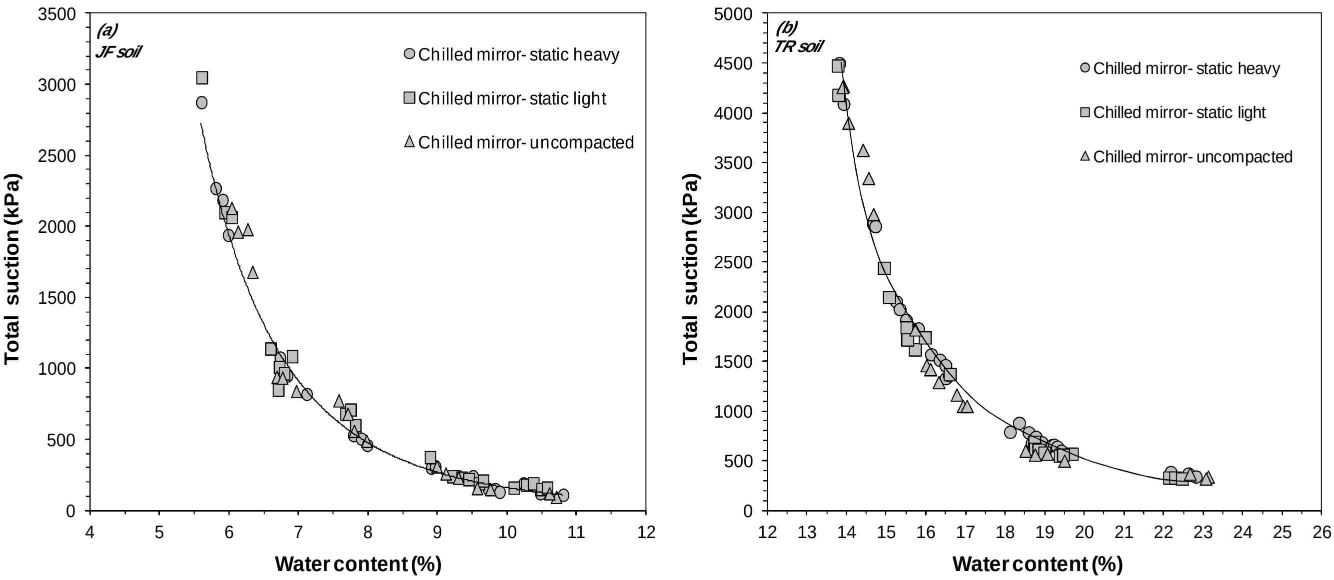



***Fig. 8.12 Water content versus total suction plot (normal scale) for (a) JF soil specimens and (b) TR soil specimens, tested using chilled-mirror device***

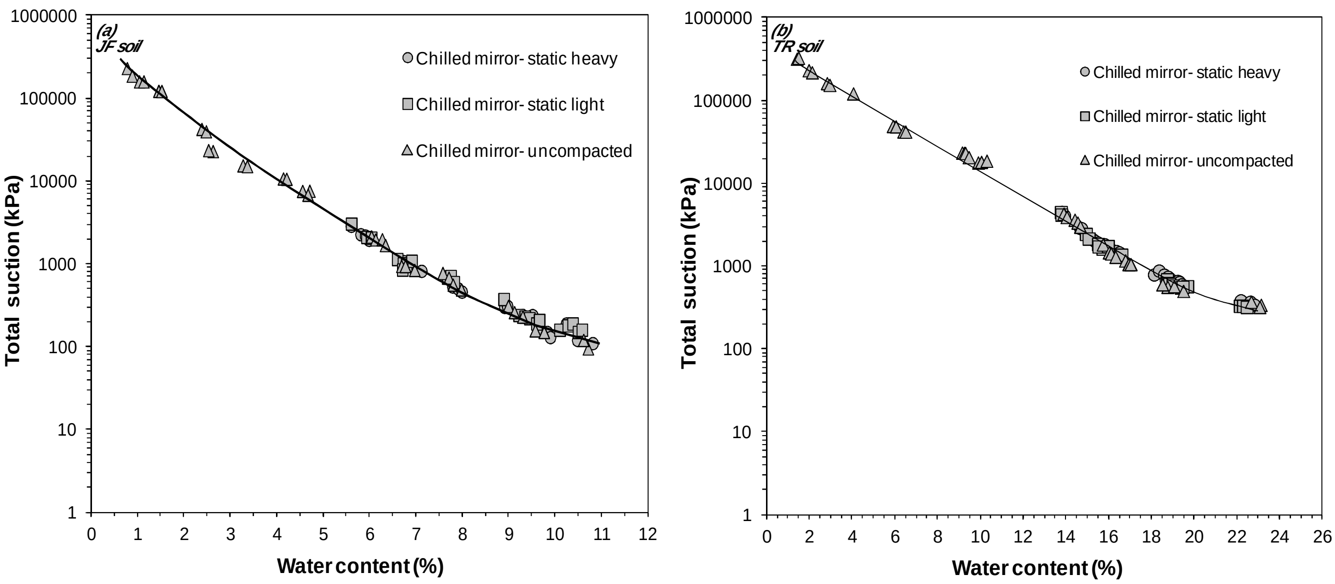



***Fig. 8.13 Water content versus total suction plot (log - scale) for (a) JF soil specimens and (b) TR soil specimens, tested using chilled-mirror device***

### *8.3.2.2 Degree of saturation versus total suction*

The test results of degree of saturation versus total suction for JF and TR soils are shown in Figs. 8.14*a* and *b*, respectively. It can be seen that the total suction of the both soils increased with an increase in the compaction effort. At any degree of saturation value, the statically heavy compacted specimens showed higher value of total suction for both soils. Gradual reductions in the total suction with an increase in the degree of saturation were noted for the specimens of JF soil specimens for both heavy and light compaction efforts (Fig. 8.14*a)*. Similar observation was made for the statically-light TR soil compacted specimens (Fig. 8.14*b*). However, the statically-heavy TR soil specimens showed a abrupt decrease in total suction between the degree of saturation of 90 and 95%.

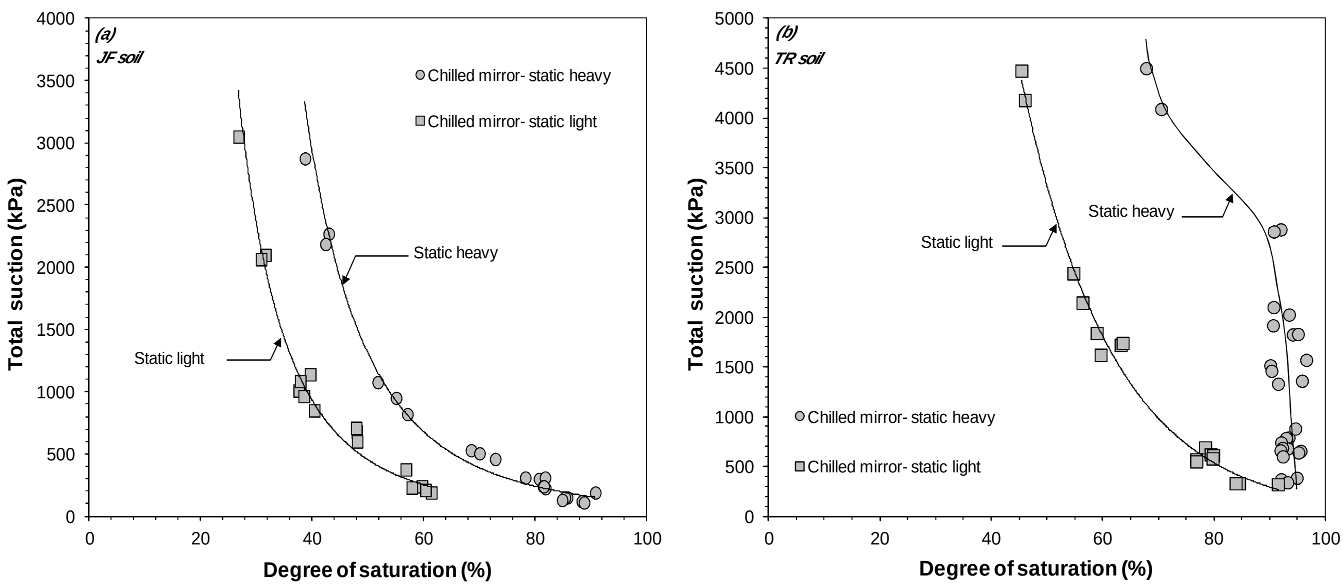



***Fig. 8.14 Degree of saturation versus total suction plot for (a) JF soil specimens and (b) TR soil specimens tested using chilled-mirror device***

The test results of the degree of saturation versus total suction with different compaction efforts are shown to be non-unique relationship, whereas, the water content versus total suction test results revealed uniqueness relationship. Agus (2005) showed that, the change in total suction for wet of optimum compacted specimens is due to the discontinuity of the air phase which reflected in a reduction in dry density with compaction water content. The increase of compaction water content decreases the total suction and dry density.

## 8.4 Concluding Remarks

Total and matric suctions of compacted specimens of JF and TR soils are presented in this chapter. Total suction measurements were carried out using filter paper and chilled-mirror dew-point tests, whereas matric suction measurements were from the filter paper tests. Test results presented in this chapter emphasized the following aspects:

- Varying the equilibration period between the filter paper and suction sources produced different calibration curves, particularly at low suction level. Furthermore, hystereses were observed between drying and wetting filter paper calibration curves. This suggested that similar calibration and measurement tests procedure should be adopted when using filter paper method.
- The water content of soil was found to influence the suctions significantly. No influence of the dry density on suction measurements using filter paper and chilled-mirror tests was observed.
- Uniqueness in relationship between suction and water content was observed while the suction-degree of saturation relationship was found to be non-unique for both soils.

# CHAPTER 9

# COMPATIBILTY OF SUCTION MEASURMENT TECHNIQUES

## 9.1 Introduction

In the past, different methods have been developed and suggested by various researchers for measuring matric and total suctions, either directly or indirectly. However, compatibility of the measurement of soil suction by different techniques still remains to be fully explored.

The objectives of this chapter were (*i*) to compare the SWCCs established by pressure plate and salt solution tests with the measured matric and total suctions determined by null-type, filter paper and chilled-mirror dew-point tests, (*ii*) to compare the test results obtained by controlled and measured suctions in pressure plate and null-type axis-translation tests, and (*iii*) to compare the total suction measurements determined by two testing procedures using the chilled-mirror dew-point device (WP4C). Both the test results of JF and TR soils were considered in this chapter.

This chapter start with a comparison between the measured suction from various suction measurement techniques and the SWCCs, then the measured matric suction using null-type axis-translation device are compared with the suction-water content SWCCs. The effects of two adopted testing procedures for total suction using chilled-mirror WP4C device are discussed. Towards the end of the chapter, the concluding remarks are presented.

## 9.2 Comparison of suction test results with SWCCs

The measured matric suctions of the specimens of JF and TR soils using null-type and contact filter paper tests are compared with the SWCCs of the soils that were established using pressure plate and salt solution in Figs. 9.1 and 9.2. For clarity, the SWCCs best-fit of the soils are shown in Figs. 9.1 and 9.2. The measured total suctions of both soils using non contact filter paper and chilled mirror tests are also included in Figs. 9.1 and 9.2. Similarly, the matric and total suction tests results are compared with the suction-degree of saturation best fit SWCCs of JF and TR soils in Figs. 9.3 and 9.4. Note that the suction-degree of saturation SWCCs of the soils were established based on suction-water content SWCCs and shrinkage curve results (chapter 5). The SWCCs of JF and TR soils are corresponding to dry and wet of optimum conditions. Therefore, the SWCCs for dry and wet of optimum conditions were considered as the lower and upper boundaries.

Figures 9.1 and 9.2 showed that the results from the null-type axis-translation tests generally agreed well with the SWCCs results at higher water contents considering that the specimens tested for the SWCCs had greater initial water contents and for different initial placement conditions. On the other hand, for water contents less than about 11.0% and 20.0% or for matric suctions greater than about 30 kPa and 100 kPa, for JF and TR soils, respectively, the measured matric suctions by null-type axis-translation tests remained somewhat below that of the applied suction in the pressure plate tests. Vanapalli et al. (1999) reported that the results of matric suction from null-type apparatus were similar to that obtained from the suction-water content SWCC for soil specimens that had similar compaction conditions.

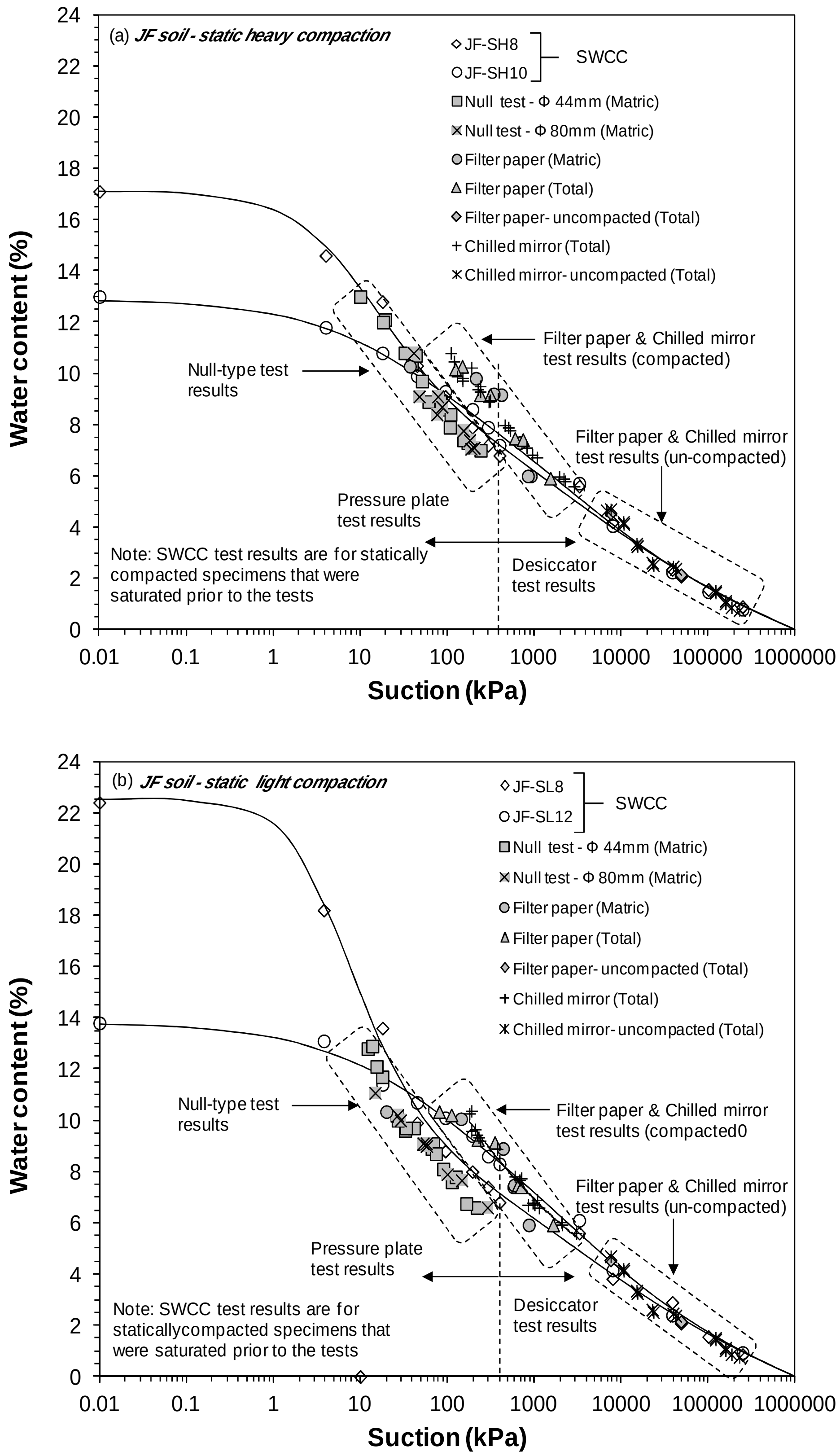



*Fig. 9.1 Comparison of suction test results with suction – water content SWCCs of JF soil*

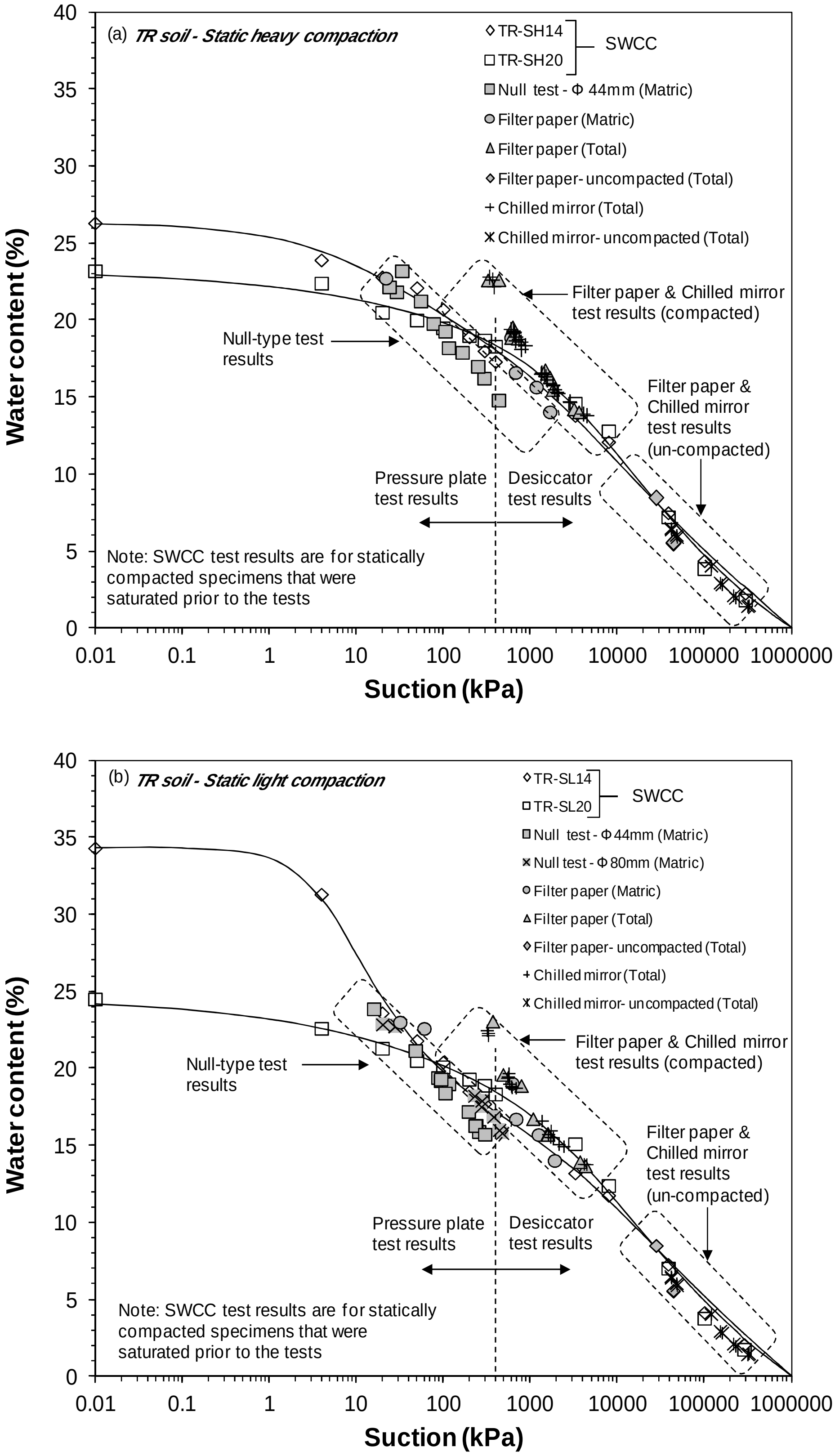



***Fig. 9.2 Comparison of suction test results with suction – water content SWCCs of TR soil***

It can be clearly noted from the Figs. 9.1 and 9.2 that for matric suctions greater than about 30 kPa and 100 kPa, for both JF and TR soils, respectively, the matric suctions measured by using null-type axis-translation and contact filter paper tests did not agree. On the other hand, measured matric suctions by filter paper method were close to the SWCC results.

For any soil and irrespective to compaction efforts (compaction dry density), total suction measurements using contact filter paper and chilled mirror tests were in good agreements. For suctions greater than about 1000 kPa, the contact filter paper and chilled mirror tests tend to give similar results in comparison with SWCCs tests (desiccator test) results. However, as the suction decreased to values less than 1000 kPa, both techniques generally provided higher suction values than the SWCCs test results. The initial compaction conditions of the soil specimens were not strictly on the compaction curves (BS-heavy and BS-light); hence, some differences can be noted between the measured total suction and the SWCC results.

Figures 9.3 and 9.4 present the best fit SWCCs for specimens corresponding to dry and wet of optimum conditions that were established using pressure plate and desiccator tests in conjunction with shrinkage tests (Clod test) for both JF and TR soils. The measured total and matric suctions of compacted specimens are shown in Figs. 9.3 and 9.4 for comparison. The test results showed that the measured total and matric suction were generally lie between the dry and wet of optimum SWCCs. It can be seen from Figs. 9.3 and 9.4 that at higher degree of saturation ($S_r$ = 90 %) the measured total and matric suction were generally close to the SWCCs. As the degree of saturation of the compacted specimens decreased, the values of total and matric suctions fall below the SWCCs. The discrepancies in the suction measurements using the null-type, filter paper, and chilled-mirror device became more pronounced with decreasing degree of saturation for both soils. Such a difference is mainly due to the difference in structure of the compacted soil specimens.

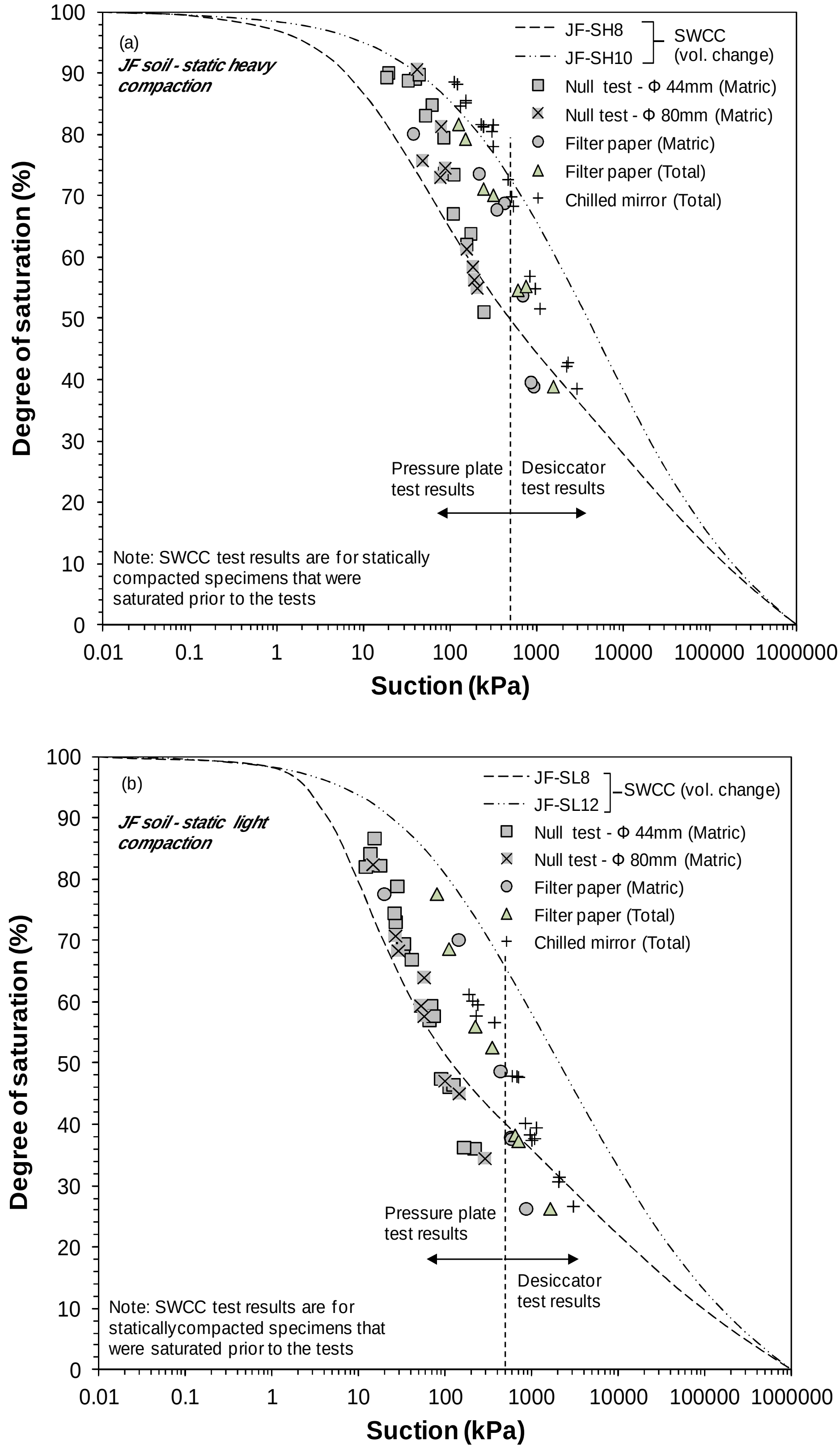
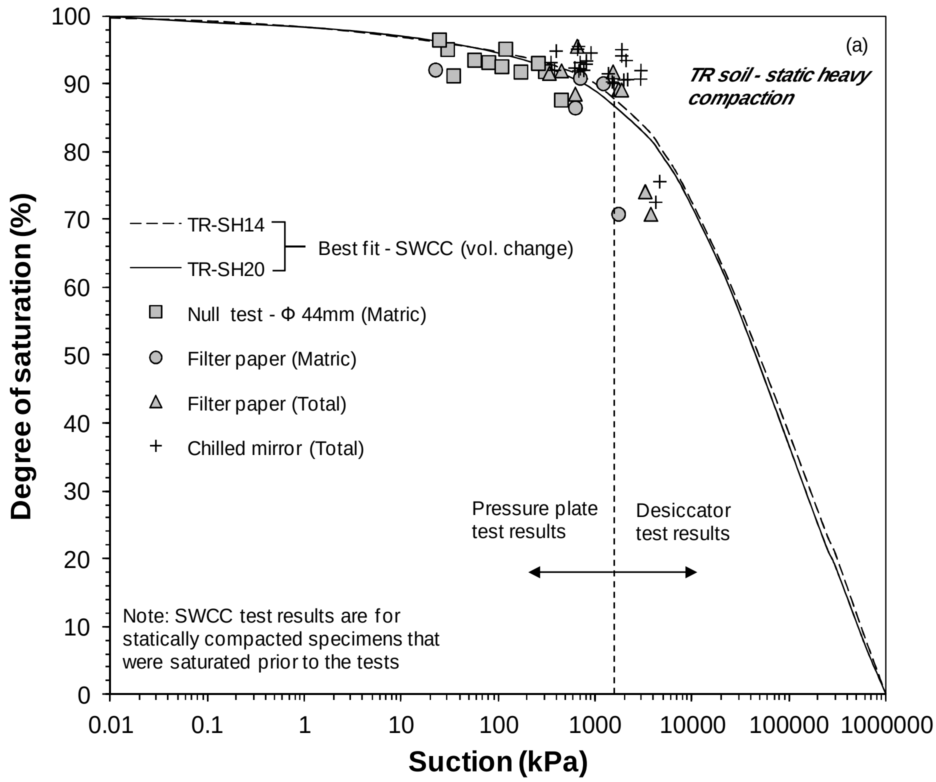



***Fig. 9.3 Comparison of suction test results with suction – degree of saturation SWCCs of JF soil***



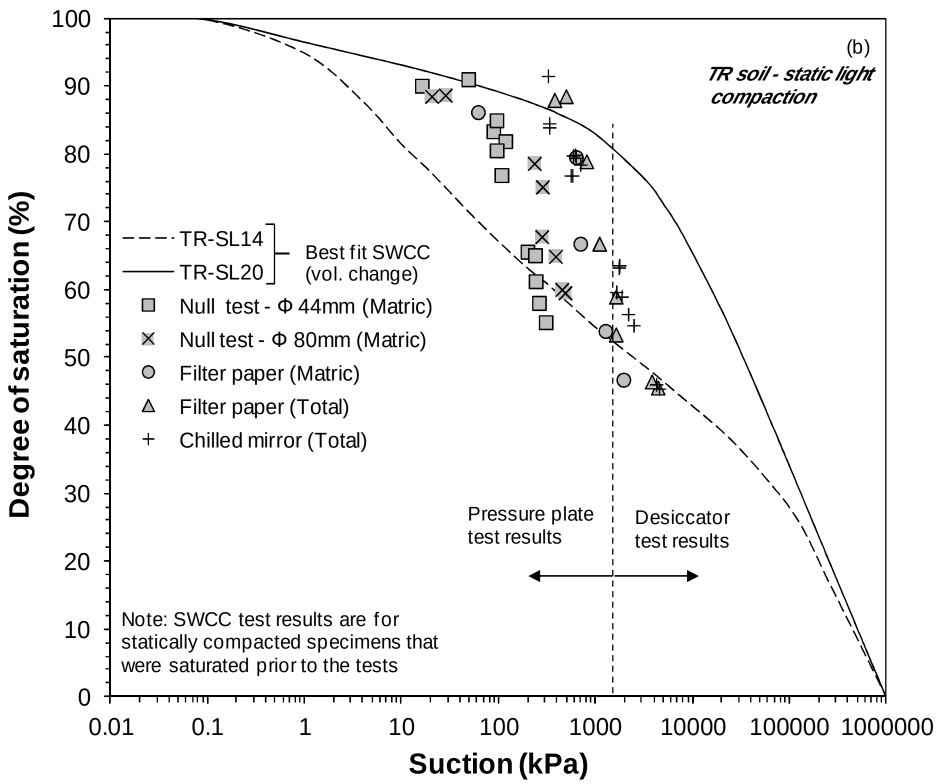




***Fig. 9.4 Comparison of suction test results with suction – degree of saturation SWCCs of TR soil***

The measured matric suctions using contact filter paper were higher than the null-type measurements. This can be explained due to a lack of water phase continuity between soil specimen and ceramic disk in the null-type device (chapter 7). Additionally, some scatter was observed on the measured total and matric suction obtained by filter paper method for soil specimens with a low degree of saturation. One possible reason could be due to the lack of contact between the filter paper and the soil specimens.

## 9.3 Comparisons between controlled and measured matric suctions using axis-translation technique

Pressure plate and null-type axis translation tests work on the same principle of axis translation technique. However in case of pressure plate test, the suction is usually controlled, whereas in null-type axis translation test the suction is actually measured. In an attempt to compare the matric suction values obtained by pressure plate and null-type axis-translation tests, additional tests were carried out. The procedure used in this testing program was to equilibrate the soil specimen under applied suction in pressure plate and then measuring the matric suction of the same specimens using null-type axis-translation device.

Statically compacted specimens of JF and TR soils were used in this testing program. Each soil specimen was saturated prior to the placement in the pressure plate and was subjected to different applied suction in different pressure plate. Once the specimen had equilibrated under a predetermined applied suction, the final weight of the specimen was taken and then the specimen was transferred immediately to the null-type device for matric suction measurement. Once the suction measurement was completed, the mass the specimen was measured and the water content was determined by oven drying method.

The water content of all specimens at end of pressure plate tests were back-calculated based on the final water contents of the corresponding specimens that were tested in the null-type device. The water contents of the specimens that were tested in null-type device were compared with the water contents of the specimens that were tested in pressure plate, and were found to be less than ± 0.05 % in all cases, which was considered to be insignificant.

The imposed matric suctions and the measured matric suction are presented in Fig. 9.5. It can be noted from Fig. 9.5 that even though the test results from both methods follow a similar pattern, the test results showed that the measured matric suctions of the soil specimens differed significantly. The differences in measured matric suction were increased as the water content decreased. This is can be attributed to the lack of water phase continuity between the water in the soil specimens and the water in the ceramic disk during null-type axis-translation test (see chapter 7).

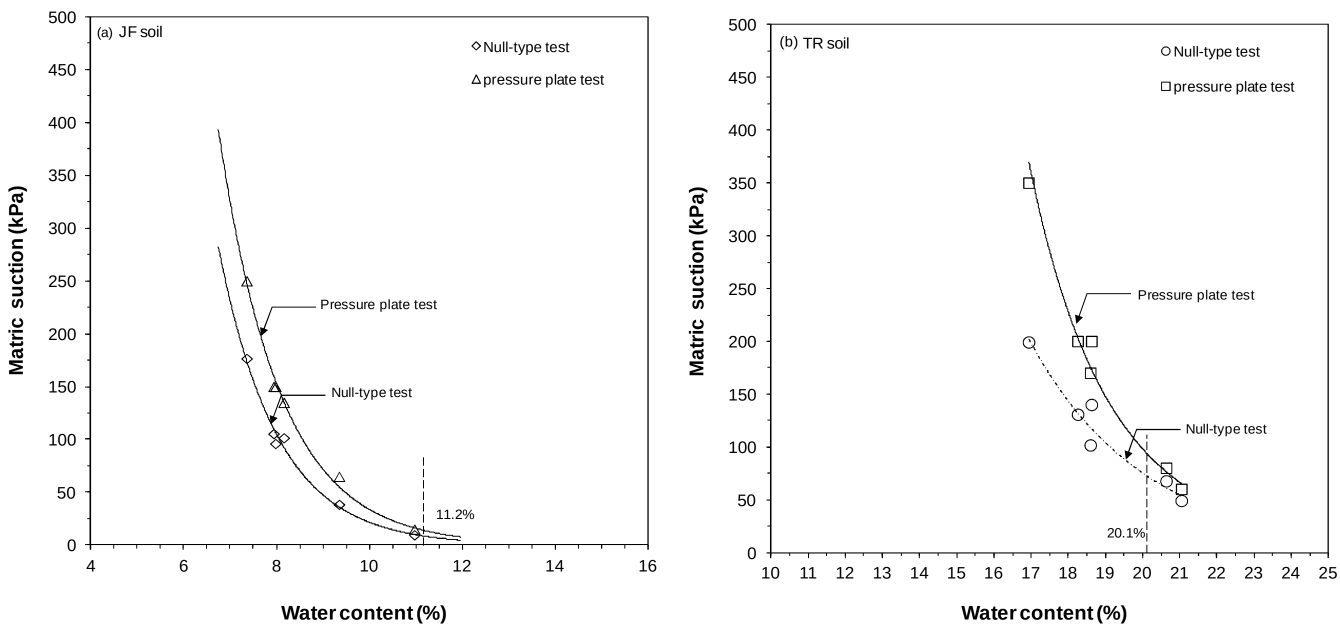


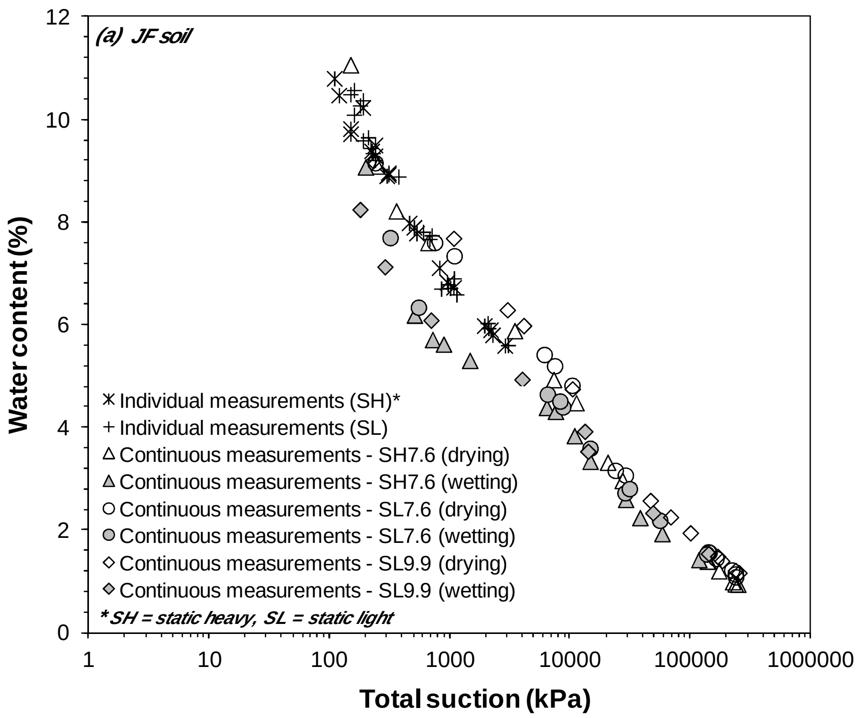

***Fig.9.5 Comparison between pressure plate and null-type test results***

## 9.4 Effect of testing procedure on measured total suction using chilled-mirror device

The chilled-mirror dew-point device (WP4C) was used to investigate the effect of testing procedure on measured total suction. Tests were carried out on statically compacted specimens following two different procedures. In the first procedure, individual measurements of total suction were performed on specimens that were prepared with different initial compaction conditions (varying in dry density and water content) as presented in chapter 8. In the second approach, continuous measurements of total suction during drying and wetting processes on independent compacted specimens were carried out.

For continuous measurement, the compacted specimens were placed in stainless steel specimen cup and then saturated by adding a predetermined amount of distilled water to achieve 100% saturation. The specimens were covered and left it to equilibrate for overnight prior to testing. The suction was then measured and the weight of the specimen was recorded. Further, the specimen was allowed to air dry for two hours and was then covered and left for equilibrium following which another suction measurement was undertaken. The procedure was repeated until the final reading during the drying process. At each stage, measurements were taken twice to ensure repeatability of the results. Measurements during the wetting process were performed in the same manner but instated of allowing the specimen to dry, drops of water were added to saturate the specimen. The water contents at each suction value were back calculated based on the measured weight changes. It should be noted that the calibration of the device was checked by measuring the suction of a 0.5M KCl solution on each day of the test.

Test results of total suction obtained from continuous and individual measurements are presented in Figs. 9.6*a* and *b* for both JF and TR soils. It can be seen clearly that measurements of suction by two procedure adopted follow similar trend in which the suction increased as the water content decreased. Additionally, the suction measurements by both procedures agreed well irrespective of the difference in the dry density of the specimens.



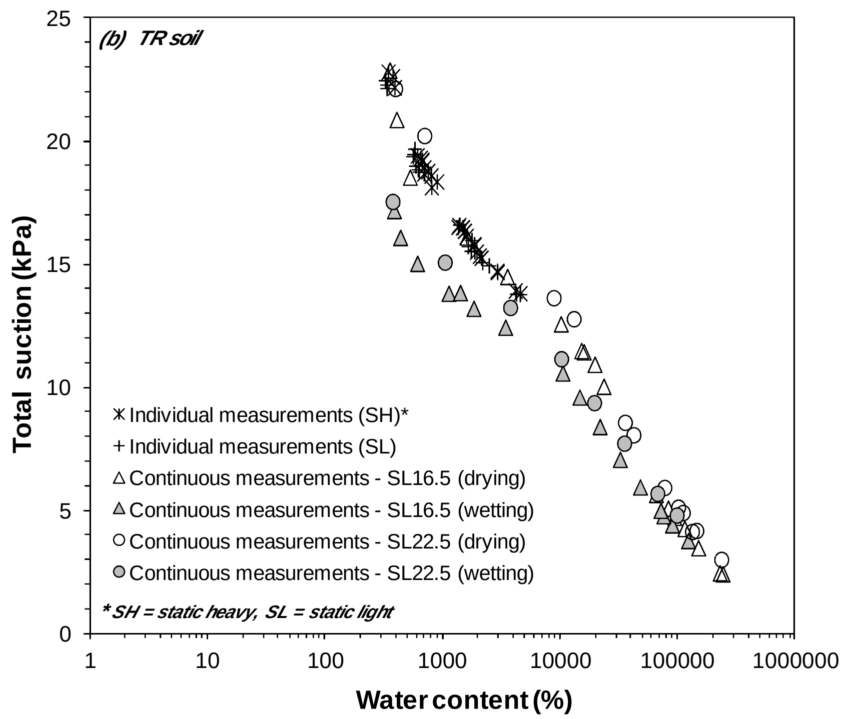




***Fig. 9.6 individual and continuous measurements of total suction versus water content using chilled-mirror device for (a JF soil, and (b) TR soils***

## 9.5 Concluding remarks

Six different methods were used to determine suctions of statically compacted specimens of JF and TR soils. Suctions were applied using pressure plate and desiccator tests, whereas null-type axis-translation, contact filter paper, chilled-mirror, and non contact filter paper methods were used for measuring matric and total suctions. Based on the study presented in this chapter, it can be concluded that:

- The results from the null-type axis-translation tests generally agreed well with the SWCCs results at higher water contents. However, for matric suctions greater than 30 kPa for JF soil, and 100 kPa for TR soil, the measured matric suctions by null-type axis-translation tests remained below that of the applied suction in the pressure plate tests. The measured matric suctions using null-type axis-translation and contact filter paper tests were found to be different. However, measured matric suctions by filter paper method were close to the SWCC results.
- For suctions greater than 1000 kPa, the contact filter paper and chilled mirror tests produced similar results when compared with the SWCC tests (from desiccator tests). However, as the suction decreased, both techniques generally provided higher suction values than the SWCCs test results.
- The test results indicated that the measured total suctions of individual soil specimens prepared with different compaction conditions and continuous measurements of total suction during drying process on independent compacted specimens using chilled-mirror device, were very consistent.

# CHAPTER 10

# CONCLUSIONS

Several geotechnical engineering problems involving soils are associated with the negative pore water pressure or suction in soils. The shear strength, the hydraulic conductivity, and the volume change behaviour of unsaturated soils are controlled by both soil suction and its relationship with the water content. Therefore, in order to understand the engineering behaviour of unsaturated soils, it is extremely vital to establish water retention behaviour soils.

This study constitutes one of the first attempts to study the behaviour of unsaturated Libyan soils. Two soils from Libya were used in this study. The soils were classified as silty sand of low plasticity (SML) and inorganic clay with intermediate plasticity (CI). The objectives of the thesis were to study the influence of compaction type, compaction effort, compaction dry density, and compaction water content on matric and total suctions of the Libyan soils.

The physical and compaction properties of the soils used were determined following the standard laboratory procedures. Compacted specimens were prepared by compacting soil-water mixtures at several dry densities and water contents. Both static and dynamic compaction type were considered corresponding to several compaction conditions of the soils. The drying and wetting suction-water content SWCCs of the soils were established by axis-translation and vapour equilibrium techniques. The drying suction-degree of saturation SWCCs and suction-void ratio SWCCs of the soils were also established based on the drying suction-water content SWCCs in conjunction the water content-void ratio shrinkage paths that in turn were established using Clod tests. Comparisons were made between the air-entry values (AEVs) of the soils determined based on suction-water content SWCCs and suction-degree of saturation SWCCs. Suction-void ratio SWCCs were also compared with pressure-void ratio determined from consolidation tests. Null-type axis-translation, filter paper, and chilled-mirror techniques were used for suction measurements.

A detailed study was carried out concerning the continuity in the water phase between soil specimens, the water in the ceramic disk, and the water in the water compartment during the null-type axis-translation tests. Some aspects that influence contact and non contact filter paper calibration curves, such as suction sources, equilibrium time, and hysteresis, were evaluated.

Based on the findings reported in this thesis, the following conclusions were drawn.

1. The compaction water content and dry density significantly influenced the suction-water content SWCCs of the soils at low suction range, whereas their influence was insignificant on the SWCCs at high suctions.
2. The AEVs of the soils increased with an increase in the compaction water content at a constant dry density, and with an increase in the compaction dry density at a constant water content.
3. Significant hysteresis was noted between the drying and the wetting SWCC of both the soils studied. Irrespective of the initial compaction conditions, the wetting SWCCs of any soil were similar
4. The measured suctions of the soils using null-type axis-translation technique was found to be dependent upon the water content, with some influence of dry density and compaction method.
5. Contact and non contact filter paper calibration curves were found to be dissimilar. The equilibration time and suction source contributed to the dissimilarity in the calibration curves.
6. The agreements between suctions measured using non contact filter paper and chilled mirror tests were found to be good. The water content of soils specimens was found have significant bearing on the test results, whereas the influence of dry density was found to be insignificant.

7. The soil classified as SML exhibited either two (residual and zero) or three shrinkage zones (normal, residual, and zero), whereas the soil classified as CI was accompanied by either three (normal, residual, and zero) or four (structural, normal, residual, and zero) shrinkage zones. The different phases of shrinkage were found to be dependent upon the soil type and the initial compaction conditions (i.e., water content and dry density).

The conclusions 1 to 7 are in consistence with the findings reported in the literature.

8. The AEVs and the residual suctions obtained from the suction-degree of saturation SWCCs (established by combining the suction-water content SWCCs with the shrinkage test results) were found to be distinctly greater than that obtained from the suction-water content SWCCs. The volume change behaviour of the soils is held responsible for the differences in the AEVs from the two approaches.
9. The desaturation points were distinct on the shrinkage paths of initially saturated slurried specimens of both soils and the water content at the desaturation points were found to be close to the plastic limits of the soils. Suctions corresponding to the desaturation points and the plastic limits of the soils were found to be in very good agreements with the AEVs determined from suction-degree of saturation SWCCs.
10. The water contents at the air entry on the shrinkage curves for the slurried soil specimens of both soils were found to be greater than that of the corresponding shrinkage limits of the soils suggesting that consideration of the shrinkage limit of a soil may overestimate the AEV. The residual suctions of initially saturated slurried specimens determined from the suction-degree of saturation SWCCs and the suctions corresponding to the shrinkage limits were found to be dissimilar.
11. Direct measurements of suctions of compacted soil specimens using the null-type device featured very high RHs (> 95%) and ambient temperature within the air pressure chamber, insignificant differences between the water contents of the specimens before and after the tests, and similar suctions for specimens that either covered partially or fully the ceramic disk during tests which clearly suggested that evaporation of water from soil specimens and from the ceramic disk did not significantly contribute to longer equilibration times in null-type tests.

12. An increase in the chamber air pressure soon after completion of the null-type tests clearly indicated that the water phase continuity between the water in the soil specimens and the water in the ceramic disk was lacking in all cases. The measured water pressures in the water compartment were found to be less than the applied chamber air pressures. The water pressure in the water compartment showed a tendency to increase for the specimens with higher water contents.
13. The water phase continuity during null-type tests could be improved by considering various interfaces between soil specimens and the ceramic disk. However, the measured suctions of soil specimens with interfaces were found to be far smaller as compared to the specimens that were tested without any interfaces. Depending upon soil type and initial compaction conditions, the matric suction reduced by about 30, 60, and 55% with interfaces as slurried kaolinite, slurry prepared from the soils, and a wet filter paper.
14. The results from the null-type axis-translation tests generally agreed well with the suction-water content SWCCs at higher water contents. However, with an increase in matric suction, the null-type test results remained below that of the SWCCs established from the pressure plate tests. The measured matric suctions using null-type and contact filter paper tests were found to be dissimilar. However, the measured matric suctions by filter paper method agreed well with the SWCC results. The differences between the null-type results and both the pressure plate results and the filter paper results are attributed due to the lack of water phase continuity during the null-type tests.
15. The total suctions determined by using techniques that employ the vapour phase equilibrium (i.e., non contact filter paper, chilled-mirror dew-point, and desiccator tests) were found to be similar.
16. Total suctions measured by the chilled-mirror dew-point technique either by using independent soil specimens with different water contents or by using a single soil specimen taken through a drying process from very high water content were very similar indicating that different experimental procedures did not introduce any errors in suction measurements.

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