Development of a laboratory technique for obtaining Soil Water Retention Curves under external loading in conjunction with high capacity tensiometers

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ABSTRACT

This article reports the development of a testing chamber and an improved and reliable laboratory procedure, capable of establishing Soil Water Retention Curves (SWRCs) under triaxial stress conditions. The system provides the ability to take soil samples through multiple wetting-drying cycles in conjunction with measurements of suction and volumetric variables. Four drying and wetting tests were carried out on samples of glacial till and kaolin to validate the testing chamber and the associated procedures. Significant desaturation of soil samples were limited by the measurement capacity of the tensiometers. The system sustained high values of suction for a prolonged period of testing involving sequence of drying and wetting. Suction was generated by circulating less humid air through the middle of the soil sample which in effect generated suction gradients along the radial directions. Consequently, this had some impact on the interpretation of the volumetric variables.

Key words: suction, clay, pore water pressure

INTRODUCTION

Climate projections estimate that the UK will experience warm and dry summers, and wet winters. The effects of wetting and drying of soils and their impacts on geotechnical infrastructure were clearly demonstrated during 2000/2001 when more than 100 slopes failed across the UK rail network (Turner, 2001). In order to ensure the resilience of geotechnical infrastructure, asset managers have turned to numerical modelling to seek the ways of evaluating the effects of changing climate on slopes (O'Brien, 2004; Jenkins *et.al.*, 2009; Murphy *et.al.*, 2010; Briggs, 2011). Such models are dependent on the reliable determination of material characteristics, particularly the "Soil Water Retention Curve (SWRC)" (Fredlund, 2000). A number of methods are currently available to both directly obtain and predict the SWRCs (Hilf, 1956; van Genuchten 1980; Klute 1986; Fredlund and Xing 1994; Barbour 1998; Aubertin *et.al.* 2003; Tang and Cui. 2005; Fredlund 2006).

Measurement of suction and the associated volumetric strains of the soil are required for establishing the SWRC. It is difficult to measure suctions greater than 100 kPa directly by using traditional water filled tensiometers as the water within the tensiometers cavitates at high suctions. Recent advances in high suction tensiometers have facilitated the development of an alternative and continuous determination of SWRCs (Ridley and Burland, 1993; Guan and Fredlund, 1997; Cunningham, 2000; Ridley *et.al.*, 2003; Take and Bolton, 2003; Boso *et.al.*, 2003; Toker *et.al.*, 2004; Lourenco *et.al.*, 2007; Toll *et.al.*,2013). Cunningham (2000) and Jotisankasa *et.al.,*(2007) proposed experimental procedures for controlling the suction during drying and wetting processes by circulating dry air at the base of soil samples until desired suction values were achieved. Lourenco (2008) implemented the above mentioned technique in a double-walled triaxial cell for measuring the volume change of soil samples. In order to minimize the suction gradient the dry air was circulated via geotextile wrapped around the soil sample. An inclusion of the geotextile to aid the air circulation may influence the stiffness and strength of the soil including impressions on the sample surface. The work presented in this paper proposes an alternative way of circulating air to generate suction in soil samples under triaxial stress conditions.

EXPERIMENTAL WORK

The determination of a SWRC requires measurements of suction and volumetric variables during drying and wetting processes. The system developed for this purpose (Fig. 1) can accommodate a soil sample of diameter 100mm and a height up to 130mm. The special features of the system are: (a) two high capacity tensiometers capable of measuring suction up to 1500 kPa; these were located at radial distances of 15 and 35mm from the center of the pedestal, but in an opposite radial directions (Figs. 1*b* and 1*c*), (b) air circulating ports (5mm dia.) at the center of the pedestal and the top cap for drying the soil samples and (c) two wetting ports (2mm dia.), which were located at a radial distance of 25mm in opposite directions, but perpendicular to the alignment of the tensiometers (Fig.1*c*) facilitated wetting. The tensiometers were attached to the pedestal from the base and sat flush with the pedestal when fastened. Necessary valves were included on the air circulation and wetting lines to facilitate either air or water circulations.

The investigations were carried out on two soils: glacial till and commercially available kaolin. The glacial till was collected from a major road cutting adjacent to the Belfast to Dublin route at Loughbrickland in Northern Ireland. The properties of the soils are shown in Table 1. The test on the kaolin was carried out on a reconstituted sample, prepared at an initial water content of 90%, and subsequently consolidated by applying a vertical pressure of 200 kPa in a 100 mm diameter consolidation chamber. The consolidated sample was extruded and trimmed to 100 mm height for the subsequent investigations. A 6 mm diameter hole was carefully formed at the center of the sample to facilitate the formation of a sand column (made of uniformly graded sand passing through 600μm and retained on 425μm). In case of the glacial till, the collected samples were oven-dried and subsequently hand crushed and sieved through a 5 mm sieve to remove bigger particles. The relevant grain size distribution parameters for the soil are listed in Table 1. Three tests were carried out on this material; one test was on a reconstituted sample and the remaining two were on re-compacted samples. For the reconstituted sample, slurry prepared at an initial water content of 35% was consolidated at a vertical pressure of 800 kPa in a consolidation chamber. Since forming a hole in the sample was difficult due to the presence of gravel, a technique was used to pre-form a hole at the center of the sample along its length. A special compressible slender rod was placed at the center of the consolidation chamber (Figure 2). The rod consisted of a piston of 5 mm in diameter and a cylinder having 6.5mm external diameter and a spring. The fully extended length of the rod was 140mm and the fully compressed length was 95mm. The mass of the slurry was pre-calculated to achieve a sample length of approximately 100mm so that at no time the piston would end up losing its travel length. At the end of consolidation the sample was extruded and the slender rod was removed and backfilled with a sand. Since the intention of the work was to begin the drying process from a low suction, the sample was then reconsolidated (i.e. allowed to swell) under an effective consolidation pressure of 50 kPa in a standard triaxial cell. Upon completion of the reconsolidation, the sample was removed from the cell and the sand column was flushed by applying a vacuum. The initial water contents of the compacted samples were 12.0 and 13.0%. In these cases, a slender rod was located at the center of the mould to pre-form the required hole in the samples.

The saturation of the tensiometers was carried out by adopting the procedure reported in various literatures (Guan and Fredlund, 1997; Take and Bolton, 2003). The chamber (Figure 1) was filled with de-aired water and pressurized to 1.9 MPa for 2 weeks. The procedure was repeated in order to ensure complete saturation of the tensiometers. The sample was subsequently located on the pedestal of the chamber, while making sure that the hole in the sample aligned itself with the air circulating port on the pedestal. The hole in the sample was filled with sand. The top cap was carefully positioned and a membrane was placed around the sample and sealed using “O” rings. The chamber was assembled and filled with de-aired water. A confining pressure of 50 kPa was applied and the flow of water into the chamber was detected using a volume change unit (Fig. 1).

The drying process commenced by circulating air through the sand column in the sample. The water permeability of the sand reduces rapidly under high suction. However it has no impact on the air permeability of the sand as extraction of water from the clay takes place in vapour form. This air was circulated in a closed-loop via another chamber which contained saturated sodium chloride solution. The air circulating port at the bottom of the testing chamber was connected to the top of the salt solution chamber. The air circulating port at the top of the sample which carried the flushed air was left immersed in the saturated salt solution. A 3.0V pump, with a line pressure of 5 kPa facilitated the circulation of air.

The salt chamber was placed on a scale that measured the mass of the chamber to an accuracy of 0.01g. The mass of the salt chamber was recorded manually 1-2 times per day. During the process, the connecting tubes to the test chamber were disconnected. After the drying process, the sample underwent a wetting process. The air circulation ports were closed and the water injection ports were opened and connected to a pressure-volume controller. During the wetting process, water was injected into the sample at a rate of 0.003 cm^3/min. This rate was approximately the same as the rate of water extraction from the sample during the drying process. Table 2 lists the testing conditions and the associated wetting and drying paths of the samples tested. Upon completion of a test, the drying-wetting chamber was dismantled and the final volume of the sample was measured by weighing the sample in air and water. Oldecop and Alonso, 2004 reported up to about 20% error in the water between the measured water content and calculated water content using test records. However the present investigation showed a significantly reduced error, a maximum of 3% in a test that involved many number of drying and wetting cycles, Table 3. In addition to the tests described above, further tests were carried out on reconstituted samples of glacial till and kaolin prepared in the same fashion as described above. Which were subjected to physical loading in order to establish the pressure-volume relationships in a standard triaxial cell.

RESULTS AND DISCUSSION

Experimental observations

Figure 3 shows the relative humidity of the air entering and leaving the sand column located in case of a kaolin sample. These measurements were made externally to the chamber at the point of entry and exit, over a period of 4 weeks. The relative humidities of the air entering and leaving the sand column are approximately 75% and 90%, equating suction values of 38MPa and 14MPa respectively. These observations clearly demonstrate a suction gradient along the length of the sand column, which may have some impact on the interpretation of the results which will be discussed later. The sand column in the sample acts as a well, drawing water from the soil sample in all radial directions. This again consequently generates a suction gradient along the radial directions. In the present investigation, drying was done continually (and that for wetting) and therefore the suction values recorded are based on the transient measurements. This may mean that, for example during the drying process, the clay away from the sand column may be wetter than the clay close to the sand column. A uniform suction can be achieved by periodically stopping the pump until a steady state is reached. However it may have some impact on the stress history of the clay close to the sand column (higher suction) which would draw water from the clay away from the column (lower suction) and therefore, the clay close to the sand column becomes overconsolidated. Nevertheless this aspect was partially examined in the test carried out on the kaolin. The air circulating valve was closed twice at low suction values (Fig. 4a) and once at a high suction value (Fig. 4b). In this test, the suction probe 2 failed to function. As it can be seen the suspension of the air circulation lead to about a reduction in suction of about 10% and it appeared to have stabilized during the resting period. This reduction in suction is considered to be not significant and would not impact the analysis presented later in this paper. Therefore it was decided not to terminate the air circulation during the tests.

Figures 5 to 7 show the suctions and the volumetric responses of the glacial till samples G1, G2, and G3 (Table 2) during the course of the drying process. Tensiometer 1 is closer to the sand column and tensiometer 2 is further away from the sand column. As to the reconstituted glacial till sample (G1) the difference between the suction values read by tensiometers 1 and 2 is approximately 50 kPa at a given time. For the recompacted samples (G2 and G3) the differences are as low as 20 kPa. The differences in the suction could be higher at any other locations closer the sand column. The reduced difference between the suction values in case of recompacted samples may have been due to high permeability of recompacted samples associated with the bimodal pore size distribution as opposed to the reconstituted sample. The increasing suction in all three samples has resulted in significant amount of volume changes in terms of the overall voids as well as the voids filled with water. The agreement between the volumetric strains and the water volumetric strains is reasonably good up to about a suction value of 300 kPa and begin to diverge as suction increased further implying that air entered into the reconstituted sample (G1). However the disparity between the volumetric and water volumetric strains is quite apparent from the very beginning of the drying in G2 and G3 implying that the desaturation may have started at low suctions which is plausible given the fact that these samples inherited bimodal pore size distribution.

Discussion

Figures 8, 9 and 10 show the volumetric responses and the degree of saturation plotted against (p+s) for the glacial till samples, where p is the net mean stress and s is the suction. As shown in these figures the degree of saturation of the samples achieved was about 88%. Any further reduction of it was limited by the maximum suction that can be sustained by the tensiometers (1500 kPa). Therefore, the interpretation is based on a simplified approach using the stress term, (p+s). As a part of the discussion, the compressibilities of the samples during drying and wetting were also evaluated using the parameters defined as follows: λ_s = the slope of the virgin drying line with respect to the void ratio (also referred to as the environmental loading), λ = the slope of the compression line under external loading (also referred to as the physical loading), λ_{ws} = the slope of the virgin drying line with respect to the water void ratio, κ_s = the slope of the wetting line with respect to the void ratio and κ_{ws} = the slope of the wetting line with respect to the water void ratio.

In the testing of the reconstituted sample of the Glacial till (G1, Fig.8), the tensiometers failed to function at the end of the first drying process and therefore no wetting process was initiated. The key observations from this test are: (a) a marginal de-saturation process began at a suction value of about 30 kPa, Fig. 8b; however, a more pronounced de-saturation process begun at a suction of about 800 kPa which agrees well with the stress history of the sample and the sample may not have possessed any bi-modal pore size distribution. As the suction increased further, emptying of the water continued to take place; however, the associated reduction in the void ratio slowly reduced as one would expect when the soil sample begins to de-saturate more intensively. The approximate value of the yield stress is about 550 kPa which is reasonably close to the average mean effective stress that the sample might have experienced during its initial formation in one dimensional consolidation chamber and assuming the angle of internal friction of glacial till = 32^o. The relevant slopes identified as above (λ_s and λ_{ws}) are approximately 0.05. However, λ_{ws} rapidly increased while λ_s fell significantly when the desaturation process became more pronounced. The volume-pressure characteristics under physical loading (G1A, Table 2) are indicated using open circular data points in Figure 8a. The value of λ and the position of the compression line under this loading condition is reasonably similar to that of environmental loading.

The glacial till sample (G2) was first dried (D) and then wetted (W) and dried (D) again (Fig. 9), whereas the sample G3 was subjected to D-W-D-W-D processes (Fig. 10), Table 2. The samples were dried up to a suction of 1400 kPa and wetted to a suction of about 60 kPa in each case. Both samples have shown some significant desaturation at very low suction values. This observation could be interpreted as air entering into the macrovoids. A more prominent de-saturation begun at suction values of about 650 kPa for G2 and 500 kPa for G3, as opposed to 750 kPa for G1. The differences in the suction at the point of pronounced de-saturation is not insignificant to ignore and can be primarily attributed to the structure within the aggregates in G2 and G3. An increasing in the compaction water content can lead to increased microvoids (Thom *et.al.* 2007; Delage et.al., 1996) and compaction process can also inflict micro-fractures at aggregate level (Sivakumar *et.al.* 2010).

The slopes of the first drying line, λ_s, for samples G2 and G3 are similar (0.04). This value is slightly lower than that observed in case of sample T1. As one would expect, the value of λ_{ws} is slightly higher than λ_s (0.05) for samples G2 and G3. The approximate values of the yield stress for samples G2 and G3 are 250kPa and 400kPa respectively. The samples G2 and G3 were expected to exhibit yielding during re-drying at 1400 kPa (the maximum suction they ever experienced); however, observations from G2 indicate that it yielded at a slightly lower value of suction. This could have been due to the localized softening at aggregate level (Wheeler *at al.* 2003; Alonso *et al.* 1995). Also it is interesting to note that the hysteresis caused by the drying and wetting cycles is more pronounced in the water phase than in the volumetric phase as the emptying and filling mechanisms upon increasing and reducing suction are different (Wheeler *at al.* 2003). The slopes of wetting and drying lines on volumetric and water volumetric phases (κ_s, κ_{ws}) are different and approximate values are 0.01. The slopes of the wetting and re-drying lines are quite different, but such responses are commonly observed under physical unloading and reloading of saturated soils.

Figure 11 shows the relationship between the void ratios (e and e_w) and the logarithm of (p+s) for the reconstituted kaolin K1. It appears that the sample may have begun to de-saturate marginally at a suction value of around 550 kPa; however, the reduction in the degree of saturation beyond this suction value is not rapid. As it can be seen the wetting and subsequent drying paths are (Figure 10a) very much identical in terms of both volumetric variables, except the fact that the wetting and re-drying paths are not identical. This was also observed in the case of the glacial till samples. The sample of kaolin was subjected to a vertical pressure of 200 kPa in the consolidation chamber prior to testing in the drying-wetting chamber (Table 2). Therefore the approximate value of the mean effective stress that the sample may have experienced would be around 145 kPa (the angle of internal friction 22^{O}). The approximate value of (p+s) at the point of yielding is about 350 kPa (Fig. 11a) and this value is higher than the expected yield stress. The values of λ_s and λ_{ws} are similar (0.15). The observations from the additional test, carried out on a kaolin sample (K1A, Table 2) to examine the pressure-void ratio relationship under physical loading, are shown using open circular data points in Fig. 11a. The approximate value of λ is 0.15 and it is in close agreement with the value for λ_s. The drying and wetting processes are associated with increasing or reducing suction (or reducing or increasing the pore water pressure) and they are analogous to increasing or reducing external pressures. While the compression indices λ and λ_s are in agreement, the positions of the normal compression lines under these two loading conditions are found to be distinctively dissimilar. This observation questions the similarities of the two different loadings. The maximum suction that the sample experienced during the first drying process was 1400 kPa. There is no significant evidence to suggest that the sample begins to yield upon second drying until the maximum suction value that was achieved during the first drying process. The approximate values of κ_s and κ_{ws} are similar (0.04).

There are some interesting observations that have emerged from the testing of the reconstituted samples of kaolin and glacial till. The most puzzling observation is the difference between the positions of the normal compression line which emerged from the physical loading and the virgin drying line of kaolin which emerged from the environmental loading. The following are plausible reasons for the observed behaviours:

(a) The suction was measured at the base of the samples at two locations (Figure 1). Due to technical difficulties (in test K1) the tensiometer 2 (35 mm away from the center of the sample) failed to work and therefore the interpretation was carried out based on the suction measurement obtained from tensiometer 1. The earlier section has highlighted the potential suction gradients along the length of the sample and in radial directions. This therefore may have resulted in overestimating the average suction contributed to the disparity in the position of the normal compression line and the virgin drying line. However such overestimation of suction may not be significant as per the observations presented in Figure 4 which clearly highlighted a potential reduction of suction of only about 10% (this reduction in suction during the resting period is not shown in Figure 11). This reduction in suction is not sufficient enough to bring the position of the normal compression line obtained from the environmental loading close to that of the physical loading. In addition, the overestimated suction value cannot be considered as the prime reason for the disparity between the two normal compression lines, as the sample of glacial till, where the differences in the suction values measured by tensiometers 1 and 2 are as low as 50 kPa in Test G1 (Fig. 5). The permeability of kaolin is considerably higher than that of the glacial till. Therefore any differences in the suction values would have been less in the case of kaolin.

(b) The volume change behaviour of clays is governed by the physico-chemical forces within the clay-water-ion systems. The magnitudes of attractive forces arising from the van der Waals and Coulombic attraction and the repulsive force stemming from the electrical double layer interaction between clay particles depend upon the specific surface area, the pore fluid characteristics and the properties of the fluid in contact with the clay (dielectric constant, concentration and pH). In the absence of an appreciable repulsive force, the factors determining the volume change behaviour of kaolinite are (Sridharan and Rao, 1973): (i) the frictional resistance, (ii) the fabric of the clay and (iii) the attractive forces. The distance between clay particles and hence the void ratio of kaolinite is affected by the attraction forces, the magnitudes of which are influenced by the dielectric constant of the interacting fluid. The attractive forces vary inversely with the dielectric constant of the pore fluid (80.4 for water and 1.0 for air). Additionally, in the presence of water phase continuity between the pore fluid and the interacting fluid, an expulsion of ions from the clay media occurs (Bolt, 1956; Tripathy *et.al.*, 2014) and that leads to a decrease in the thickness of the electrical double layer and an increase in the dielectric constant of the pore fluid leading to a greater compression of saturated clay. In the current case, the chemical composition of the clay remains unchanged during the drying process as the drainage of water takes place in the vapor form. This therefore implies that a higher void ratio attained by the kaolinite sample under suction loading is primarily due to the removal of water in the vapor form than that of the sample under mechanical loading of the same magnitude, resulting in the drainage of the pore fluid in the liquid form. The physico-chemical forces in the case of glacial till is not of paramount of importance since the percentage of the fine fractions is less than 16%.

CONCLUSIONS

A novel system was developed for establishing SWRCs under triaxial stress conditions. Compacted and reconstituted samples of two soils were subjected to cycles of drying and wetting spanning over several weeks during which the tensiometers functioned satisfactorily. Continuous drying was achieved by circulating air through the centre of the soil samples, whereas wetting occurred by injecting water into the samples in a controlled fashion. The agreements between the volumetric variables (e and e_w) are found to be excellent until the point of desaturation indicating that the system functioned effectively. The method of drying by circulating air through the middle of the soil samples generated suction gradient along the radial directions which had some impact on the interpretation of the volumetric variables. The disagreement between physical and environmental loadings is attributed primarily to the depletion of ions during the drainage under physical loading specifically for clay-rich soils such as kaolin in the present study.

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Figure

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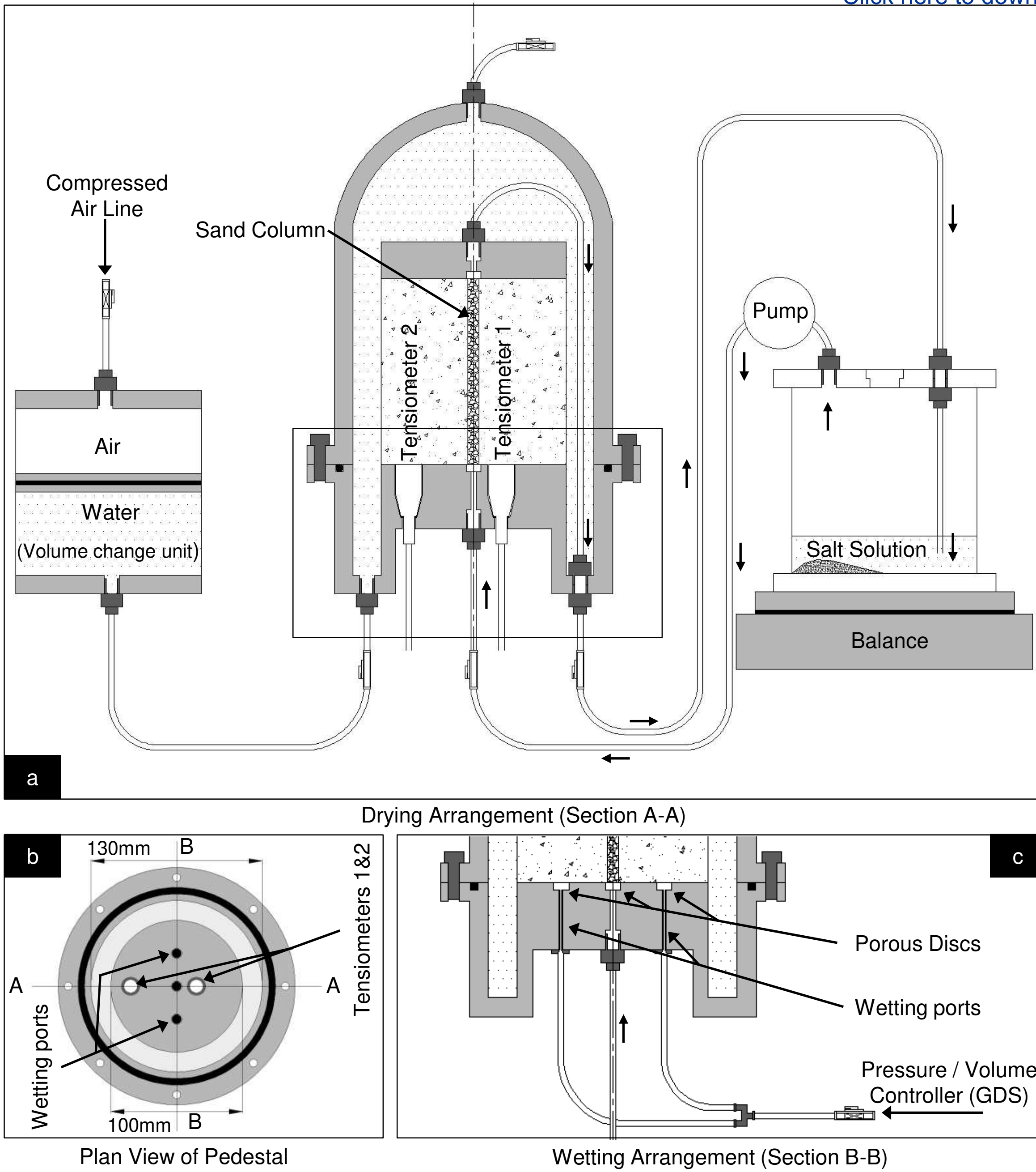


Figure 1 - Schematic of testing arrangement

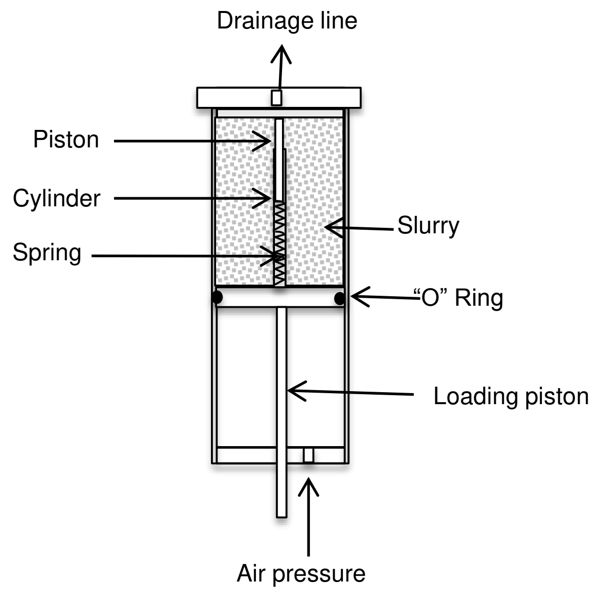


Figure 2 - Consolidation chamber

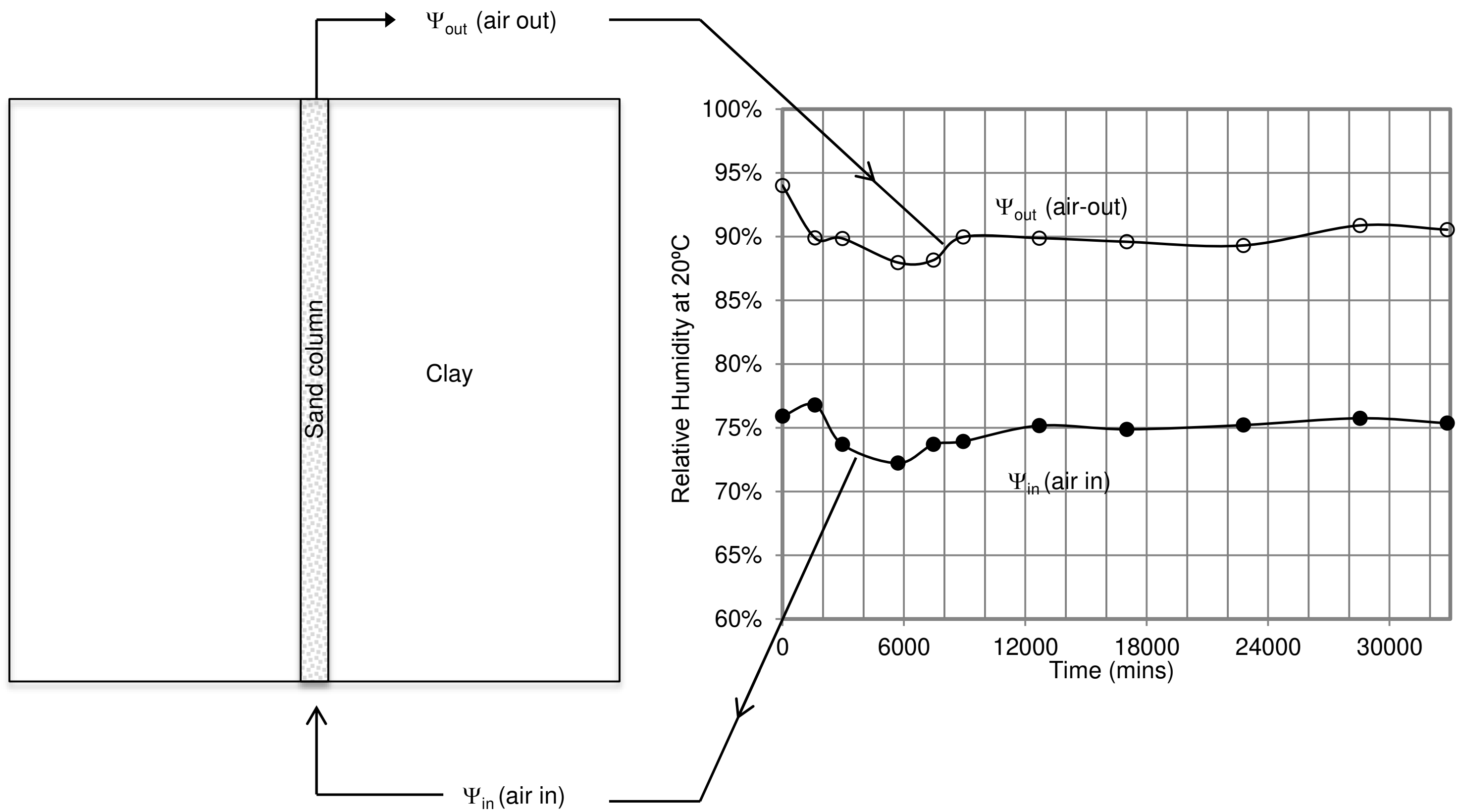
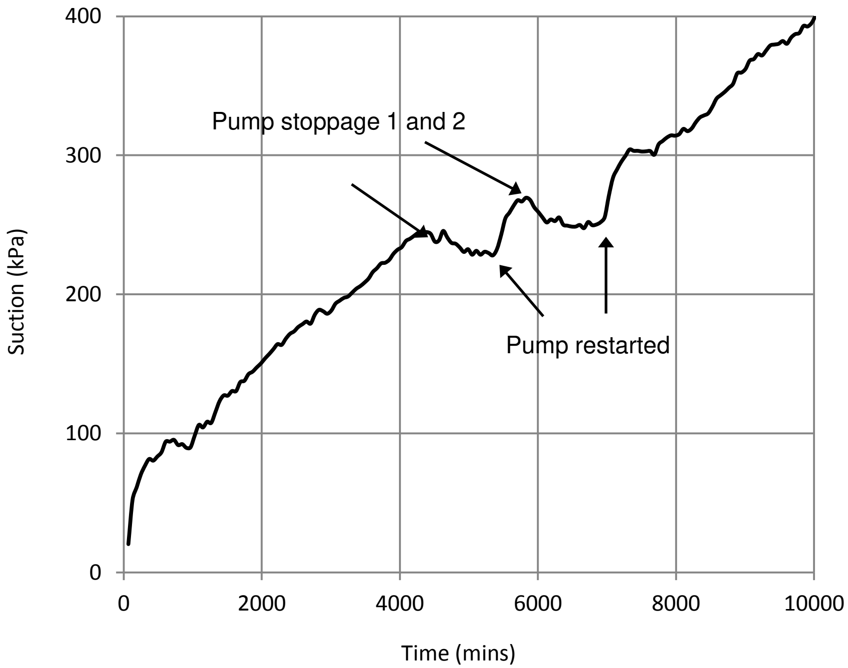
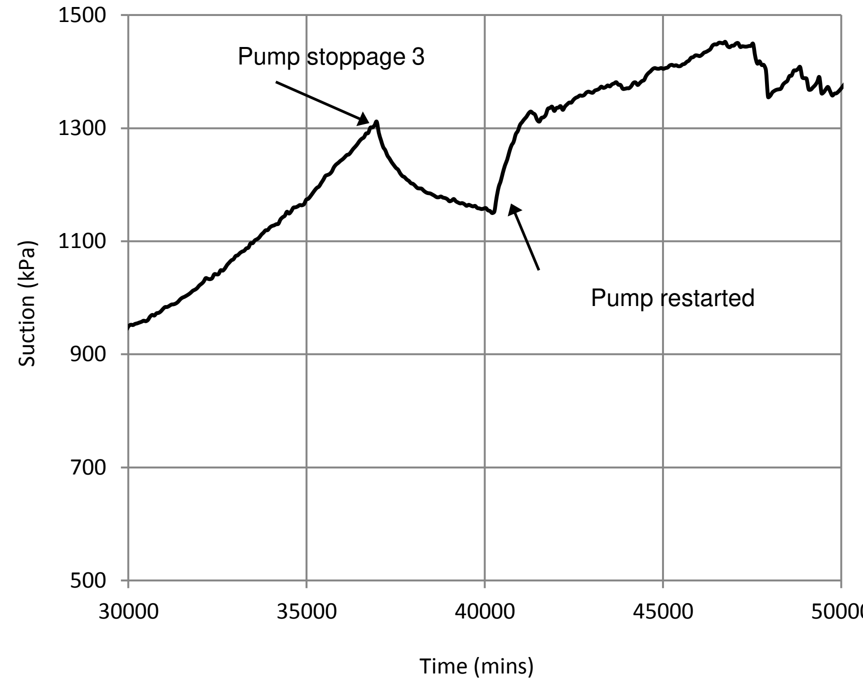


Figure 3 - Relative humidity of air entering and leaving sample



(a) Pump stopped at early stage of drying



(b) Pump stopped at later stage of drying

Figure 4 – Equalization of suction during resting period

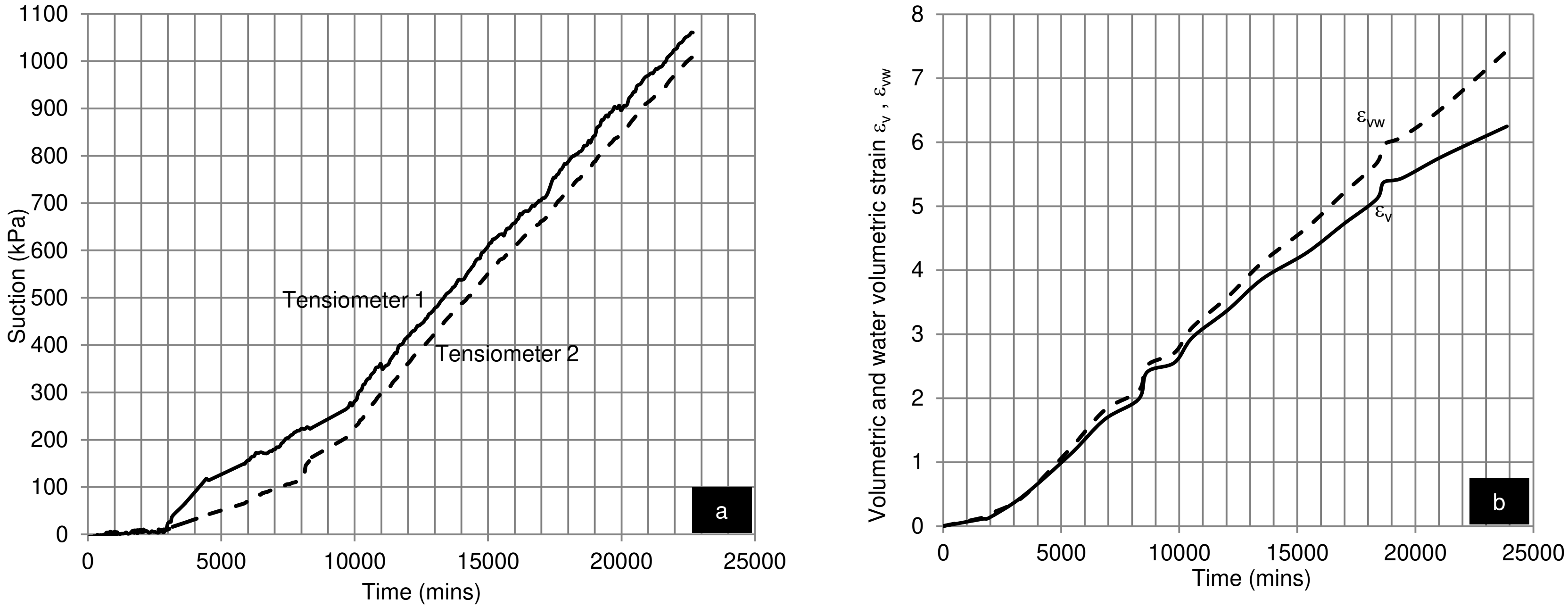


Figure 5 - Suction and volumetric strains of water and void phases with time (G1)

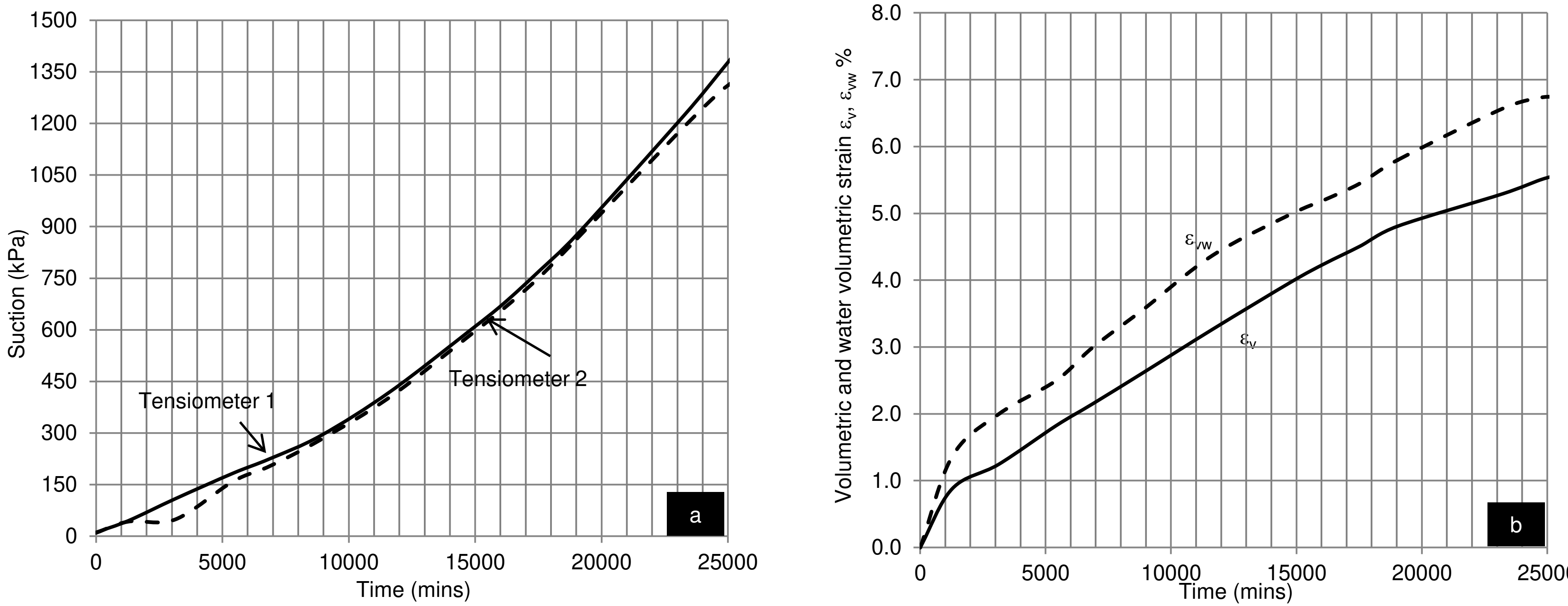


Figure 6 - Suction and volumetric strains of water and void phases with time (G2)

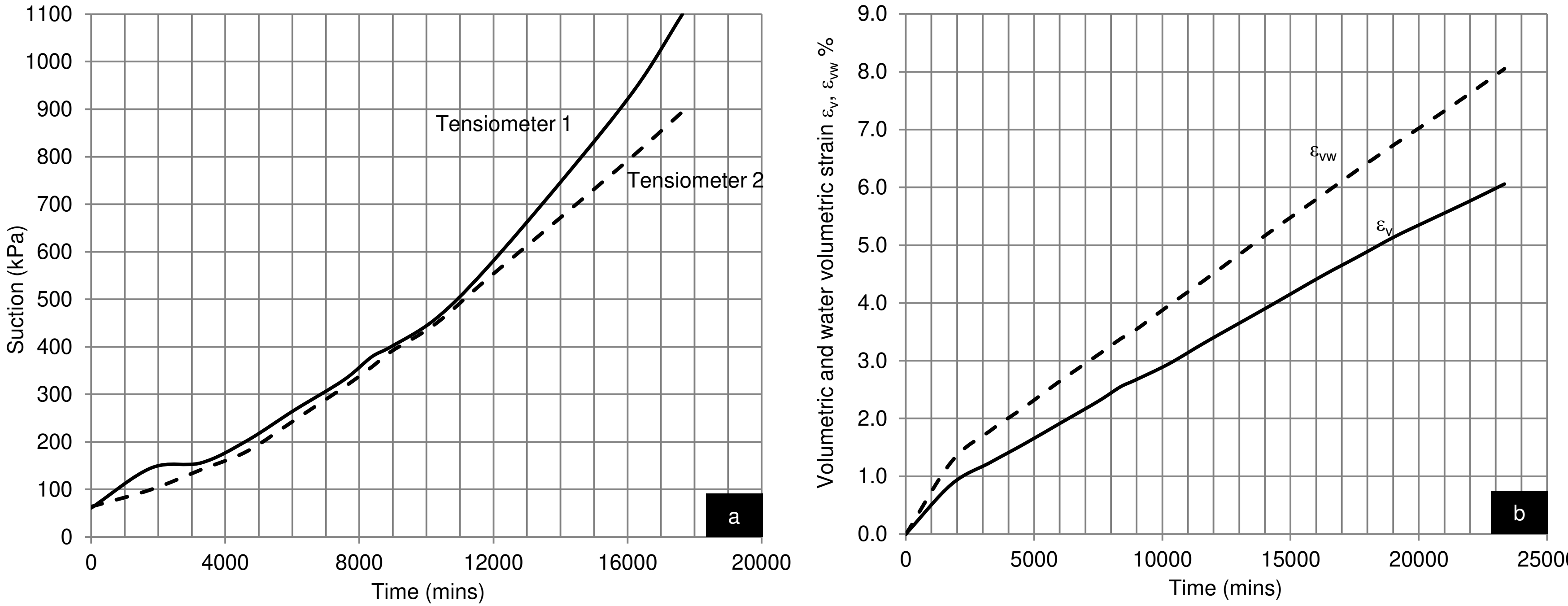


Figure 7 - Suction and volumetric strains of water and void phases with time (G3)

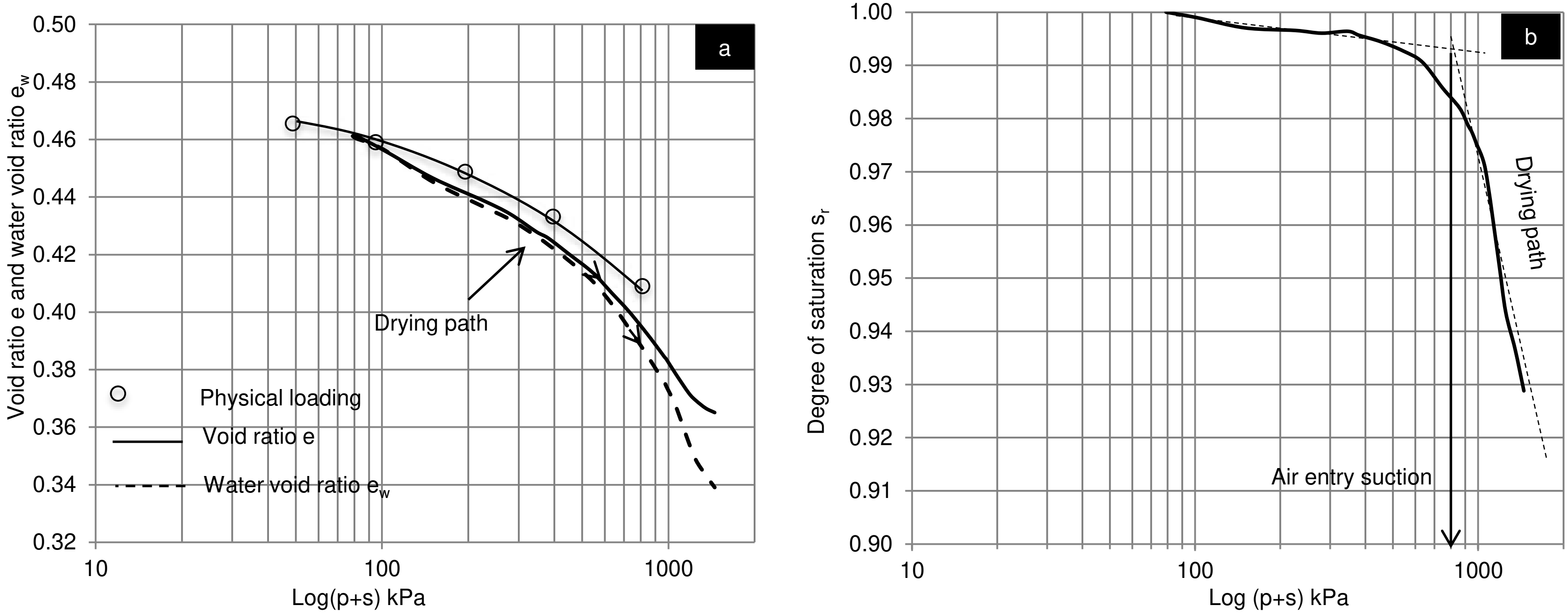


Figure 8 - Void ratio, degree of saturation vs suction for reconstituted Glacial (G1)

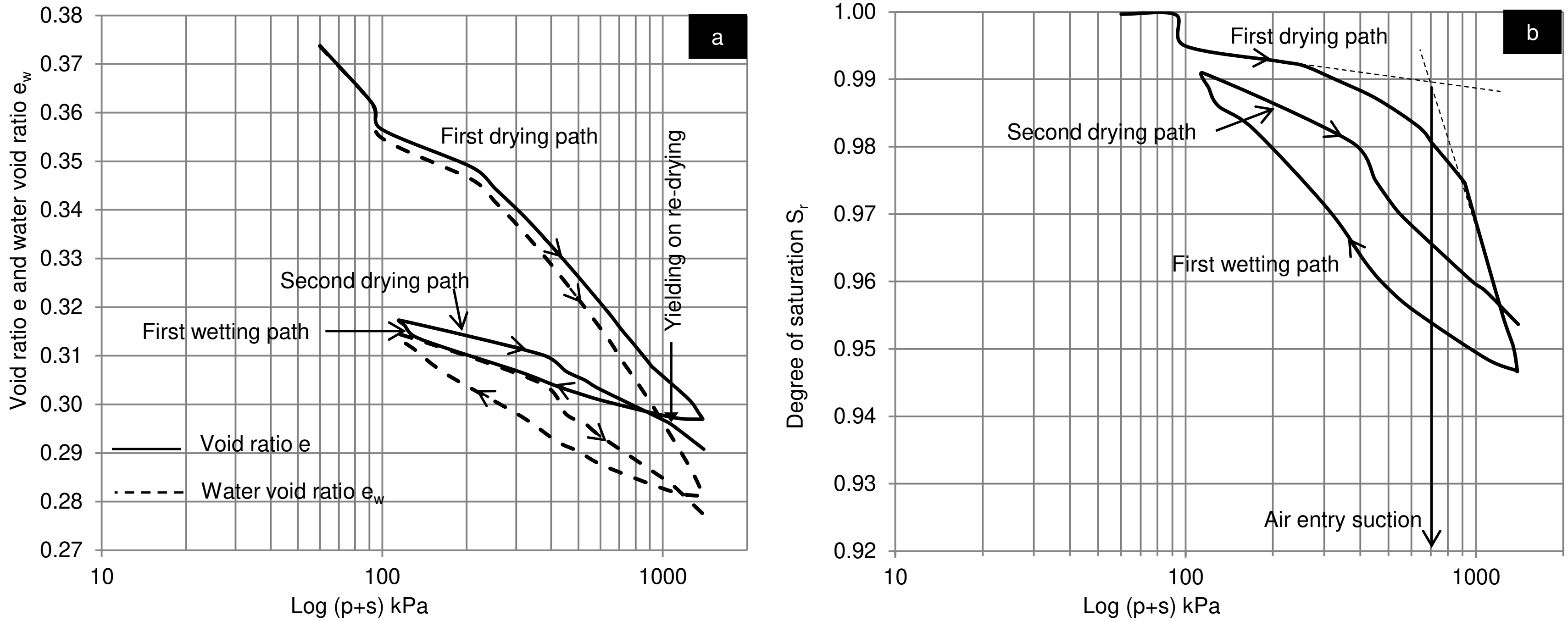


Figure 9 - Void ratio, degree of saturation vs suction for Glacial till compacted at 12% water content (G2)

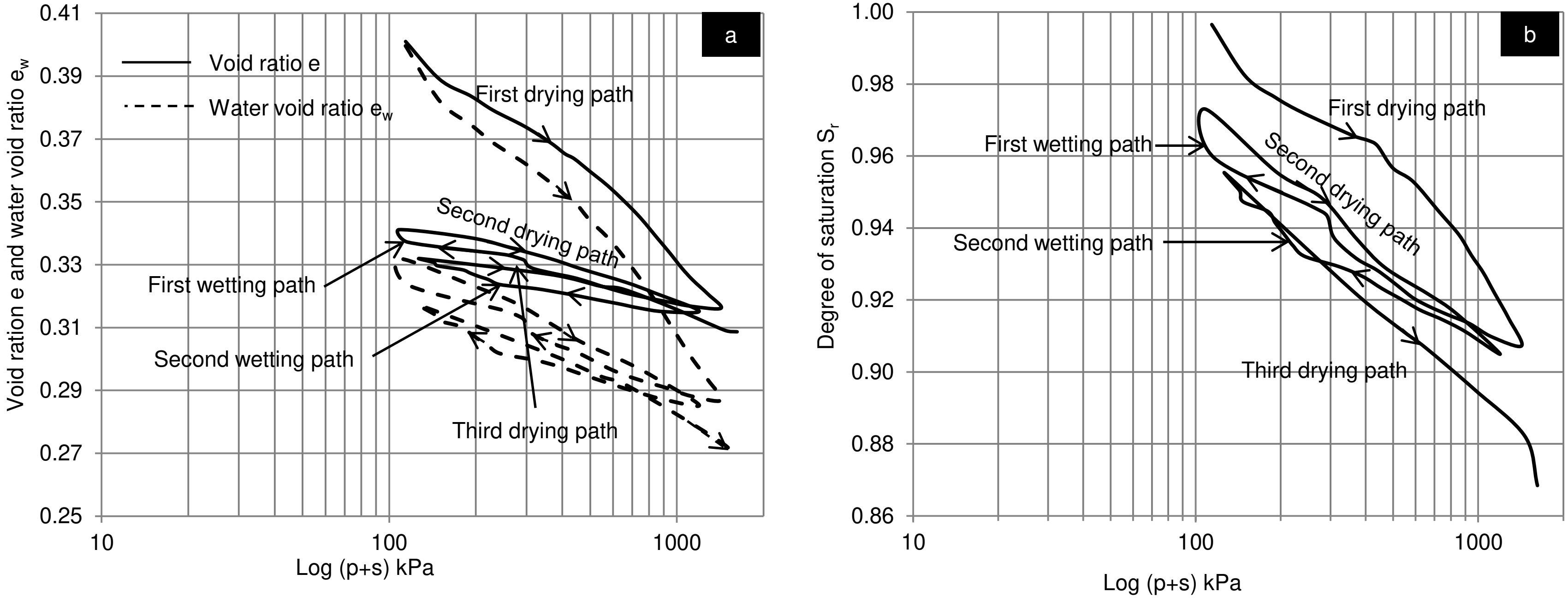


Figure 10 - Void ratio, degree of saturation suction relationship for Glacial till compacted at 13% water content (G3)

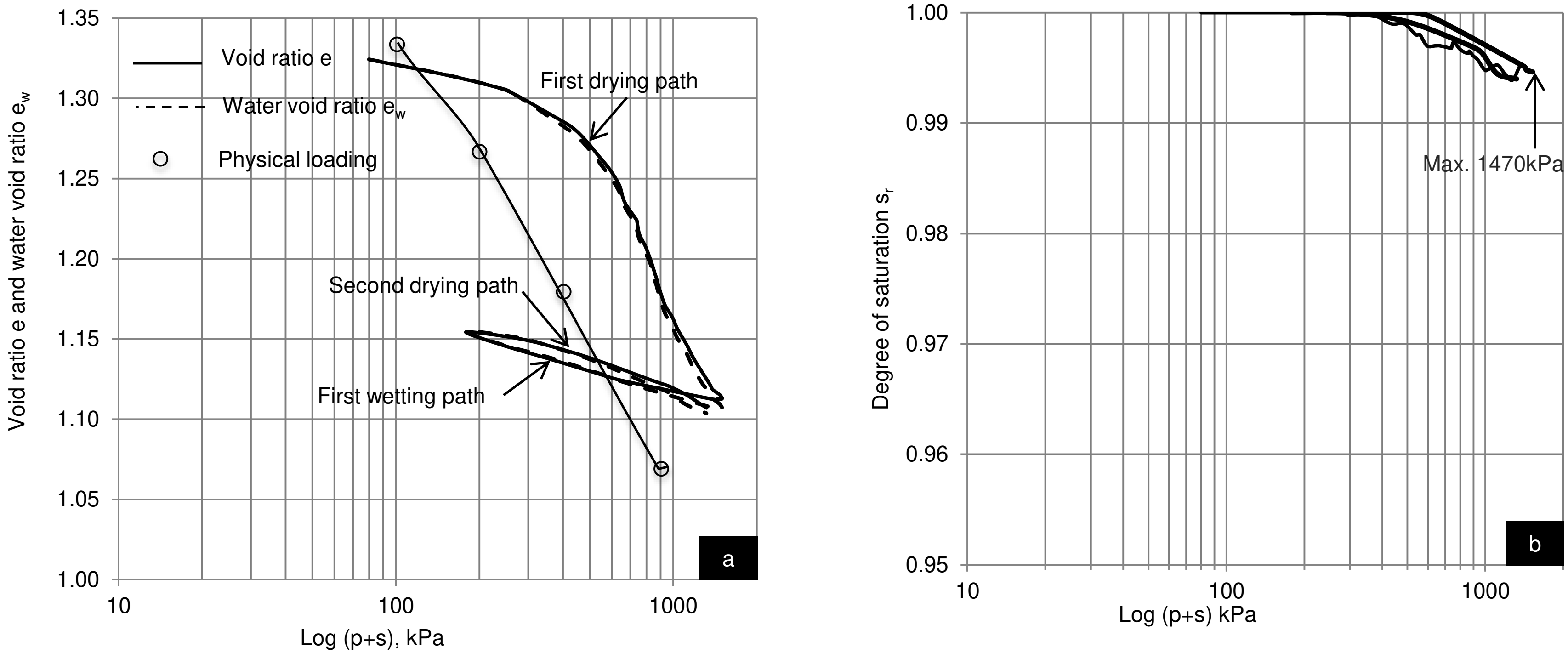


Figure 11 - Void ratio, water void ratio and degree of saturation vs suction for kaolin (K1)