

A modified Suction-controlled Triaxial Equipment

Muayad A. Al-Sharrad
Department of Civil Eng
University of Anbar
an_mission@yahoo.com

Salem M. Al-Ani
Department of Civil Eng
University of Tikrit
salimalani39@yahoo.com

Adnan J. Zedan
Department of Civil Eng
University of Tikrit
jayedadn@yahoo.com



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Abstract

The paper presents a modified equipment for triaxial testing of soil samples under unsaturated as well as saturated conditions. The equipment is capable of performing various types of hydro-mechanical loading including wetting and drying stress paths under constant or varying net stresses. The suction is controlled/ measured by using axis translation technique. Initial investigation on the performance of the testing system after appropriate calibrations had been conducted indicated good level of accuracy in measuring various soil properties.

Keywords: Unsaturated soils, Triaxial equipment, Matric suction

1- Introduction

Since 1960's researchers achieved significant development in the measuring and controlling techniques for suction and volume changes in unsaturated soils. As for saturated soils, triaxial equipment for unsaturated soils is the most widely used equipment in the lab for the characterisation of soil stiffness, strength and hydraulic properties. Measurement of the volume changes in terms of the volume of water flowing into or out of the cell is broadly used due to its simplicity. Triaxial cells adopting this volume measuring technique are categorised into double wall and single wall cells. In principle, the inner cell of a double walled-apparatus exhibits zero expansion/ contraction as long as equal confining pressures are applied on both wall sides. The original form of the double wall cells was developed in the pioneering work of Bishop and Donald [1]. The working principle was further extended by many researchers such as Wheeler [2], Sivakumar [3], Aversa and Nicotera [4], Ng et al. [5] and Sivakumar et al. [6], further discussion can be found in [7]. In the single wall arrangement, the cell wall is normally made of stiff material with significantly small or none capacity of water absorption. It is therefore important for the material to behave elastically, under working pressures, with insignificant creep or physical hysteresis under cyclic loading conditions. Example of this arrangement is found in Buisson [8] who developed a single wall

triaxial cell in which the wall was made of stainless steel of 30 mm thickness.

In addition to the abovementioned issues, the accuracy of overall volume change measurement is susceptible to errors caused by, for example, temperature variation, air trapping between sample and the rubber membrane, expansion of other system parts such as PTFE tubes, undetectable leak, air diffusion from the rubber membrane and movement of the loading shaft inside the cell. For these reasons, extensive physical calibration work is normally conducted to achieve better representation of the actual volume changes such as that shown in Raveendiraraj [9] and Al-Sharrad [10].

The triaxial equipment presented in this paper is a single wall apparatus developed at the University of Anbar- Iraq as a part of an on-going research on unsaturated soils.

2- Single wall cell apparatus

2-1 General view

The existing apparatus was in a brand-new condition and was provided by the company ELE International. The system comprises of the triaxial cell (1700 kPa working pressure capacity and capable of testing triaxial samples of 100 mm maximum height and 50 mm diameter), rigid loading frame, pore water drainage with a digital volume gauge, 3 kN load cell, LVDT (linear variable displacement transducer), 17 bars pressure transducers and de-airing system. Cell and pore water pressures are applied manually by using fine threaded screw pistons installed on a pressure panel. The data acquisition system consists of eight-channel data logger and software called DS7, provided by the same company. The data is stored in a specific location within the software and can be collected for post processing in another standard software such as MS Excel.

In order to perform suction controlled triaxial tests, a set of modifications had to be achieved on the available equipment including:

- Replacing the existing cell wall, made of acrylic, to solve problems associated to water absorption and relatively high expansion/ contraction given the dependency on time, pressure and temperature.

- Replacing the top cap and base pedestal of the cell to adapt for suction application and air drainage.
- Installing a second volume gauge to measure volume changes of the water surrounding the sample during sample deformation.
- Arranging for pore water and pore air drainage and installing proper flushing system to remove unwanted diffused air from the system.
- Installing temperature sensor so that the unwanted fluctuation in volume, normally recorded when temperature oscillates in the lab, can be calibrated for and minimised.
- Finally, arranging a temperature controlled room to reduce the effect of daily and seasonal variations of temperature on equipment performance.

Some of the important features of the equipment are presented in detail in this paper and for a detailed description, see [11].

2-2 The triaxial cell

A schematic diagram of the triaxial cell mounted on the loading frame is shown in Figure 1. The acrylic wall of the cell was replaced by 6 mm in thickness carbon steel wall, among many other alternatives, mainly due to its excellent stiffness, strength and creep properties. To give a sense of the improvement, the modulus of elasticity and the coefficient of linear thermal expansion are 200-250 GPa and 10-18 (10^{-6} m/(m °C)) for carbon steel respectively while these values are 2.1-3.4 GPa and 70-140 (10^{-6} m/(m °C)) for acrylic respectively [12]. In addition, the carbon steel possesses very low rate of corrosion and no tendency to absorb water unlike acrylic which can, on saturation, absorb up to 2% by weight water [13].

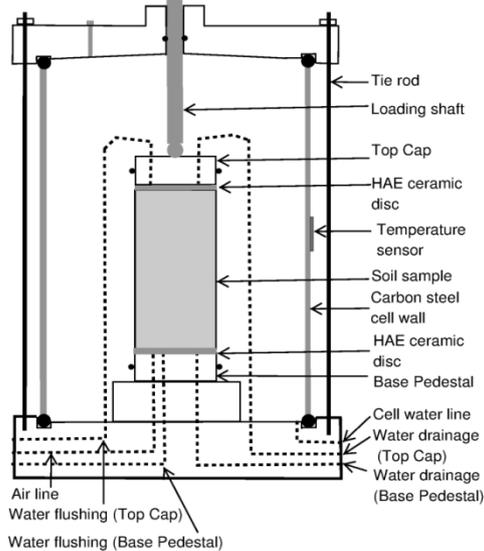


Figure 1: Schematic diagram of the triaxial cell

Expansion of the cell wall

Quantifying the possible volumetric expansion of the cell in a sensible way would involve a sort of sophisticated stress-strain analysis due to the complicated structure of the cell. A simple manual calculations were instead performed to roughly estimate the amount of cell volumetric expansion with pressure. The material is assumed to exhibit linear isotropic elastic behaviour under the applied internal pressure. Also, end effects are ignored and thereby the wall is expected to deform uniformly with pressure in the lateral direction.

In mechanics, a cylinder is usually considered “thin-walled” when wall thickness does not exceed one-tenth of the internal radius [12], which is the case for the new wall. Consequently, the wall can be treated as a surface and be analysed by using Young-Laplace Equation. Under internal pressure on a cylinder with closed ends and a given geometry, three internal stresses are developed [12], namely; circumferential stresses (σ_{θ}) (normal stress works in the tangential direction), longitudinal stress (σ_L) (normal stress works in the direction of the axis of cylindrical symmetry) and radial stress (σ_r) (in directions perpendicular to the symmetry axis). The above stresses can be quantified from the following equations (negative sign refers to tensile stresses):

$$\sigma_{\theta} = \frac{-Pr}{2t} \quad \dots (1)$$

$$\sigma_L = \frac{-Pr}{4t} \quad \dots (2)$$

$$\sigma_r = \frac{P}{2} \quad \dots (3)$$

where p is the internal pressure (given that outer side of the cylinder is subjected to only atmospheric pressure), r is the inside radius of the cylinder and t is the wall thickness. In regards to the elastic strains, circumferential strain ϵ_{θ} and axial strain ϵ_L are calculated as shown below, respectively:

$$\epsilon_{\theta} = \frac{1}{E} (\sigma_{\theta} - \mu\sigma_L) \quad \dots (4)$$

$$\epsilon_L = \frac{1}{E} (\sigma_L - \mu\sigma_{\theta}) \quad \dots (5)$$

The volumetric strain can be approximated by:

$$\epsilon_v = (\epsilon_L + 2\epsilon_{\theta}) \quad \dots (6)$$

Inserting typical values for material properties and dimensions in Equations 1 to 6 resulted in a volumetric expansion of approximately 0.20 cm³, under a working pressure of 1000 kPa, which is remarkably small.

Despite this improvement, the new cell wall is not transparent hence the sample cannot be visualised during the progression of the test. Also, carbon steel owns a coefficient of thermal conductivity (36-54(W/m-K)) which is higher

than that of acrylic (0.17-0.2 (W/m-K)) by more than two orders of magnitudes. Nevertheless, this emphasizes the importance of temperature control inside the testing room.

Suction application

Matric suction is applied with axis translation technique in which pore air pressure is elevated above the atmospheric level by means of compressed air in such a way that total pressure is kept constant while positive values of pore water pressure are attained (to prevent cavitation that is associated with highly negative pore water pressure).

The original top cap and base pedestal (i.e. for testing 50 mm in diameter saturated soil samples) were removed and new parts, made of brass, were manufactured to accommodate for suction application. One way air drainage was arranged from the base pedestal as soil is highly permeable to air. Figure 2 shows the layout of the base pedestal together with the high air entry filter holder. As shown in Figure 2, three holes were made through the pedestal where two of them are for water drainage and water flushing (to remove diffused air) beneath the HAE filter whereas the third is for air drainage. These holes coincide with those ones on the base plate. The water drainage is separated from air drainage by a rubber “O” ring. A set of “O” rings were also used on the bottom side of the pedestal to prevent cell water or air from breaking through the pore water drainage. Figure 3 shows the layout of the brass filter holder inside which 1 bar ceramic HAE filter was glued. An “O” ring groove was hosted on the bottom face of the holder to prevent air from entering water drainage. The filter holder is attached to the base pedestal by using 4 screws.

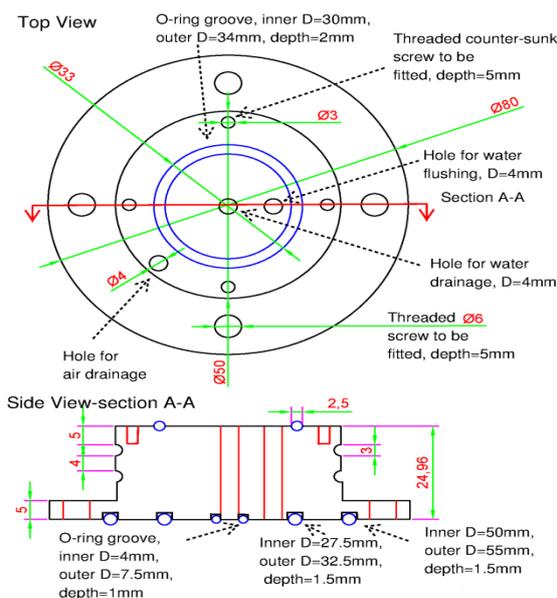


Figure 2: Base Pedestal layout

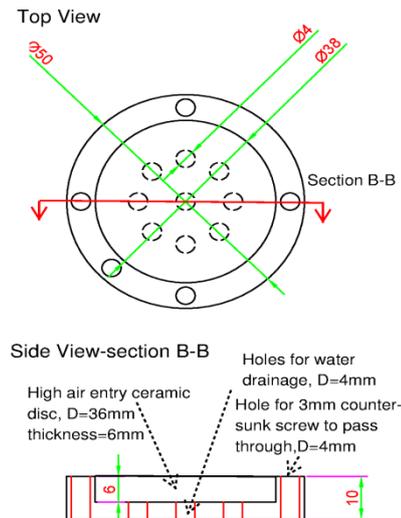


Figure 3: Filter holder layout (base pedestal)

3- System layout

Figure 4 shows the layout of the developed suction controlled triaxial equipment. A photograph of the system is shown in Figure 5. Cell pressure and pore water pressure were applied by using the screw pistons on panels 1 and 2 respectively. Air pressure was supplied by an air compressor at a line pressure of 800 kPa and controlled via air pressure regulator installed on panel 3. A distilled water would be used in the system instead of tap water as tap water might increase the osmotic suction component due to the none zero salt contents. Also, some of the insoluble salts particles might inhabit the micro pores of the HAE filter causing a decrease in the permeability.

Transducers can be recalibrated while they are in position, then the software performs linear regression to obtain calibration constants. The readings of the transducers can be initialised (i.e. transducer’s reading is set to zero). For instance, cell pressure can be initialised by filling the cell, opening the vent on the top of the cell and then pressing the relevant key in the software to consider the current value as zero pressure.

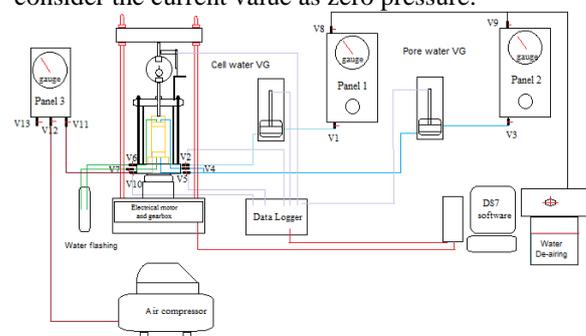


Figure 4: Overall layout of the developed suction- controlled triaxial equipment.



Figure 5: Photograph of the suction-controlled triaxial equipment

4- Calibrations

It is essential to assure that variation of pressure, volume and displacement are accurately captured during a real test. Apparent volume changes of the cell caused by the expansion/contraction of cell, connecting PTFE tube and other parts of the measuring system due to changes in pressure and temperature is of particular importance for unsaturated soils. Accordingly, these calibrations were conducted following the methodology and the arrangement outlined in [10] and more details are given in the subsequent paragraphs. It was planned to conduct the real constant-suction testing by holding the cell pressure at the constant value 800 kPa while varying pore air and pore water simultaneously in a standard constant-suction test. This has the implication that during apparent cell water volume change calibration, cell pressure should be kept constant while during apparent pore water volume change calibration pore water pressure should be varying.

For the analysis of the results, linear calibration was investigated where applicable by following standard best fit procedure to obtain the values of the constants of the simple regression model *a* and *b* shown in the equation below.

$$y = ax + b \quad \dots (7)$$

Values of these constants for each fitting exercise are listed in Table 1. It is worth mentioning that all transducers were in a brand-new condition and they were well stored in the soil lab, therefore, the original calibration by the manufacturer was considered valid.

4-1 Apparent cell volume change calibration

The apparent cell volume change calibration was conducted under the constant cell pressure 800 kPa with all components of the measuring system were involved in this calibration. An acrylic stoppers were used instead of the HAE filters to avoid cell water breaking through the pore water drainage system. The results of this calibration are plotted in Figure 6 together with the temperature variation measured at the external

surface of the cell's wall. The values at time *t*=0 represent the volume change after few hours of cell pressurising, demonstrating an immediate cell volume change of about 7 cm³. This volume change is attributed mainly to existence of free air inside the cell (keeping in mind that air is highly compressibility compared to water where the bulk modulus of air and water are approximately 1.01 *10² kPa and 2.2 *10⁶ kPa respectively). This value is significantly higher than the calculated value of cell expansion (i.e. 0.20 cm³, see Section 2). The correspondence between the variation in temperature and the variation in the volume of the water in the system is apparent. The time lag (of probably 2 hours) is due to the fact that temperature sensor was mounted outside the cell. For the sample size 100mm *50 mm, such fluctuation in temperature would produce an error in specific volume of ±0.01. To increase the accuracy of the measurement, a volume correction exercise was performed to obtain the best value for temperature correction which would reduce the long term fluctuation but, on the other hand, produce the smallest short term volume fluctuation. This value was found to be 0.4 cm³/°C at which the apparent volume change is as shown in Figure 6. This correction would reduce error in specific volume to about 0.005. Subsequently, the apparent volume change per day was worked out by performing a best-fit exercise which gave a value of nearly 0.1 cm³/day (this positive rate indicates that water is flowing out the volume gauge).

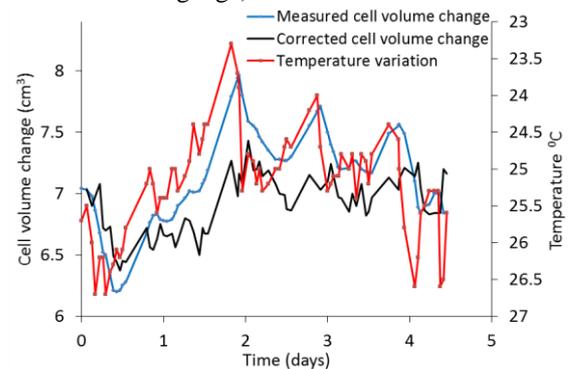


Figure 6: Cell apparent volume change calibration

4-2 Apparent pore water volume change

This calibration was conducted in parallel with the cell apparent volume change calibration. In this calibration the pore water pressure was elevated in steps to 200, 400 and 600 kPa then decreased to 400 then to 200 kPa with a rest period of 24 hours between each successive steps, see Figure 7. The abrupt changes in pore water volume is caused by the step-changing of pore water pressure. It is clear that temperature had less impact on the pore water volume which is

expected due to the smaller amount of water in that system. Each set of data points, at a given constant pore water pressure, was fitted with the best fit line to obtain the slope of the calibration in terms of volume change per day as remarked in Figure 7. For the pressure increase path, this slope increased with increasing pressure (i.e. more water leaved the volume gauge). For the pressure decrease path, the slope was nearly zero with a suggesting that very little amount water was flowing to the volume gauge. Regression analysis of the slopes obtained during pressure increase or pressure decrease showed that either sets can be approximated by a line in the plot of pressure against slope of the calibration.

The immediate accumulative volume changes caused by step changes in pore water pressure are plotted in Figure 8. When the pressure decreased, the immediate volume changes followed a new path differs from that followed during stress increase indicating the hysteresis in the pressure-volume relationship for water. For practical reasons, both variation of pore water volume during the pressure increase and the pressure decrease might be approximated by a single line as shown in Figure 8. It can be shown that, for the pore water pressure range 200 kPa to 600 kPa, the error in specific water volume v_w (where $v_w = 1 + wG_s$ in which w is the water content and G_s is the specific gravity) would be reduced from ± 0.007 to ± 0.002 . This could be valuable when the hydro-mechanical properties of unsaturated soils, such as that including wetting and drying cycles, are investigated on a smaller scale.

Values of the relevant correction factors obtained from the above calibrations are listed in Table 1. In general, analysis of the calibration results indicated that equipment performs well in regards to volume changes measurement and that the various corrections should be applied to increase the accuracy.

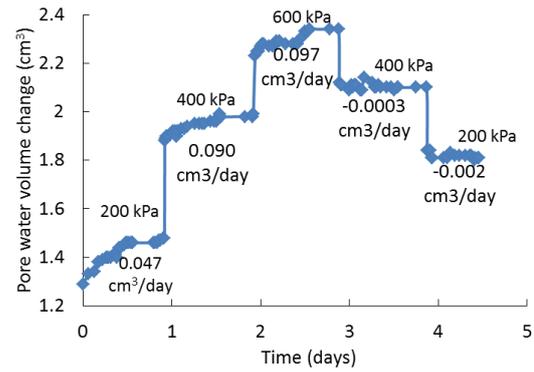


Figure 7: Pore water apparent volume change calibration

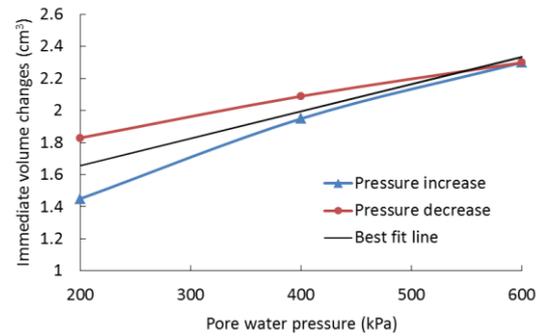


Figure 8: Immediate accumulative pore water volume changes

5- Preliminary tests

Due to time limitation of this study, only one suction controlled test with a mechanical loading stage was conducted on compacted kaolin clay sample namely, A50. Another test consisting of only suction equalization stage namely, B50 was also performed. Samples of these tests (100 mm *50 mm) were prepared by one-dimensional static compaction of a wet kaolin (at water content, $w=0.25$). Each sample was compacted in layers of equal height with the intention of achieving the same initial specific volume,

Table 1: Calibration constants

Calibration	Simple linear regression model		Linear regression constants	
	y	x	a	b
Apparent cell water volume change	Cell water volume change (cm ³)	Time (days)	0.098 cm ³ /day	-
	Cell water volume change (cm ³)	Temperature (°C)	0.4 cm ³ /°C	-
Apparent pore water volume change	Slopes of the pore water volume-time plot for pressure increase path (cm ³ /day)	Pore water pressure (kPa)	0.000125 (cm ³ /day/ kPa)	-
	Slopes of the pore water volume-time plot for pressure decrease path (cm ³ /day)	Pore water pressure (kPa)	-0.000250 (cm ³ /day/ kPa)	-
	Immediate pore water volume change (cm ³)	Pore water pressure (kPa)	0.001686 (cm ³ / kPa)	1.317 (cm ³)

degree of saturation and suction in these samples. Afterwards, each sample was wetted to a matric suction of $s=50$ kPa under a mean net stress of $\bar{p}=20$ kPa and zero deviator stress. Subsequently, sample A50 was loaded isotropically to a final mean net stress of $\bar{p}=350$ kPa.

5-1 Suction equalization stage

Table 2 shows the values of specific volume (v), water content (w) and degree of saturation (S_r) immediately after compaction and after wetting during the test. Figure 9 shows the increase in water content, specific volume and degree of saturation against square root of time during the initial equalization stage for the tests. The increase in the values of these state variables indicates that initial suction value in the samples was much higher than 50 kPa. The increase in specific volume, in particular, indicates that only elastic swelling took place. Investigation of the plots shows that both samples followed the same pattern during suction equalization reflecting a good level of repeatability in material behavior and an acceptable level of equipment performance. After about 30 hrs, the rate of sample volume change and pore water volume change decreased significantly indicating that equilibrium condition was nearly attained.

Table 2: Specific volume, water content and degree of saturation values after compaction and after equalization

State	State variable	Sample	
		A50	B50
After compaction	v	2.168	2.189
	w	0.227	0.225
	S_r	0.512	0.512
	v	2.231	2.224
	w	0.321	0.318

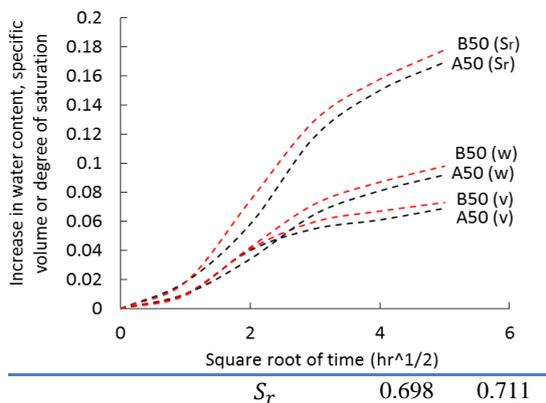


Figure 9: Increase in water content, specific volume and degree of saturation during suction equalization stage

5-2 Loading stage

Isotropic loading in Test A50 was carried out by decreasing in steps the pore water and pore air

pressure simultaneously while maintaining cell pressure constant at 800 kPa. A rest period of 24 hours was imposed between successive loading stages to allow for equilibrium. Figures 10 and 11 show the semi-logarithmic plots of specific volume and degree of saturation against mean net stress respectively (bearing in mind that the values of state variables, i.e. mean net stress, specific volume, degree of saturation, at equilibrium are only plotted). For the first portion of both curves, only small change took place in specific volume and degree of saturation, indicating that the behavior was mainly elastic. Then as loading progresses, gradual transition was observed followed by notable change in specific volume and degree of saturation, indicating that the behavior was mainly plastic (irreversible). The correspondence between the two curves can be explained by the fact that the volumetric compressibility of pore spaces is much greater than the amount of water flowing out the sample during the loading stage. By other words, the change is S_r was always positive.

Despite that the elastoplastic behavior described above is typical for an unsaturated compacted clay soil, the researchers cannot confirm the accuracy and repeatability of those results due to the lack of experimental data.

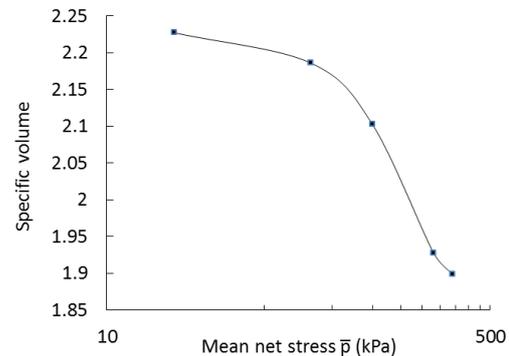


Figure 10: Variation of specific volume with mean net stress for Test A(50)

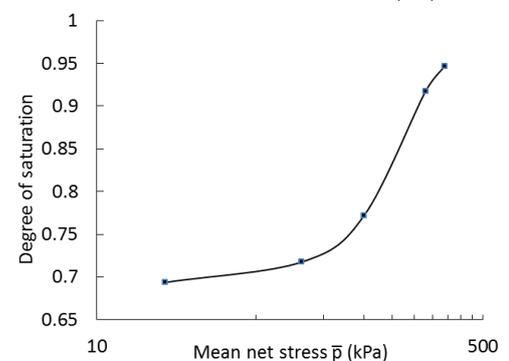


Figure 11: Variation of degree saturated with mean net stress for Test A(50)

6- Conclusions

The paper presents a modified triaxial equipment for testing soil samples under unsaturated conditions as a part of an on-going research on unsaturated soils at the University of Anbar- Iraq. The modifications involved replacing the existing acrylic cell wall with a new carbon steel wall that is stiffer and does not show tendency to absorb water. New top cap and base pedestal arrangements were made to accommodate for matric suction application. A New drainage system was arranged to accommodate for cell water volume, pore water volume measurements and for air bubbles removal for the measuring system. The overall testing system was installed in a temperature controlled room.

Data obtained from various calibration exercises performed in this study indicated that the equipment performs well as no significant leak was detected and that the apparent volume change rates and immediate volume changes were within the expected ranges. Furthermore, the adequate performance of the equipment was also partly justified by means of real triaxial test where good agreement was found between the measured values of water content, specific volume and degree of saturation of two identical unsaturated soil samples during a wetting stage.

Despite the above advantages, the new cell wall suffers from the disadvantage that soil specimen (also any trapping air bubbles) cannot be visualized during a real test. Finally, further investigation may be required to examine equipment performance under conditions of anisotropic loading and drying/ wetting cycles.

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جهاز مطور لفحص القص الثلاثي المحاور باستخدام تقنية ضغط الامتصاص

د. عدنان جايد زيدان
قسم الهندسة المدنية
جامعة تكريت

jayedadn@yahoo.com

سالم محمود العاني
قسم الهندسة المدنية
جامعة تكريت

salimalani39@yahoo.com

د. مؤيد عبد الجبار الشَّراد
قسم الهندسة المدنية
جامعة الأنبار

an_mission@yahoo.com

الخلاصة:

يعرض البحث جهازاً مطوراً لفحص القص الثلاثي المحاور للترب غير المشبعة بالإضافة الى تلك المشبعة. يمكن استخدام الجهاز لاجراء الفحوصات المزوجة الميكانيكية- الهيدوليكية بما في ذلك اجراء دورات الترطيب والتجفيف تحت تأثير اجهادات ثابتة او متغيرة ويعتمد الجهاز على مبدأ تقنية نقل المحور لتسليط ضغط الامتصاص. اثبتت المعايير التي اجريت على الجهاز دقة القياسات المسجلة لخصائص التربة.

الكلمات المفتاحية: الترب غير المشبعة, جهاز فحص القص ثلاثي المحاور, ضغط الامتصاص