Consolidation behavior of an unsaturated silty soil during drying and wetting

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Abstract

In this work the effect of hysteresis phenomenon on the consolidation behavior of an unsaturated silty soil was investigated through a program of experimental tests. Compacted samples were prepared by the slurry method and experimental tests were carried out in a double-walled triaxial cell. The consolidation tests were conducted by the ramping method at suctions of 0, 100, 200, 250 and 300 kPa on drying and wetting paths of soil water characteristic curve. The results show that during stabilization, for both conditions (drying and wetting), the paths of specific water volume and specific volume are not consistent. In addition, the yield stress for the wetting path is higher than that for drying. The trend of variations of specific water volume during loading is similar to the consolidation curves for different suction. For both conditions of drying and wetting, the slope and intercept of virgin line due to variations of specific volume and specific water volume are function of suction. The values of them are decreased with increasing suction and the amounts of them are greater for dry path than wetting.

Key words: unsaturated soil, hysteresis, consolidation, specific volume, specific water volume

1- Introduction

Unsaturated soil is a three phase material containing soil particles, water and air. The mechanical behavior of unsaturated soil is strongly influenced by both pore air pressure (u_a) and pore water pressure (u_w). The difference between u_a and u_w is defined as matric suction ($s = u_a - u_w$).

Drying and wetting

It is possible to obtain an experimental relationship between matric suction and water content (volumetric or gravimetric) or degree of saturation, which is usually represented in a plot in terms of water content or degree of saturation versus matric suction. Such relationships are known as Soil Water Characteristic Curves (SWCC). Physically this will correspond to a reduction in the thickness of the water envelopes around clay particles, as well as the progressive emptying of the inter-particle pores. As expected, the opposite will be true whenever the matric suction decreases. In a situation of equilibrium, and for a given value of matric suction, the amount of fluid retained within the soil skeleton will be a function of the size and volume of the saturated pores, as well as the amount of adsorption films surrounding the individual clay particles. The exact nature of the relationship between matric suction and water content or degree of saturation is dependent on a number of soil parameters, such as its mineralogical composition, particle size distribution, fabric, etc. The hysteresis phenomenon results from different water content or degree of saturation in the drying and wetting curves at a given value of suction. For two points at the same suction (on wetting and drying curve) the water content or degree of saturation on a drying path is much higher than a wetting path. The hysteresis phenomenon has been attributed to a number of different causes such as geometrical non-uniformity of pores (known as ink bottle), the effect of contact angle between the solid and liquid phase and encapsulation of air in pores (Yong and Warkentin, 1966; Fredlund and Rahardjo, 1993 and Dineen, 1997). Wheeler and Karube (1996) stated that hysteresis has an important effect on the mechanical behavior of unsaturated soil. Researchers such as Wheeler *et al.* (2003), Gallipoli *et al.* (2003), Phm *et al.* (2005), Likos and Lu (2004) and Tamagnini (2004) attempted to incorporate the hysteresis effect into constitutive models. Sivakumar *et al.* (2006) conducted a number of tests on compacted clay soil to investigate the effect of wetting and drying on compression of the soil. They concluded that the yielding of the samples during drying is less than the one during wetting. Khalili and Zargarbashi (2010) studied the effect of hysteresis on effective stress in unsaturated soil. They presented a simple model for contributing the effect of suction on effective stress during hysteresis. Guan *et al.* (2010) developed shear strength equations for unsaturated soil by involving the hysteresis phenomenon. Lu *et al.* (2013) indicted that there is a significant difference between the hydraulic conductivity and porosity of soil due to the hysteresis that influences the properties of soil. Likos *et al.* (2014) established soil water characteristic curves for different soils and presented an approach to find the parameters needed for estimating wetting path.

Consolidation

The application of load to an unsaturated soil sample will result in the generation of excess pore-air and pore-water pressures. The excess pore pressures will dissipate with time and will eventually return to their original values before loading. The dissipation process of pore pressure is called consolidation and results in a volume decrease or settlement (Fredlund and Rahardjo, 1993). In saturated soils, the instantaneously applied total stress is first supported by the pore water and the soil skeleton is progressively loaded during pore-pressure dissipation. Researchers such as Barden and Sides (1970), Fredlund and Morgenstern (1977), Fredlund and Rahardjo (1986), Escario and Juca (1989) and Rahardjo and Fredlund (1995 and 1996) modified a conventional odometer and conducted consolidation tests on soil samples under different suctions. They used the axis translation technique for creating the desired suction in the sample. In this test the lateral deformation of the sample is confined and the volume change is obtained only in vertical direction. Isotropic consolidation tests were also conducted in triaxial apparatus by researchers such as Wheeler and Sivakumar (1995), Cui and Delage (1996), Estabragh *et al*. (2004) and Estabragh and Javadi (2015) among others. In isotropic consolidation the sample is compressed isotropically to a normally consolidated condition by increasing the mean net stress, p^{net} ($p^{net} = \frac{\sigma_1 + 2\sigma_3}{3} - u_a$, where σ_1 and σ_3 are axial and radial stress) with increasing the cell pressure while holding the suction constant. The increasing mean net stress (applied load) is usually carried out by step loading or ramp loading. Cui and Delage (1996) showed that the application of step loading is not suitable for unsaturated soils because this method overestimates the coefficient of compressibility and underestimates the value of yield stress of the soil.

Aim of this work

A review of the literature shows that the majority of the relationships and models for unsaturated soils have been developed based on the study of mechanical behavior of soils under drying paths. However, there is very limited information on the mechanical properties of unsaturated soils in during wetting paths and particularly in transition from drying to wetting.). In nature, there are also changes in suction from high values to low values due to rainfall, etc (corresponding to the wetting path of SWCC) that may cause failure in embankments or other structures. In this paper, the investigation focuses on isotropic consolidation of soil at the same suctions on both the dry and wet paths of soil water characteristic curve. In what follows, the experimental procedure and the results are presented and discussed. A comparison is made between the consolidation behaviors in drying and wetting paths.

2. Experimental study

Most practicing geotechnical engineers employ classical (saturated) soil mechanics to analyze geotechnical engineering problems even if unsaturated conditions are involved. This is wrong, because some of the fundamental features of unsaturated soil behavior, such as volumetric compression during wetting (often called “collapse compression”) can not be properly represented without an understanding based on unsaturated soil mechanics. In reality, field applications such as analysis of slope instabilities, landslides, underground disposal of radioactive waste, earth dams, embankments and highways all require proper understanding of the behavior of unsaturated soils, as do foundations and all other geotechnical activities in regions where the natural soil is unsaturated to considerable depth. Therefor the experimental program in this paper focuses on testing of soils in unsaturated conditions.

2.1. Soil properties

The soil that was used in this experimental work was silt with low plasticity. The soil was composed of 12% clay, 53 % silt and 35 % sand. It had a liquid limit of 34% and plasticity index of 2%. The soil can be classified as ML (silt with low plasticity) according to the Unified Soil Classification System (USCS). Standard Proctor compaction tests were carried out on the soil according to ASTM D 698-07. The optimum water content in the standard compaction test was 16.0 % corresponding to a maximum dry unit weight of 15.0 kN/m^3.

2.2. Sample preparation

The test program included a number of isotropic consolidation tests on the samples of the soil. The soil samples that were prepared by researchers such as Wheeler and Sivakumar (1995) and Estabragh and Javadi (2008) were relatively dry initially, with an open void structure (i.e. specific volume nearly equal to 2) and then were wetted to different target suctions. Following this approach would have introduced structure and collapsibility well beyond what would be expected from the effect of suction in the soil. To avoid collapsibility and hardening arising from the sample preparation, it was decided to prepare saturated samples after the compaction and then subject them to different values of target suction. The slurry method was selected for preparing the samples to use for testing. Saturated samples were used by some other researchers such as Rahardjo *et al*. (2004) and Thu *et al*. (2007). In the slurry method the selected water was prepared about four times the liquid limit of the desired soil and added to the soil. The resultant slurry was mixed by hand. A number of cylindrical tubes with 150 mm diameter and 300 mm height (hereafter referred to as consolidation moulds) were used. Before filling each mould with slurry a filter paper with the same diameter as the tube was placed over the drainage base to prevent clogging of the drainage paths with soil particles. A saturated porous stone was placed on top of the filter paper that was itself covered with another filter paper which was used to stop the soil particle from clogging the porous stone. The tube was then screwed to the base. After preparing the moulds the slurry was poured slowly into each mould. In order to achieve an equilibrium condition this mixture was covered with a nylon wrap and kept for about two days. During this time, settlement of particles occurred and a liquid was formed on the top of the settled particles. This liquid was removed from the mould by siphoning, then a filter paper was used to cover the slurry to prevent the top porous stone from being clogged with soil particles. Then the top loading plate with drainage assembly was gradually lowered into the mould, allowing the air to be removed through the drainage line. The slurry was then consolidated by applying overburden stress in increments of 10 kPa using a hydraulic jack, to the maximum consolidation pressure of 80 kPa, while drainage was allowed from the top and bottom of the tube. The procedure of consolidation was conducted according to the ASTM D2435-11 standard. Consolidation was generally completed within about 7 days. After consolidation the samples were extruded into 38 mm diameter thin walled stainless steel tubes. They were waxed at both ends to retain the initial water content of the soil samples. The samples were then stored in a controlled temperature of 20^{oC} ± 1 before being used for testing. The samples that were prepared by this method were uniform and homogeous. Sample uniformity is described as avoiding the presence of interfaces between layers in a compacted sample (Sivakumar, 1993). Uniformity and homogeneity mean uniform distribution of water content and particles in the samples. The samples (38 mm diameter and 76 mm length) that were extracted from the consolidation tubes had no interfaces between the soil layers in the main sample. For uniformity and homogeneity the water content was measured at several random points of sample and they were nearly the same. This ensured that the samples were uniform and homogeneous.

2.3. Experimental apparatus

The tests were conducted in a double-walled triaxial cell. In the design of the apparatus, a conventional triaxial cell was modified to a double-walled cell and used for testing the unsaturated soil samples. A double-walled cell was used to avoid the difficulties that would otherwise have resulted from creep or hysteresis of the inner acrylic cell wall (Wheeler, 1988)). A schematic of the developed apparatus is shown in Fig. 1. Pore-water pressure (u_w) was applied and measured at the base of the sample through a saturated porous filter with an air-entry value of 500 kPa. Pore-air pressure (u_a) was applied at the top of the sample through a hydrophobic membrane and a filter with a low air-entry value. The free air could not pass through the high air-entry disk, but the diffused air could pass through it in solution with water, gather underneath the high air-entry disk, and form air bubbles. The accumulation of air bubbles under the high air-entry disk could prevent the passage of the water from the pore-water controller into the sample through the high air-entry disk and cause serious errors in the measurement of water volume change. To overcome this problem, a flushing system was designed and used, as suggested by Fredlund (1975). The axis translation technique, proposed by Hilf (1956), was used for creating the desired suctions in the samples. In this way, the values of u_w were maintained above atmospheric pressure. The pressures of the inner and outer cells and the pore water pressure were controlled by three pressure controllers. Each pressure controller was controlled independently by stepper motors operating regulation on desired pressure. Pressure transducers were used for measuring the pore water pressure and cell pressures. The stepper motors were operated by a computerized control and logging system that enabled any required stress path to be followed. The stepper motors controlled the pressures of the inner and outer cells, pore water pressure as well as the deviator stress, and measured the axial displacement, sample volume change and flow of water from in or out of the sample. Two Imperial College type volume change measuring devices (as used by Sharma, 1998 and Raveendiraraj, 2009) were used for measuring the flow of water into or out of the soil sample and the inner cell. Before conducting the main tests the apparatus and its accessories were calibrated and then used to carry out the tests.

2.4. Experimental procedure

A program of experimental tests was designed and carried out to examine the effect of hysteresis on the consolidation behavior of the silty soil. As shown in Fig.2 the tests were conducted on samples with suctions of 0, 100, 200, 250 and 300 kPa on both dry and wet sides of soil water characteristic curve. The main stage of the experiments are equalization and consolidation. In addition a soil water characteristic curve was achieved by conducting the drying and wetting cycles on the sample. The test procedures were as follows:

2.4.1. Equalization

In this stage the samples were allowed to equalize to desired suction, which varied between 0 and 300 kPa for different tests (0,100, 200, 250 or 300 kPa) under a given mean net stress (20 kPa) on the drying path of the curve. For the wetting path the initial suction of the sample was brought to 300 kPa and it subsequently followed the desired suction (250, 200, 100 or 0 kPa. In addition, the equalization stage was also conducted on a sample for creating initial suction of 20 kPa, and this sample was used for establishing the soil water characteristic curve.

After setting up the sample in the triaxial cell, all the tubes and fittings between the two cells and the spiral groove at the bottom of the high air-entry disk were flushed to prevent any air entrapment in the system that could affect the results. The pressure of the two cells was increased simultaneously to 10 kPa while the back pressure and air pressure were increased to 5 and 6 kPa, respectively. To achieve a desired matric suction in a sample on the drying path the target values of cell pressure, back pressure, and air pressure were selected. The target and initial values of inner cell pressure and back pressure together with the required time to reach the target values were set in the control program. The pressures were then ramped from the initial values to the target values at the rate of 1.6 kPa/min (6 kPa/hour was used by Thu *et al*. (2007) and 4 kPa/hour by Vassalo *et al*. (2007)) for samples of silty soil). The volumes of water inflow or outflow to the sample and to the inner cell were monitored during equalization. The equalization stage varied in length between tests but usually took between 5 and 8 days. The equalization stage was terminated when the flow of water decreased to less than 0.1cm^3/day (as used by Sivakumar, 1993; Zakaria, 1994 and Sharma, 1998)). For achieving the desired suction in the sample on the wetting path first the initial suction of the sample was brought to 300 kPa. Then the desired suction in the sample was achieved by keeping the air pressure constant (350 kPa) and increasing the back pressure with a suitable rate to a predefined value (100, 150, 250 or 350 kPa).

2.4.2. Test to determine the soil water characteristic curve

The purpose of conducting this test was to determine the air entry value for the soil. The soil water characteristic curve was established after equalizing the sample at the suction of 20 kPa The air pressure and cell pressure were kept constant (350 and 370 kPa respectively) and pore water pressure was decreased with a rate of 0.5 kPa/h (as used by Khallili and Zargarbashi (2010)) until it reached to 50 kPa. During this procedure the drying curve was established so, the suction at the end of the drying path was 300 kPa. For the wetting section, the air and cell pressures were kept constant and pore air pressure was increased at the same rate as drying. It was continued until 300 kPa so, the beginning and end of the wetting section were 300 and 50 kPa as shown in Fig.3. The air entry value was found from this curve to be about 60 kPa by using the method that was proposed by Fredlund and Xing (1994).

2.4.3. Consolidation stage

After the sample was equalized at a pre-specified suction (0, 100, 200, 250 or 300 kPa on dry or wet side of soil characteristic curve) and mean net stress, it was loaded isotropically under the constant suction (air back pressure and water back pressure were kept constant) to a predefined value of mean net stress (usually 550 kPa). The process of ramped consolidation was used to limit the excess pore-water pressure generated at the top face of the sample. The target and initial values of cell pressure, back pressure, and the required time to achieve the target pressures were inserted in the control program. The required information during the ramp consolidation was recorded in a file. At the end of each stage the sample was left until the excess pore-water pressure was dissipated. Loading was continued until virgin state was attained.

3. Results

Fig.4 shows the variations of specific volume and specific water volume with time during the equalization stage for samples tested with suctions of 0, 100, 200, 250 and 300 kPa (drying). The results show that the specific volume changed very slightly for suction of 0 kPa but it decreased for the other suctions (Fig.4a). It can be concluded that by increasing the suction the outflow of water from the sample is increased and specific volume and specific water volume are decreased. Fig.5 shows the variations of specific volume and specific water volume for creating the suctions of 250, 200, 100 and 0 kPa in samples (wetting path).

As explained above, the equalization consisted of two stages; in the first stage the suction of 300 kPa was created in the sample and then it was reduced to a predefined suction. As shown in Fig.5a, the variations of specific volume are made of two stages; in the first stage the specific volume was reduced but in the next stage it was increased until it reached to equilibrium state. Fig.5b shows the variation of specifici water volume with time over 135 hours. During the time that the suction of 300 kPa was created in the sample, the water flowed out of the sample. In the next stage the suction of 300 kPa was changed to 250, 200, 100 and 0 kPa and the water flowed into the sample. It is shown that by decreasing suction more water flowed into the sample.

In the ramped consolidation stage the mean net stress p^{net} was increased from 20 kPa to 550 kPa (the target value of p^{net}) while holding the suction constant (at 0, 100, 200, 250 or 300 kPa on the drying path and 300, 250, 200, 100 or 0 kPa on the wetting path). The variations of specific volume (ν) and specific water volume (v_w) with mean net stress (p^{net}, with p^{net} on a logarithmic scale) during ramped consolidation are shown in Figs. 6 and 7 for the samples on the drying and wetting paths respectively. It is shown from these figures that the volume of the soil and its water content decreased as the mean net stress increased. A continuous increase in mean net stress caused the soil to start to yield at some point due to decrease of specific volume or specific water volume. The values of yield stresses due to specific volume were estimated by the method of intersection of the two linear segments of the consolidation curve as proposed by Cui and Delage (1996) and Sharma (1998). The values of yield stress for suctions of 0, 100, 200, 250 and 300 kPa (dry section) were 60, 105, 145, 160 and 170 kPa respectively. These values were estimated as 85, 125, 155, 165 kPa for suctions of 0, 100, 200 and 250 kPa on the wetting section of the soil water characteristic curve. As expected, the yield stress increased with increasing suction. Figs 6a and 7a compare the behaviors of the samples on the drying and wetting paths of the soil-water characteristic curve, observed during the isotropic consolidation stage. Inspection of these figures shows that, as expected, under the same constant suction, the values of yield stress are higher for the samples on the wetting path than the samples on the drying path.

4. Discussion

Fig.8 shows the variations of specific water volume and specific volume with suction at the end of the equalization stage. Significant differences can be seen in the drying and wetting curves that can be attributed to the hysteresis phenomenon. Similar effects have been reported by a number of researchers such as Ng and Pang (2000); Wheeler *et al*. (2003) and Sivakumar *et al*. (2006). As shown in this figure (Fig.8a) by increasing the suction more water flowed out of the sample and the specific volume was also decreased (Fig.8b). Wheeler and Karube (1996) indicated the pore water in unsaturated soil is divided into three categories: adsorbed water, bulk water and meniscus water. Adsorbed water is considered as a part of solid particles because it is tightly bounded to the soil particles. Bulk water fills the void space and meniscus water occurs at the inter particles contacts around air filled voids. The soil samples that were used in this work were initially saturated and hence all the voids were filled by water (bulk water). When a desired suction higher than the air entry value of the soil is applied to the sample, some water is expelled from the sample and the amount of bulk water is reduced. A number of voids are filled with air and meniscus water is formed at the contact of particles between air and bulk water. Therefore, a curved interface is formed separating the water in the void from the air within two adjacent air filled voids which increases the stability of the soil. As the suction is increased during drying, more water flows out of the sample and air replaces it; so, the radius of curvature of the meniscus water is reduced. By increasing suction the meniscus water is increased which results in higher stability of the soil. When the soil samples are wetted from the initial suction (i.e. 300 kPa) the specific volume is increased. so, it shows that the particles are swelled and water covered the particles and the volume of voids are decreased (Sivakumar *et al*., 2006). At a given suction, the values of specific water volume are not the same on the drying and wetting curves. This indicates that the volume of water that flows into the sample is less than the water that flows out of the sample on the drying path. In other words it may be postulated that water that flows into the sample through large pore space during equalization stage was drawn into smaller pores by suction on establishment of equilibrium condition. Therefore, the number of soil meniscus water contacts is increased on the wet side in comparison with the dry side which leads to higher stability of the sample. This conclusion is consistent with the suggestion by Wheeler *et al*. (2003) who indicated that the stability of a soil skeleton is not particularly influenced by the suction in the meniscus water but is determined by the number of soil/meniscus water contacts. Therefore it is obvious that, at a given suction, the yield stress on the wet side will be more than the dry side. In other words the compressibility of soil samples on wet side is less than dry side.

Fig.9 shows the LC (Loading-Collapse) yield curves for the drying and wetting sections of the soil water characteristic curve. At a given suction, the values of yield stress on the drying and wetting sections are not the same; for drying section they are less than wetting section. It is also shown that the value of yield stress is increased with increasing suction. It appears that the difference in the condition of sample (dry or wet side) at the same suction reflect in the different LC yield curve. It can be said that the location of the yield surface is closely related to the specific volume that sample in any condition achieved. Shifting of the LC yield curve to the right is reflected the lower specific volume of the sample. Consolidation tests were conducted in isotropic stress state. As indicated by Alonso et al. (1987), for the isotropic loading condition the intersection of the yield surface with the $q = 0$ (zero deviator stress) plane defines a loading–collapse (LC) yield curve. The LC yield curve corresponds to the virgin conditions, and the resulting values of specific volume lie on a unique isotropic normal compression surface. The shape of these LC yield curves is consistent with that proposed in the model of Alonso *et al*. (1990) and that reported by Raveendiraraj (2009) and Jotisankasa *et al*. (2009). Zhang and Lyttton (2009a) and (2009b) concluded from a theoretical investigation that the yield stress is decreased with increasing suction which is opposite to the previous research work. To date no experimental evidence has been reported to support this conclusion that yield stress decreases with increasing suction.

Further inspection of the consolidation results (Figs.6a and 7a) shows that when the yield stress at a particular value of suction was exceeded, the soil states fell on an isotropic normal consolidation line (Figs. 10a and b) defined by a linear relationship as used by Alonso *et al*. (1990):

$$v = N(s) - \lambda(s)\ln\frac{p^{net}}{p_c}$$

where v is specific volume, p_c is reference pressure and $N(s)$ and $\lambda(s)$ are intercept and slope of normal compression line and vary with suction. Variation of v_w during loading shows a curve similar to consolidation curve (Figs 11a and b). There a unique straight line for a particular suction in each curve. It can be defined by a linear relationship as used by Wheeler (1996)):

$$v_w = N_w(s) - \lambda_w(s)\ln\frac{p^{net}}{p_c}$$

where $N_w(s)$ and $\lambda_w(s)$ are intercept and the slope of normal compression line respectively and vary with suction.

Figs. 10a and b show the experimental results of normal consolidation line for different values of suction for both drying and wetting conditions of samples. They are straight lines and diverge with increasing suction. This behavior of normal consolidation lines is more consistent with the model of Alonso *et al*. (1990). They predicted that normal consolidation lines for different values of suction in the v- p^{net} (with p^{net} plotted on a logarithmic scale) are straight and the slope of them decrease monotonically with increasing suction. These finding are not consistent with the model of Wheeler and Sivakumar (1995) who suggested that normal consolidation lines converge with increasing suction. Figs 12 show the variations of λ(s) and N(s) for the drying and wetting paths. It was found from this figure (Fig.12a and 12b) that both λ(s) and N(s) in drying and wetting conditions are function of suction and their values of them are decreased with increasing suction. The results (Fig.12 a) show that the value of λ(s) at saturation condition (s =0 kPa) for drying and wetting conditions are 0.077 and 0.067 respectively. These values are decreased with increasing suction so at the suction of 300 kPa the value of λ(s) is changed to 0.05. These results are consistent with the model of Alonso *et al*. (1990) who proposed a monotonic reduction of λ(s) with increasing suction. Rahardjo et al. (2004), Thu et al. (2007) and Vassalo et al. (2007) also showed similar results to this work that the values of λ(s) is decreased with increasing suction. These results are not in agreement with the findings of Wheeler and Sivakumar (1995) and Estabragh *et al*. (2004) who indicated from their experimental tests that λ(s) is increased from saturated condition with increasing suction up to a specific value and then decreased with increasing suction. It may be to the initial condition of the used samples that were in unsaturated condition. The results showed that the value of N(s) for both condition is decreased with increasing suction that is in agreement with the results that were reported by Thu *et al*. (2007). Sivakumar (1993) showed that the value of N(s) is increased with increasing suction that is due to the initial condition of used samples

Figs.13 shows the variations of $\lambda_w(s)$ and $N_w(s)$ with suction for both conditions of samples (dry and wet sides). The results show that the value of $\lambda_w(s)$ is a function of suction and its value is decreased with increasing suction. The results in Fig.13a show that the value of $\lambda_w(s)$ for the dry samples is more than the samples on wet side of soil water characteristic curve. Comparing the result for both conditions show that the vale of $\lambda_w(s)$ is less than λ(s) for the range of applied suction but at saturation they are nearly the same. The results show that the variations of $\lambda_w(s)$ with suction is consistent with the results that were reported by Thu *et al*. (2007) who indicated that $\lambda_w(s)$ decreased with increasing suction. The value of $N_w(s)$ (see Fig.13b) for dry and wet conditions condition are is decreased with increasing suction but for samples on wet condition they are less than the amounts of $N_w(s)$ on dry side.

Conclusion

This work includes some experimental data obtained on samples of a silty soil when taken through drying, wetting and isotropic consolidation. The results showed that during drying and wetting stabilization, the paths of specific water volume and specific volume are not the same and this can be attributed to the hysteresis phenomenon. The results have revealed that at the same suction, the yield stress is higher on the wetting curve than the drying curve. It was also shown that LC yield curve exists for the wetting path but its expansion in wetting is due to the formation a new fabric in the soil. These changes are resulted from hysteresis phenomenon. In addition the variations of specific water volume are the same for both conditions. These data can be used for developing exiting models of unsaturated soil. It is concluded that hysteresis phenomenon affects the yield stress and the parameters of the normal consolidation line and normal line of specific volume water.

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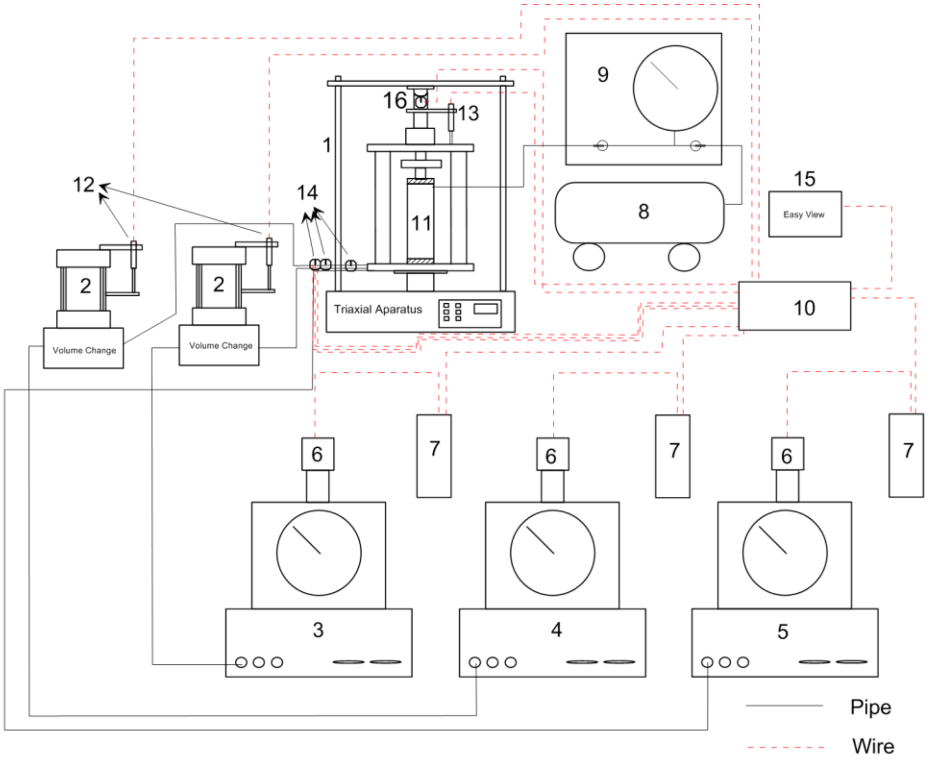


- 1- Triaxial Apparatus
- 2- Volume change Apparatus
- 3- Constant Pressure App. for back pressure
- 4- Constant Pressure App. for internal cell
- 5- Constant Pressure App. for external cell
- 6- Servomotor
- 7- Driver
- 8- Air Compressor
- 9- Valve Pannel
- 10- PLC
- 11- Soil Specimen
- 12- Volume Change Transducer
- 13- Strain Transducer
- 14- Pressure Transducer
- 15- Easy View
- 16- Load cell Transducer

Fig.1. A schematic of the apparatus

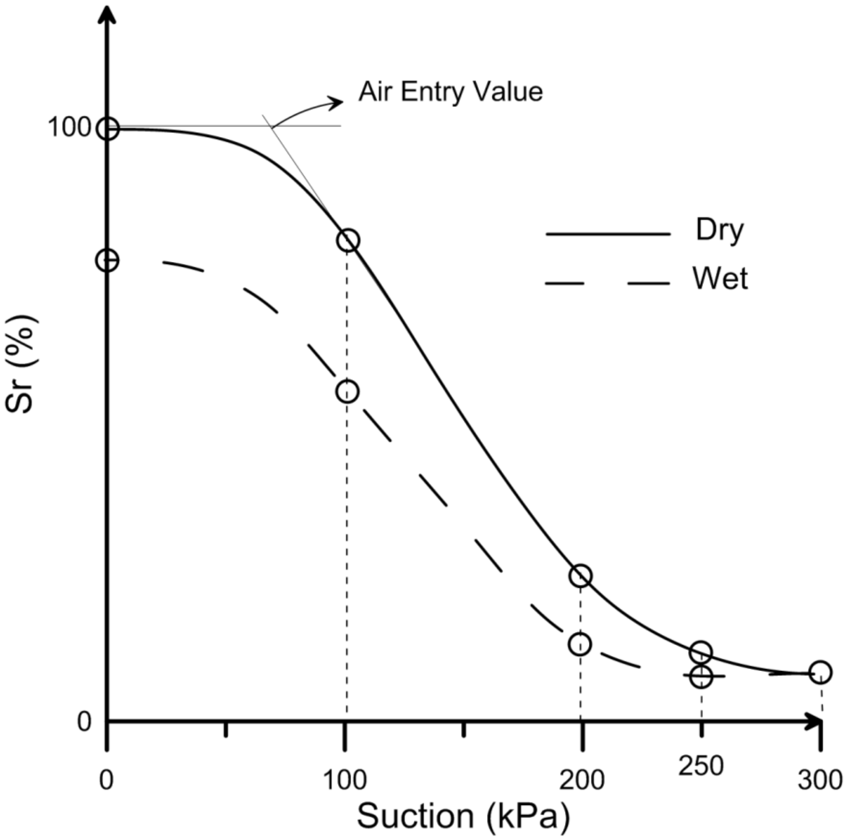


Fig.2. Selected suctions on drying and wetting curves that were used in test program

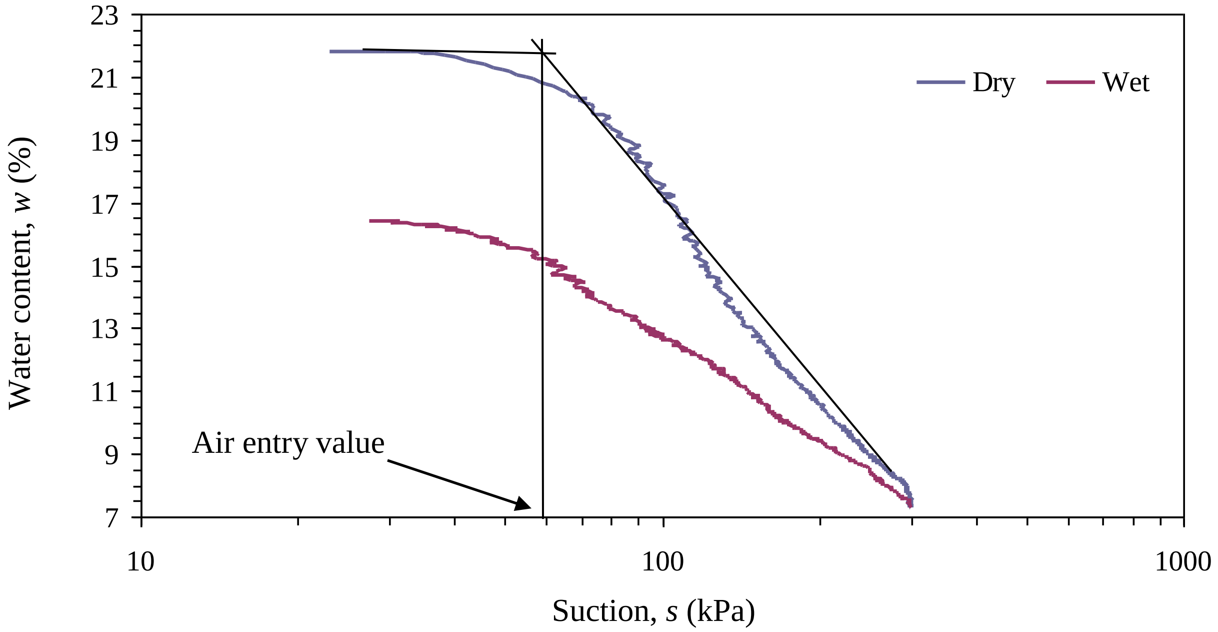


Fig.3. Soil water characteristic curves in the drying and wetting paths

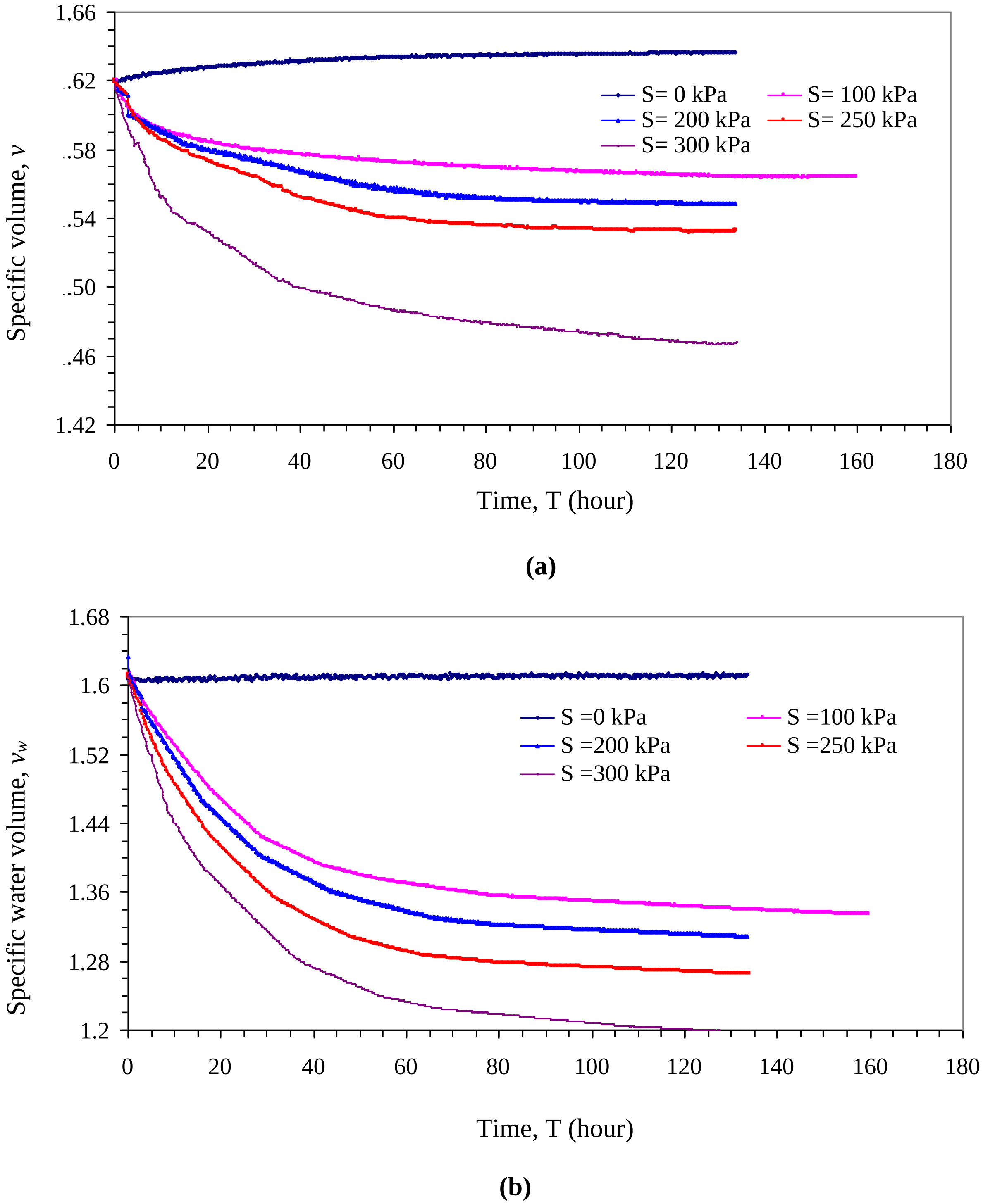


Fig.4. Variations of (a) specific volume and (b) specific water volume during equalization for samples on the drying path

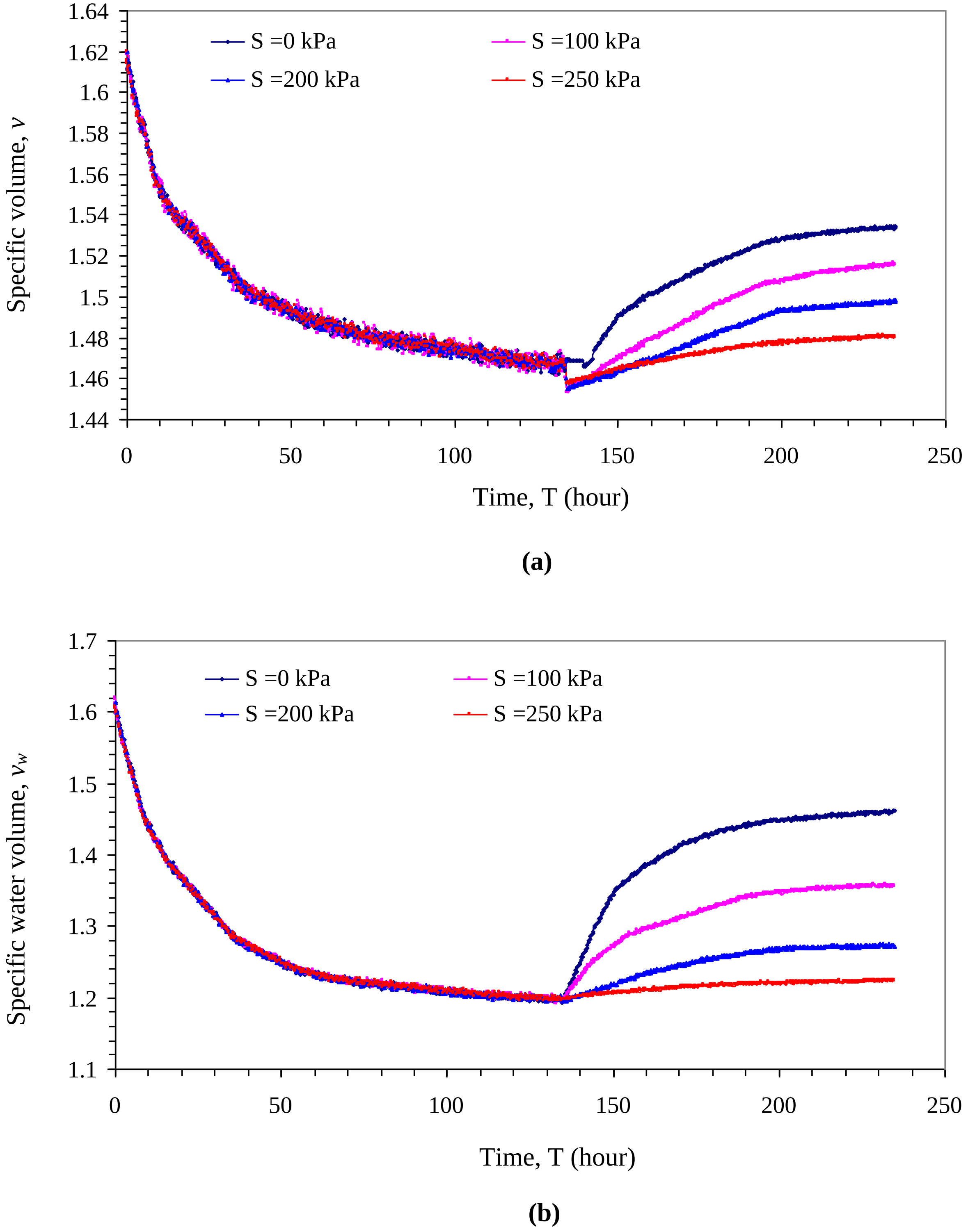
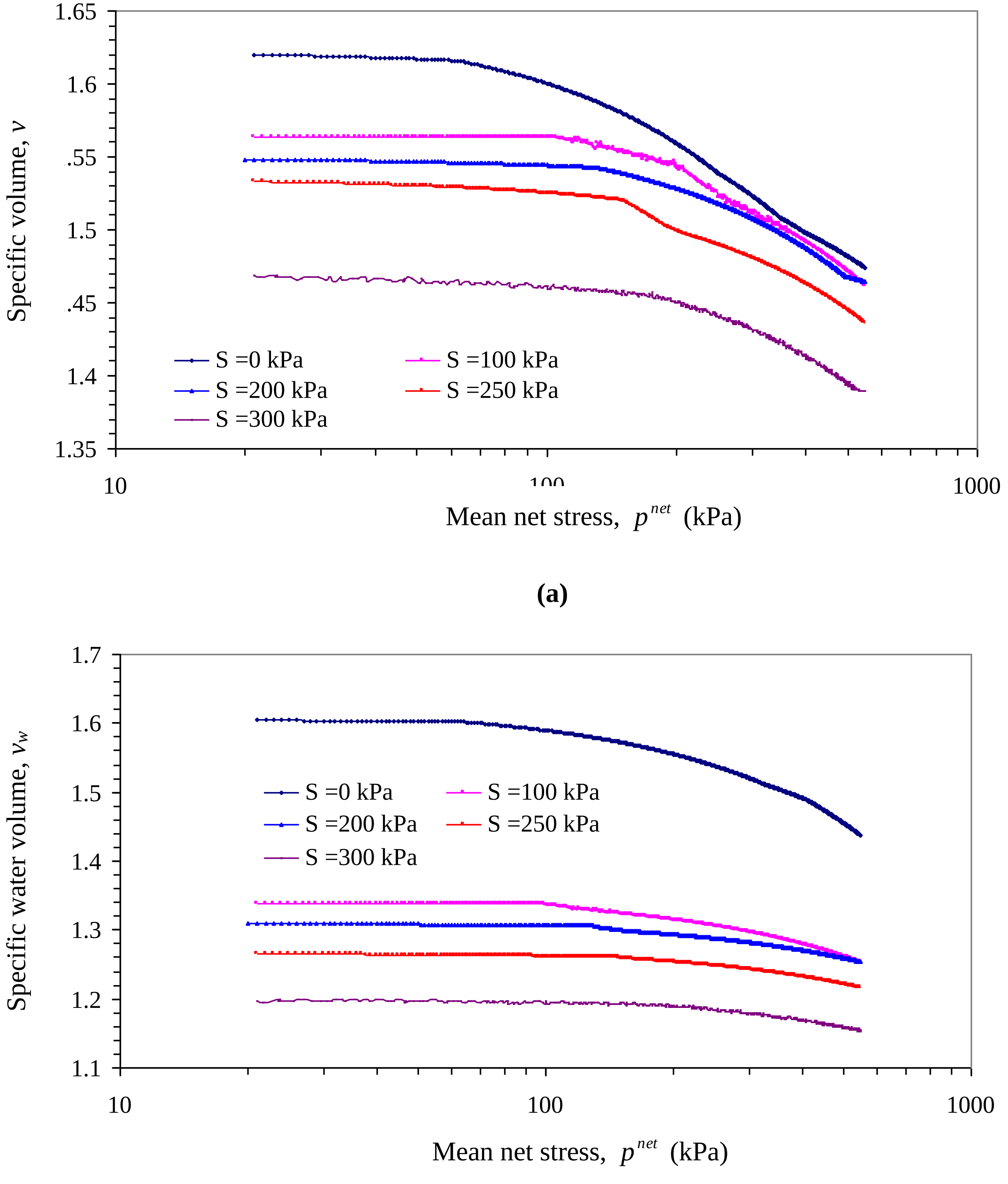


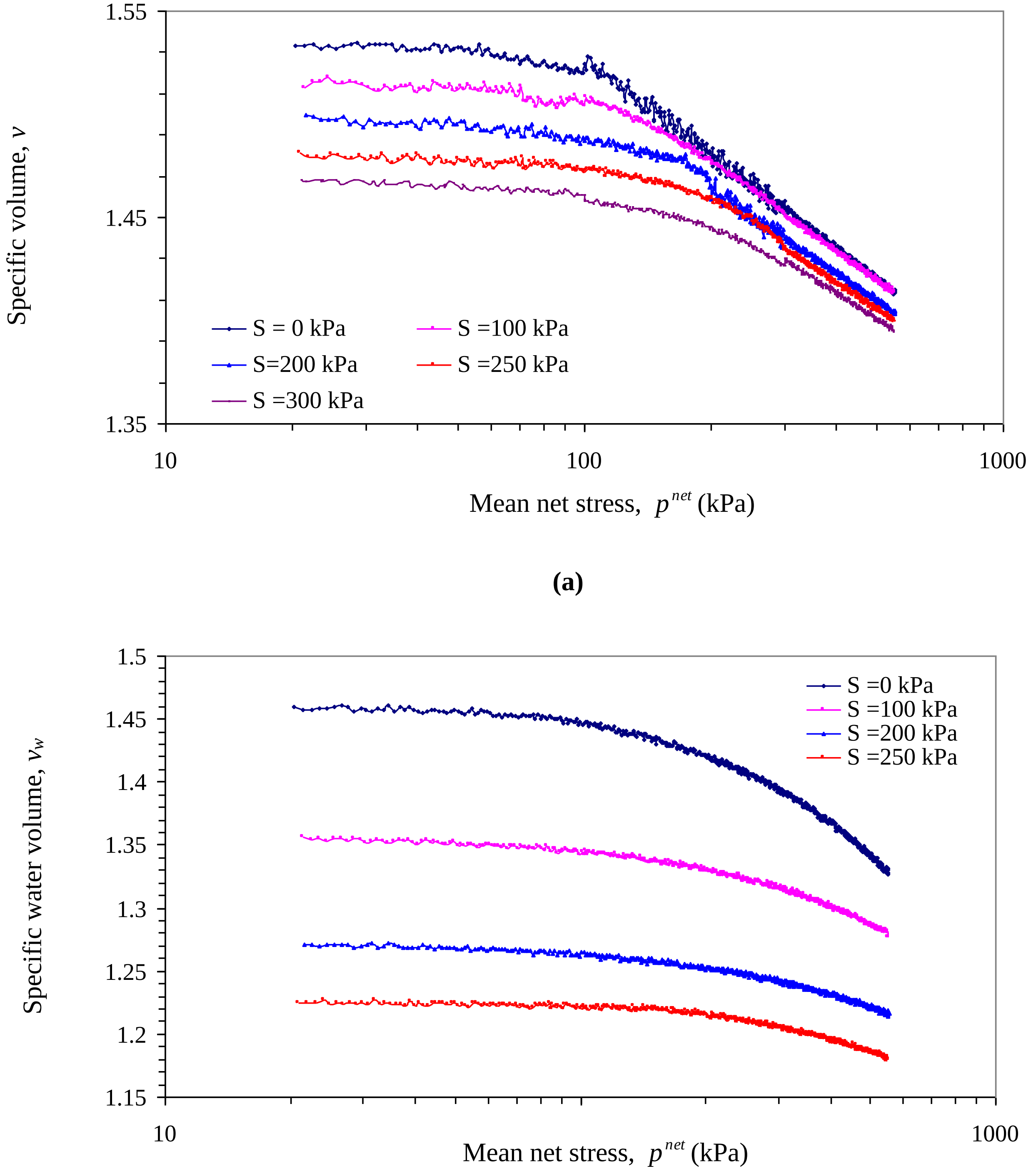
Fig.5. Variations of (a) specific volume, and (b) specific water volume during equalization for samples on the wetting path



(a)

(b)

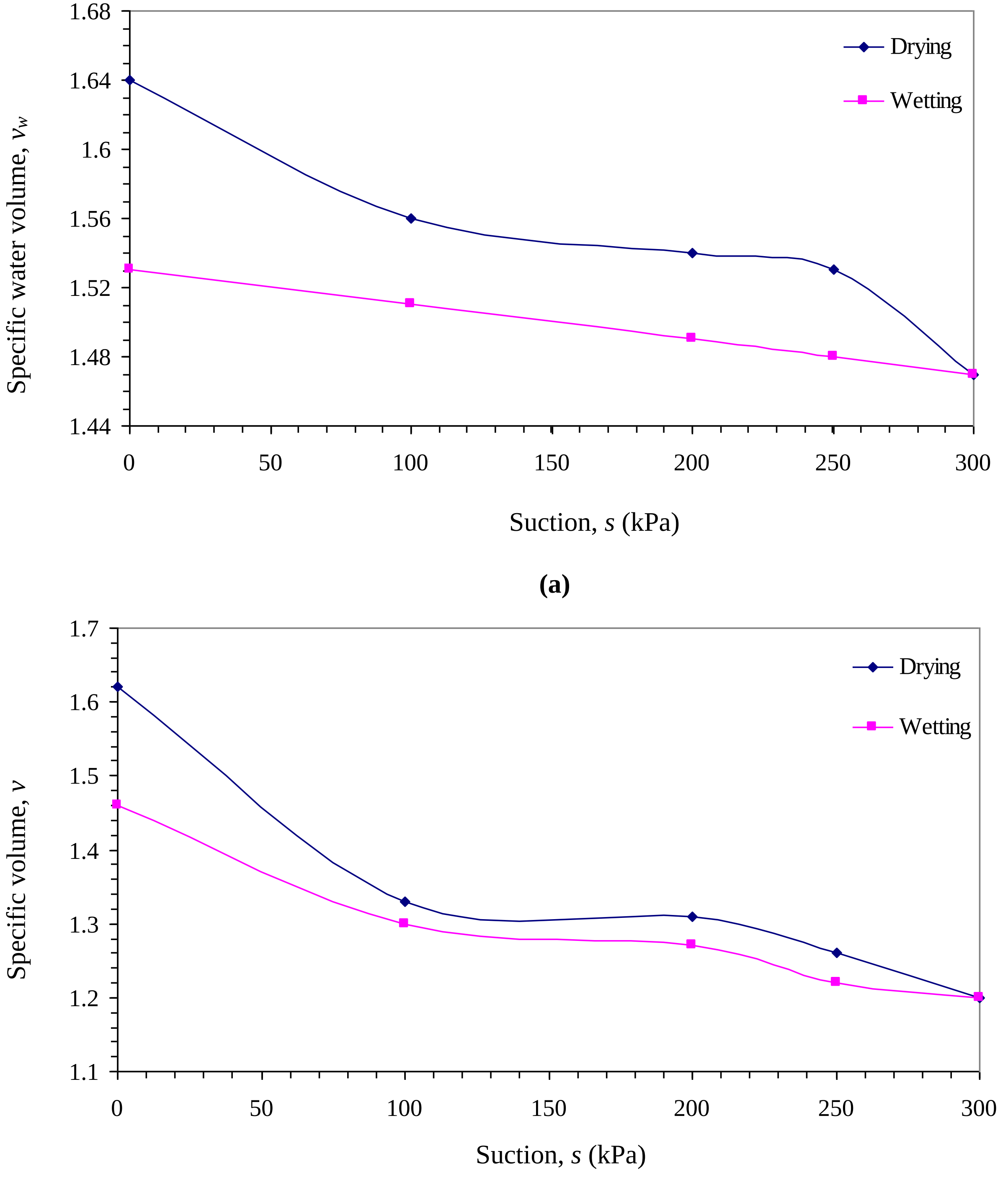
Fig.6. Variations of (a) specific volume, and (b) specific water volume during consolidation for samples on the drying path



(a)

(b)

Fig.7. Variations of (a) specific volume, and (b) specific water volume during consolidation for samples on the wetting path



(a)

(b)

Fig.8. Variations of (a) specific water volume (b) specific volume with suction at the end of the equalization stage

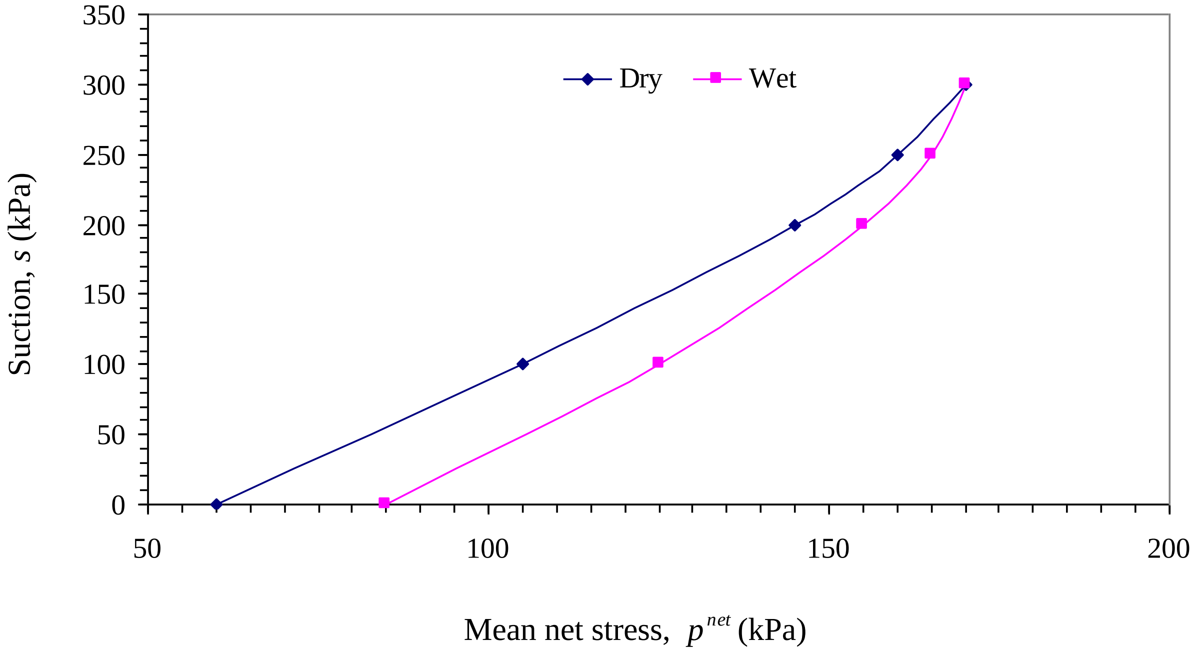
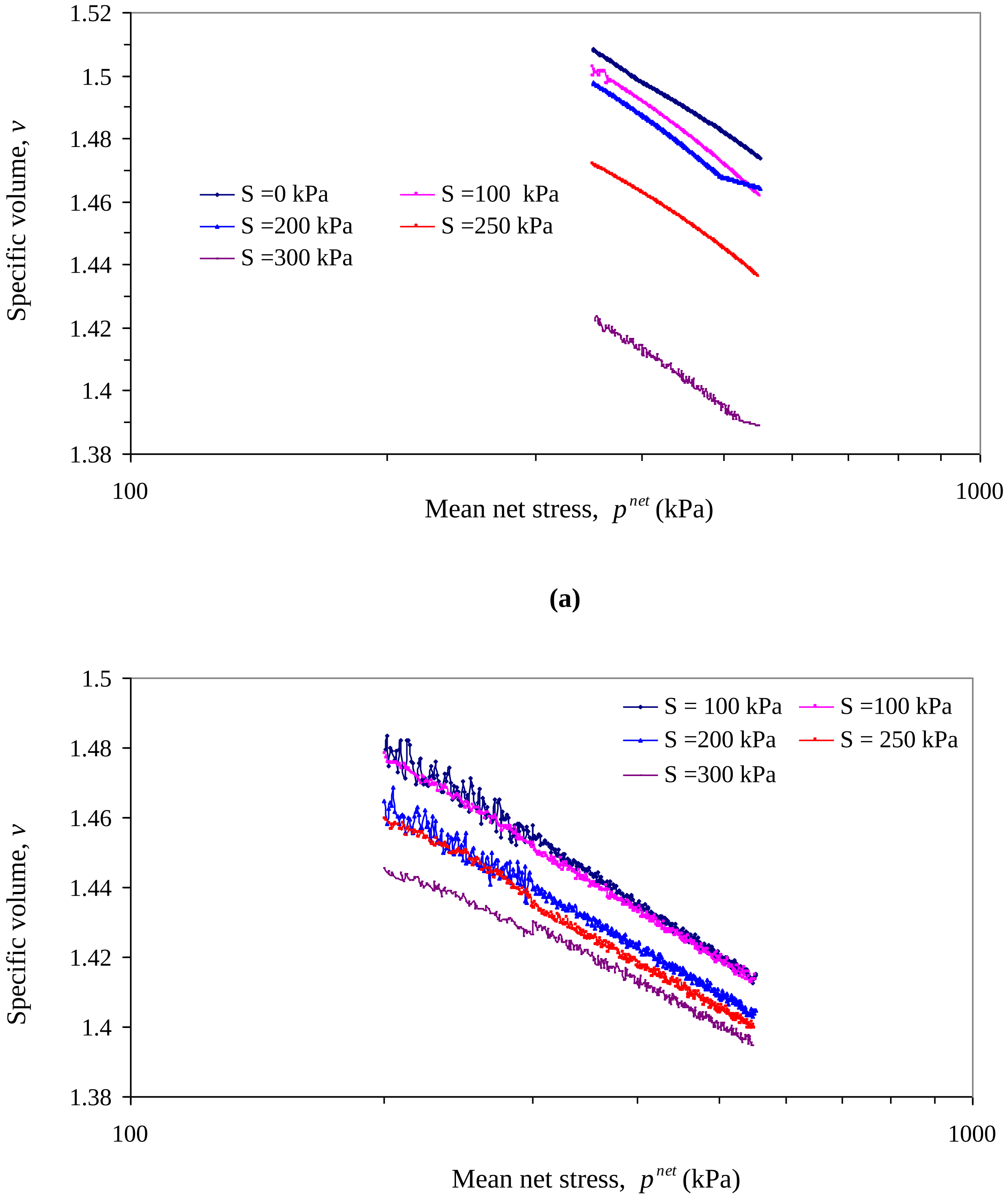


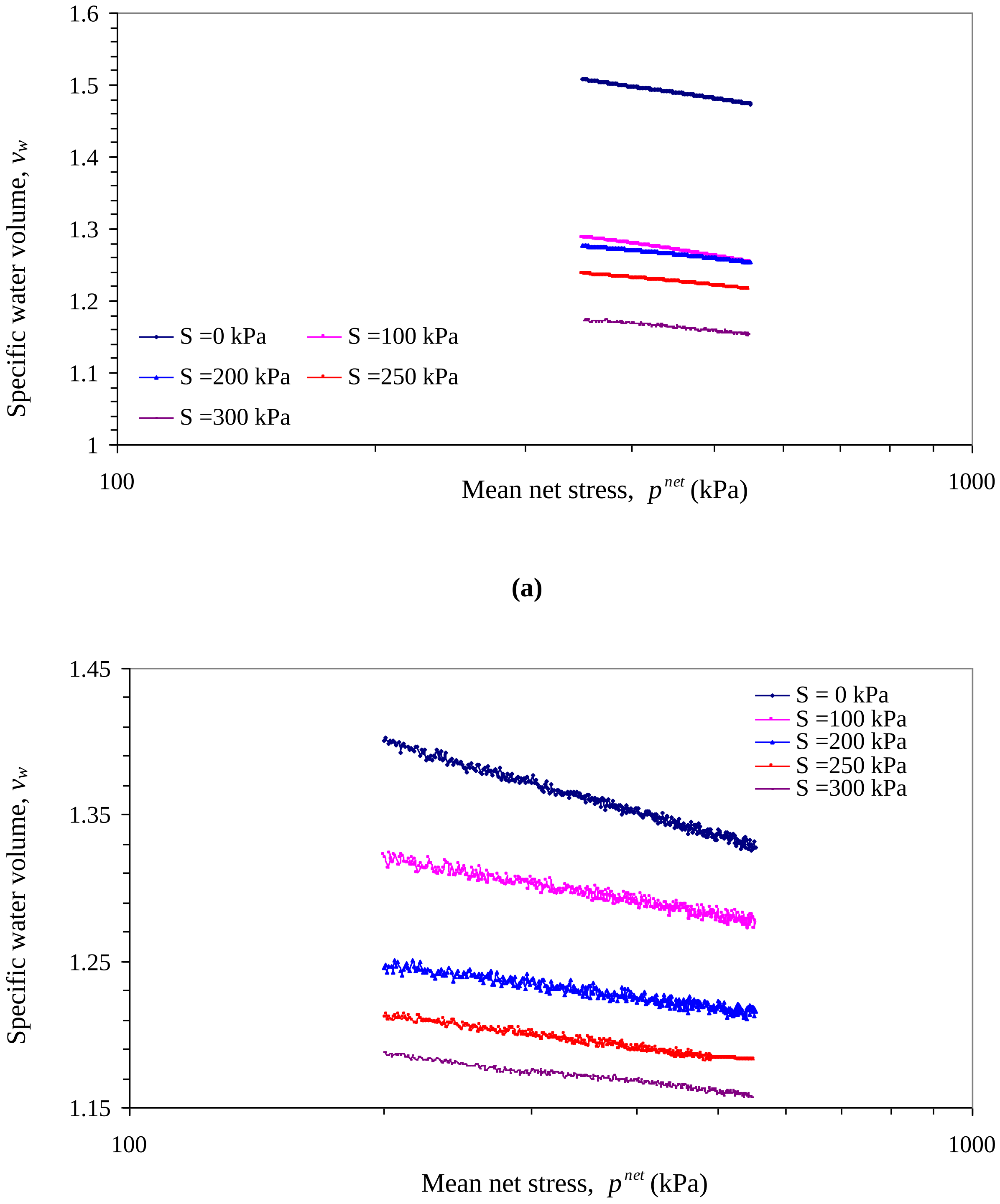
Fig.9. LC yield curves for dry and wet conditions



(a)

(b)

Fig.10, Normal consolidation lines **(a)**: dry condition, **(b)**: wet condition



(a)

(b)

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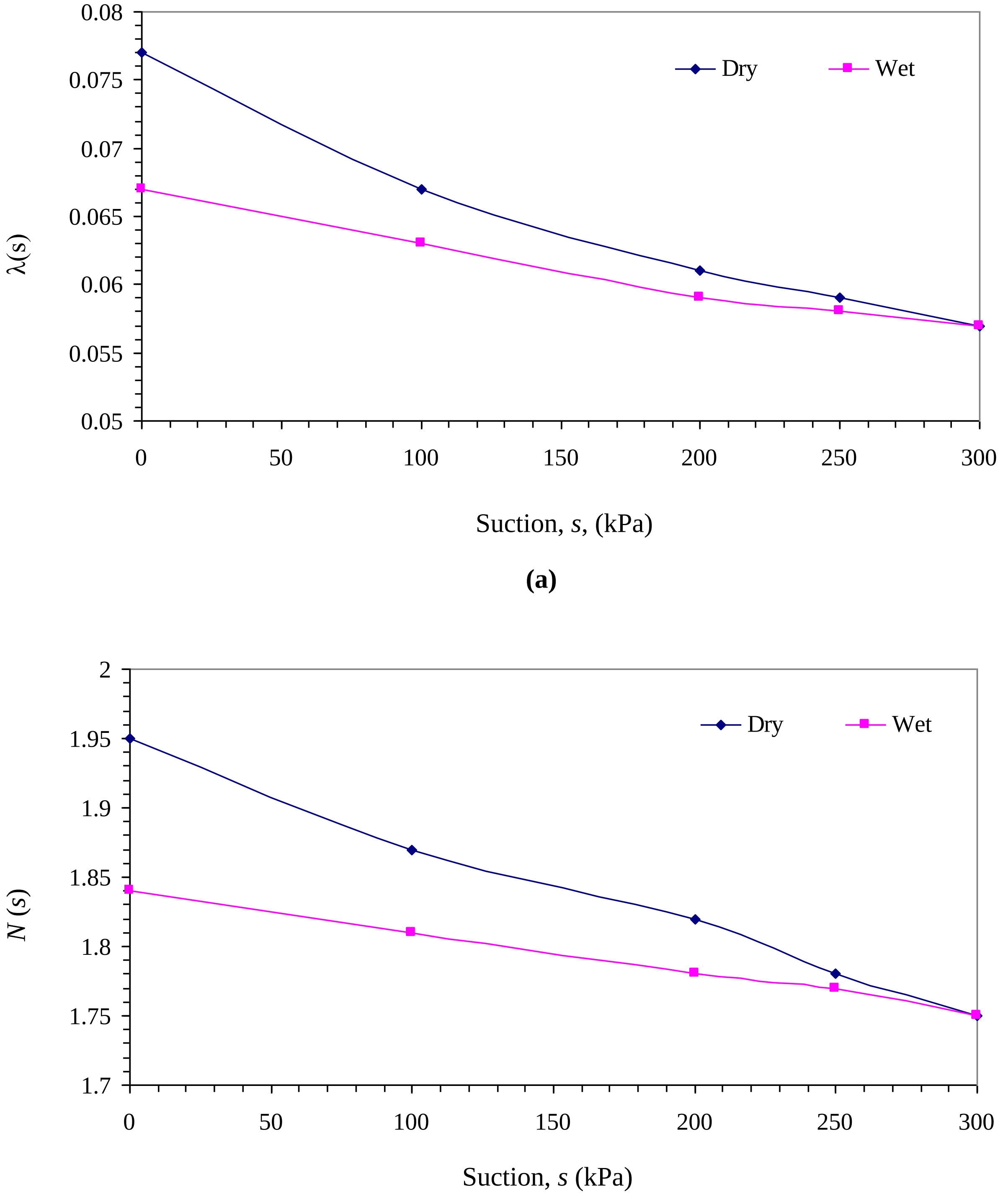

(a)

(b)

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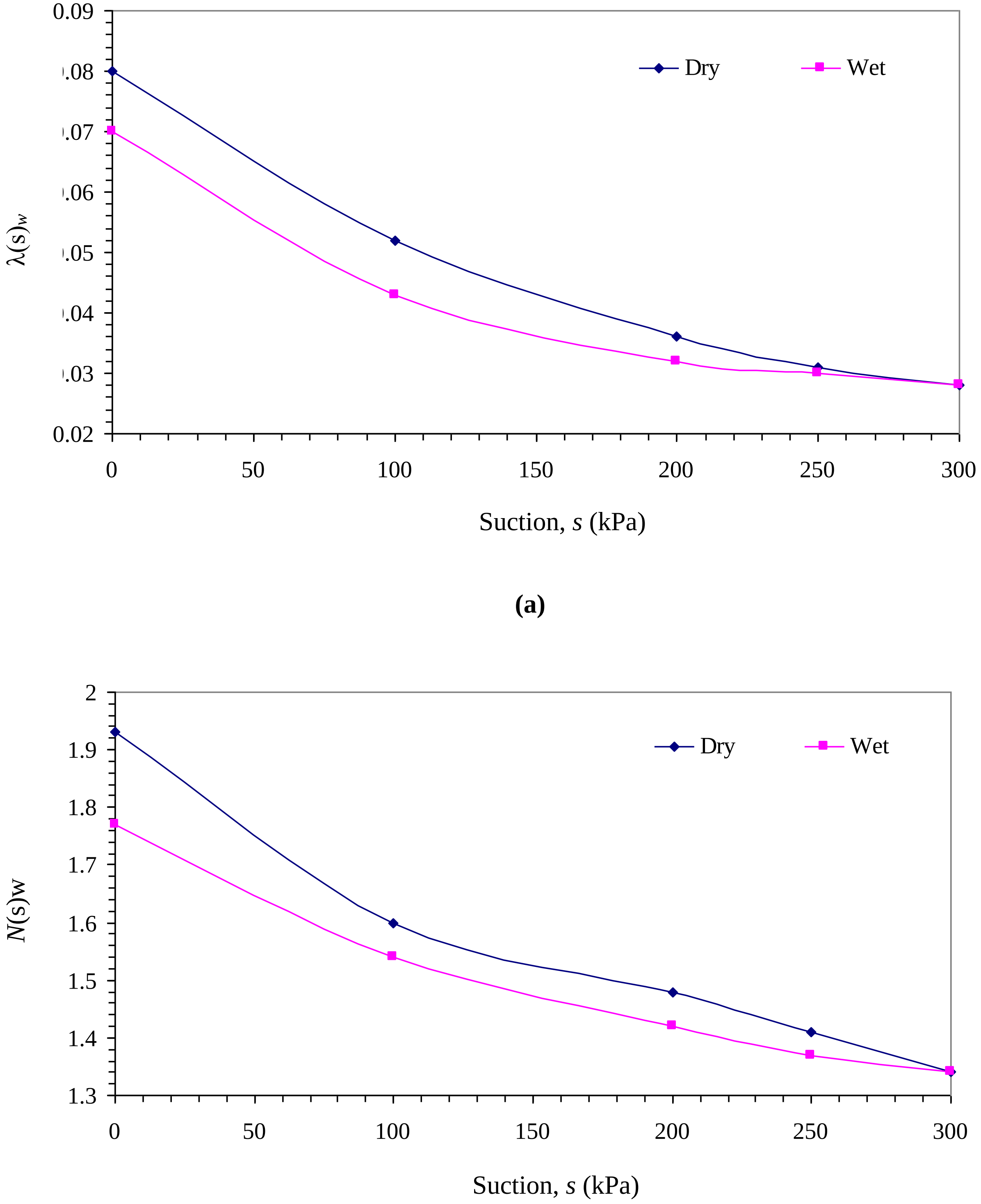

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