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A MODIFIED OEDOMETER WITH CONTROL SUCTION AND TEMPERATURE

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Abstract

Pressure plate devices have been developed to investigate the hydromechanical behaviour of unsaturated soils using the axis translation technique (ATT). Despite the progress in experimental methods, there are still some problems concerning the ATT application, e.g., the evaporation and condensation of water on cell walls. This investigation discusses a fabricated device-dissolving condensation problem linked to the ATT. A modified suction temperature-controlled oedometer was developed and successfully employed to perform various experiments on unsaturated soils by controlling the vertical net stress, suction, and temperature simultaneously as well as minimizing any problems related to water condensation. The heating system employed for the modified device significantly reduced the water volume errors involving condensation, which varied from 0 to 1.12% in the soil-water characteristic curve (SWCC) test. In addition, the established SWCC of residual granite soil using the modified oedometer was verified by the pressure plate technique.

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Key words

- Unsaturated soil
- Modified oedometer,
- Suction,
- Temperature.

1 INTRODUCTION

Any variation of the humidity conditions in an area affects the condition of the soil. Consequently, soil is neither completely saturated nor completely dry in its natural state. In this case, the soil is usually called semi-saturated or unsaturated soil. Many experiments have been performed by researchers on unsaturated soils (Yilmaz et al., 2016; Ahmadinezhad et al., 2019; Kholghifard, 2020). To investigate the volumetric behaviour (stress or strain) of unsaturated soils, one-dimensional stress testing is applied using a modified oedometer based on the Axis Translation Technique (ATT). Suction-controlled oedometer testing is essential to study the volumetric parameters of unsaturated soils. However, one of the major limitations of this technique is evaporation on the cell walls due to water condensation, which causes errors in changes in the water volume, as reported by previous researchers (Fredlund and Rahardjo, 1993; Tanner and Elrick, 1958). The results of previous conducted experiments based on the ATT showed that some water condensed on the cell walls of the pressure plate. Fluctuations in the temperature are mainly caused by condensation on the cell walls as a result of the oedometer test. To solve this problem, Tanner and Elrick (1958) suggested placing a block heater above the chamber to avoid water condensation. Fredlund and Rahardjo (1993) stated that the evaporation or condensation of water on the cell wall of equipment used for unsaturated soil based on the axis translation technique generates errors in the outflow readings, especially related to long-term experiments for grained soils. They recommended the use of block heaters on the top and bottom of the cell, but this approach did not work very well. Perez-Garcia et al. (2008) tested Yuma sand with a block heater and reported water condensation on the top of the plate, o-ring, and the groove where the cell walls are located. The condensation of water on the cells of these devices as well as the use of a heater system was also reported by other researchers such as Marinho et al. (2008), Vanapalli et al. (2008), and Perez-Garcia et al. (2008). As a result, the design and fabrication of a device based on the ATT was the goal of this research to dissolve the condensation problem.

2 MATERIAL AND METHODS

2.1 Modified oedometer

This section is separated into two basic subsections. The first subsection consists of the design and fabrication of a modified suction temperature-controlled odometer, while the second part explains the calibration of the modified device. The modified oedometer was produced based on the application of ATT and ASTM D 6836-02 (2008) to apply a consolidation test on unsaturated soil with control of the suction and temperature. For an unsaturated soil sample, the alteration between the air pressure (u_a) and the water pressure (u_w) in an unsaturated soil sample is known as matric suction and expressed as (u_a - u_w). In fact, the measurement of a differential pressure across a high air entry value (HAVE) ceramic disk is considered as matric suction in unsaturated soils using the ATT (Thudi, 2006).

The modification was conducted on a conventional oedometer so that the improved device could be employed for a consolidation test under saturated and unsaturated conditions. The ATT was selected as the most appropriate technique for applying a moderate level of matric suction (from zero to 1500 kPa) to the soil samples. To apply only suction, an airtight chamber, air pressure supplier, and a pore water pressure measurement tool are needed. However, to apply the axis translation technique along with the suction imposed, an extremely saturated porous ceramic disk and water tank are needed as well to allow water to flow into or out of the sample (Pereira and Fredlund, 2000). In order to control the temperature and minimize evaporation on the cell wall during the tests, the oedometer device was also improved with a temperature chamber linked to a thermo-controller unit with an accuracy rate of ±1 ºC. The thermo-controller is a controlled temperature of up to 90 ºC. The external cell was designed such that heated water covered the entire internal air cell tightly. The design and fabrication procedures are described in the following subsections.

2.2 HAVE ceramic disk

One of the most important parameters necessary for designing a modified odometer is the selection of a ceramic disk. The ceramic should be compatible with the level of matric suction desired and the type of soil. Tab. 1 shows the suggestions of Perera (2003) for the selection of the ceramic disk based on the type of soil. In this research, a 15 bar (1500 kPa) ceramic disk was selected for the possibility of applying air pressure that permits applying a level of suction of up to 1500 kPa. The physical properties of the selected ceramics are presented in Tab. 2. The high air entry ceramic disk was provided by the Soilmoisture Equipment Corporation.

When designing an axis translation device, air leakage is one of the main obstacles. Air can leak along the interface between the boundaries of the ceramic disk and a pedestal, where glue should be applied to create a seal with the pedestal. Furthermore, the bonding strength between the stainless steel pedestal and ceramic disk will decrease due to air bubbles. To minimize the formation of air bubbles, the most recommended process for efficiently gluing the ceramic disk is in two or three stages (Power, 2005) as shown in Fig. 1. Air or water can leak during the testing if the gluing area (where epoxy is applied between the boundaries of the ceramic disk and pedestal) is not working properly. In order to check for leakage in this area, some water was poured above the ceramic surface to a height of about 2 mm, and then about 5 to 10 kPa of air pressure was applied to the device from a valve beneath the ceramic disk. Thus, the leakage points were detected where the air bubbles leaked out. These points must be opened and filled again with epoxy. The permeability of the ceramic disk was also controlled based on the properties of the ceramic used (Tab. 1). The calculated and measured water volumes flowing across the ceramic disk under different pressures were approximately the same. This means that the ceramic disk was working quite well.

Tab. 1 *The physical properties of the ceramic disks selected*

Type	Air Entry Value (bar)	Saturated Hydraulic Conductivity (cm/s)	Max. Pore Size (µm)	Diameter (cm)	Thickness (cm)
0604D04-B15M1	15	2.59E-9	0.16	10.49	0.714

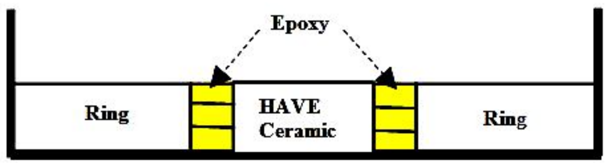

Fig. 1 *Placement of the ceramic disk in the ring*

It is essential to expel any air bubbles from the spiral chamber beneath the ceramic disc. Therefore, a flushing system must be considered to periodically remove any air bubbles formed in the spiral water grooves under the ceramic disc during the experiment. Many researchers, such as Vanapalli et al. (2008), Marinho et al. (2008), and Power (2005), have recommended that air diffusion through the ceramic disk can be minimized by applying back water pressure. A valve is linked to the spiral grooves under the ceramic disk to flush air bubbles from the water compartment. The ceramic disk acts as an interface between the soil water pores and the water in the pressure controller, which prevents the transition of free air passing into the water measurement system. To measure any vertical displacements, a Linear Variable Displacement Transducer (LVDT) is placed above the loading frame. Changes in the water volume, water pressure, air pressure, and vertical displacements are frequently recorded by a data logger linked to a computer. Vertical net stress is applied using a loading frame. The temperature is controlled using a digital controller system during the test. For monitoring and controlling the variants during the test, two consolidation and triaxial cods of DS 7 software (ELE International, 2007) are combined and modified for the oedometer.

2.3 Details of the cell body and system network

A temperature-controlled suction oedometer was designed and fabricated using stainless steel. The design was based on modification of a conventional oedometer. The schematic diagram and apparatus network are set out in Fig. 2. Fig. 3 shows the main parts of the oedometer cell and the assembled system.

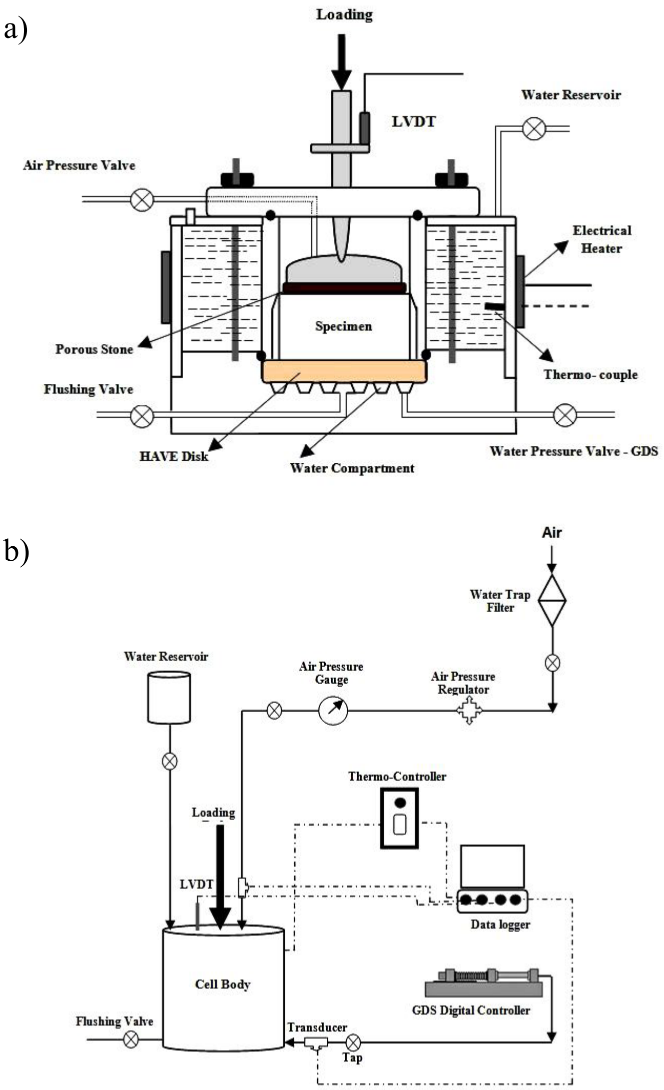

Fig. 2 ***a)*** *Schematic diagram* ***b)*** *Network diagram of the modified oedometer*

2.4 Calibration of the modified oedometer

Prior to performing each experiment with the modified oedometer, all the parts connected to the system were calibrated based on the ASTM D 6836-02 (2008) and various researchers' recommendations, e.g., Abul-Naga et al. (2006) and Fredlund and Rahardjo (1993).

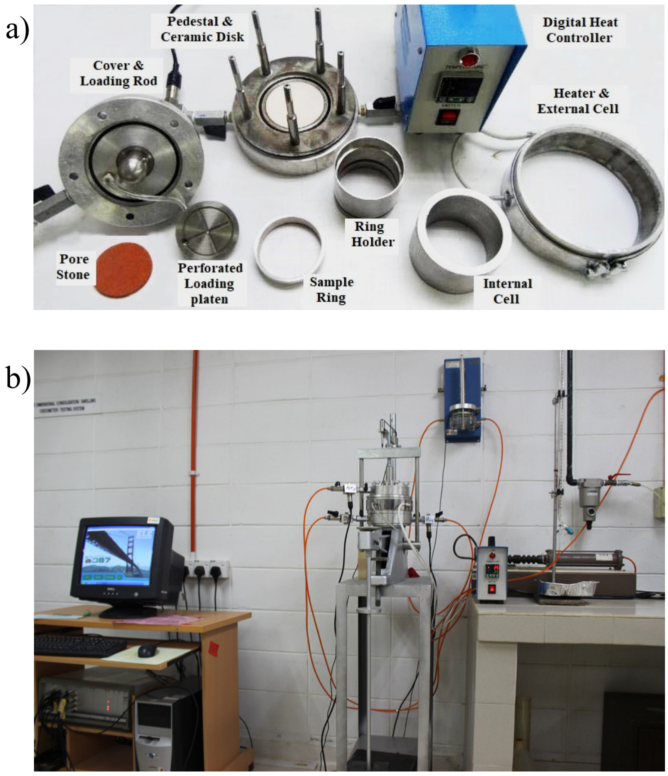

Fig. 3 *a) Modified oedometer components b) Assembled system of the modified oedometer*

Calibration of the vertical load applied: The vertical load conducted by the perforated loading plate to the soil sample was not the same as the load applied through the loading frame. The alteration was due to the friction between the loading rod and the O-ring seal, the weight of the loading rod, and the weight of the perforated loading plate. This difference should be measured in terms of the vertical stress applied during the mechanical loading. Fig. 4 shows the loading unit for the cell body, which is derived from Fig. 2-a. The loading rod and the loading platen are made of stainless steel, and they have a considerable amount of weight (W_{lr}=799 g and W_{lp}=470 g, respectively). Before the start of the loading in each test, the weights of the loading rod and the loading platen exert preloading on the sample. This overload caused an error in the test, which must be calibrated. On the other hand, the O-ring seal between the loading rod and the platen creates friction, which causes an error in the loading. This error must also be corrected before each test.

The vertical net stress (σ-u_a) applied by the loading frame can theoretically be calculated by the following expression when considering the vertical equilibrium as shown in Fig. 4.

where

$$\sigma - u_a = \left(\frac{P_f}{A_{lp}} + \frac{W_{lr} + W_{lp}}{A_{lp}} \right) - u_a \qquad (1)$$

P_f = load transferred to the platen by the loading frame
A_{lp} = area of the loading platen with a diameter of 73.6 mm
W_{lr} = 799 g, weight of the loading rod
W_{lp} = 470 g, weight of the loading platen

Taking W_{lr} and W_{lp} into account in Equation 1, the vertical net stress is:

$$\sigma - u_a = \frac{P_f}{A_{lp}} + 2.98 \ - u_a \quad (2)$$

In order to calculate the actual load transferred by the loading rod to the soil sample, the modified oedometer cell was calibrated by a calibrated load cell (SSM-AJ: 5000N) as shown in Fig. 4. The load cell was placed between the loading rod and the loading frame. The force transferred to the load cell was recorded by a data logger while applying a range of vertical loads that were under constant air pressure inside the cell. The net vertical stresses calculated by the use of Equation 2 and measured using the load cell are presented in Fig. 5 under various vertical loads at different air pressure values (e.g., u_a=0 and u_a=50 kPa). The lines can also be expressed in the following expressions:

$u_a = 0$ kPa: $(\sigma - u_a)_{measured} = 0.9996\,(\sigma)_{calculated} - 1.999$ (3)

$u_a = 50$ kPa: $(\sigma - u_a)_{measured} = 0.9996(\sigma)_{calculated} - 52.01$ (4)

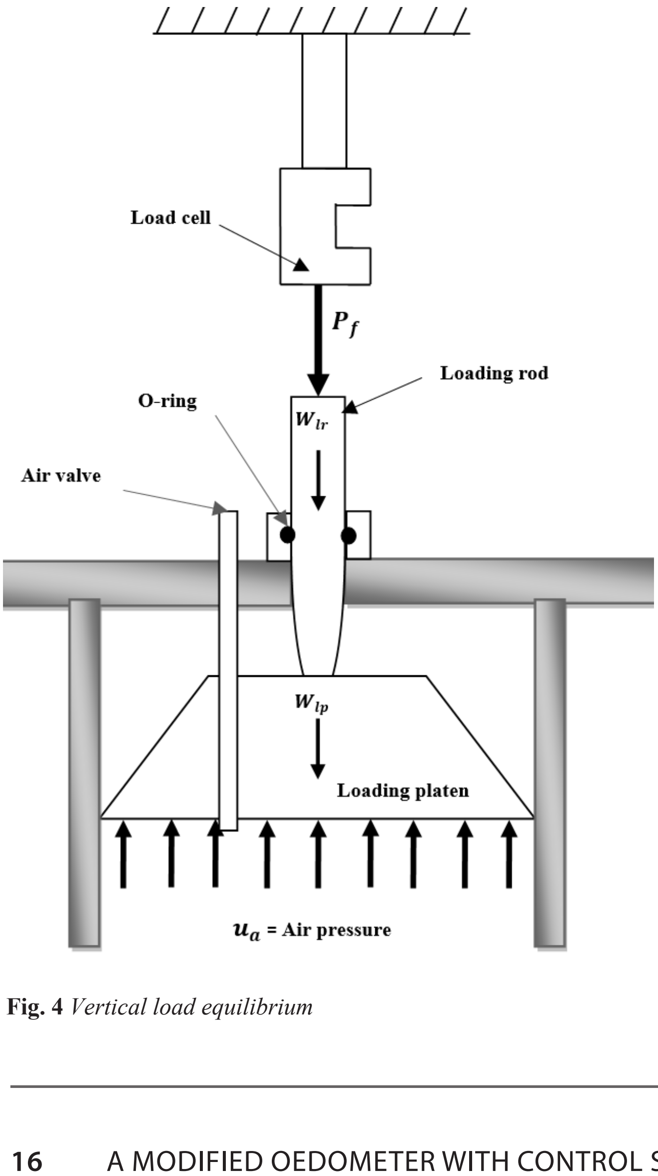

Fig. 4 *Vertical load equilibrium*

As can be seen in Figure 5, the lines are parallel with a slope of around 1. This means that the theoretical values and measured values of the vertical net stresses are approximately equal with a minor difference of around 2 kPa. This is due to the difference between the weight of the loading part (rod and platen) and the friction of the O-ring seal. The vertical net stress readings under the vertical loads during the actual experiments on the soil samples were corrected, as can be seen in Fig. 5. When the device was employed to get the SWCC of the soil without applying any vertical load, the loading lever of the oedometer was fixed so that no load was imposed on the sample.

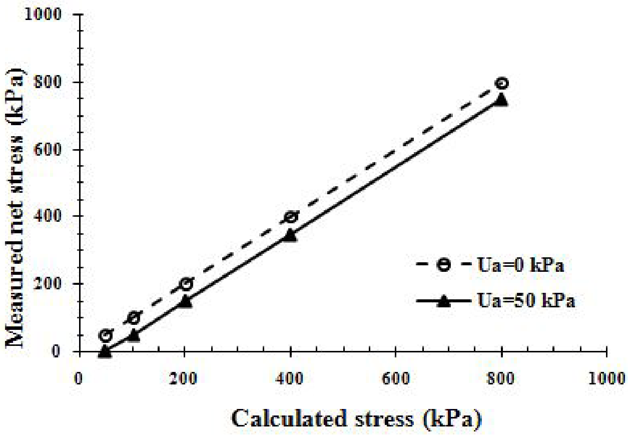

Fig. 5 *Calibration test results for the vertical loading*

Calibration of the effect of the temperature on the cell structure and the sample ring: The thermal effects on the deformation of the modified oedometer were studied. Two thermal effects were considered. The first was the thermal deformation of the cell structure, which might affect the measurement of the vertical displacement. Another one was the thermal deformation of the sample ring, which could induce a small radial strain in the soil sample. During the thermal test, the thermal deformation of the oedometer must be calibrated and considered when a change in the thermal volume is measured. The deformation produced by the application of the mechanical load is subtracted from the total displacement recorded by the LVDT transducer.

A non-deformable steel disc was placed inside the sample chamber to minimize the above deformation. The sample disc was mechanically loaded up to 800 kPa at various temperatures, and the LVDT transducer recorded the relevant deformations. The changes in the vertical deformations of the steel disc due to heating under the different amounts of the stress are shown in Fig. 6. From the figure, it can be seen that the deformations are insignificant. As most of the tests were conducted under 40 °C conditions, the deformability of the cell structure under mechanical loading was ignored. The diametrical thermal deformation of the sample ring during the consolidation tests using the modified oedometer could also influence the accuracy of the measured displacement; therefore, the measurements of the thermal volume could change. To estimate this error, the thermal diametrical expansion of the oedometer ring was calculated at different temperature levels from 27 °C to 60 °C using the linear thermal expansion coefficient of the stainless steel material for the oedometer ring. The linear thermal expansion of an object can be expressed, as seen in Equation 5 (Francois and Laloui, 2010). The thermal diametrical strain (expansion) of the oedometer ring is shown in Figure 7.

$$\Delta d = \beta'_a d_0 \, \Delta T \qquad (5)$$

Where
Δd = change in the diameter (mm),
d_0 = 75 mm, initial diameter
ΔT = $T - T_0 = T$, temperature change from zero to T (°C)
β'_a = 1.59×10^{-5} °C^{-1}, linear thermal strain coefficient of the sample ring

The temperature effect of the deformation of the sample ring on the change in the void ratio (Δe) was determined by the following equation (Abuel-Naga et al. 2007; Romero 1999; Francois and Laloui 2012):

$$\frac{\Delta e^{T}}{1+e_0} = \frac{(2\beta'_a - \beta'_s)\Delta T}{1+\beta'_s \Delta T} \qquad (6)$$

Where
Δe^T = changes in the void ratio under various amounts of the temperature,
β'_s = 3.5×10^{-6} °C^{-1}, coefficient of the volumetric thermal strain of the soil particles (Campanella and Mitchell, 1968)
β'_a = 1.59×10^{-5} °C^{-1}, linear thermal expansion coefficient of the sample ring (stainless steel) of the oedometer
d_0 = 75 mm, oedometer ring diameter at room temperature
e_0 = 1.207, initial void ratio of the soil

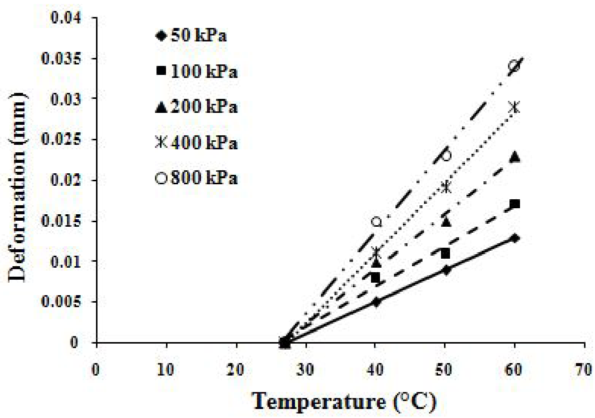

Fig. 6 *Thermal vertical deformations*

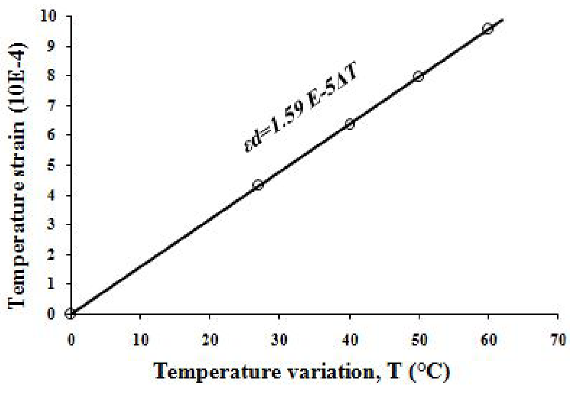

Fig. 7 *Strain ($\Delta d/d_0$) of the sample ring due to heating*

For the maximum level of the temperature used in this research ($T = 60$ °C), the change in the void ratio was calculated by Equation 6 for the ring and soil, which amounted to $\Delta e^T = 0.00037$, which is negligible and can therefore be ignored. Similar results were reported by Romero (2001), Francois and Laloui (2010), and Abul-Naga et al. (2006). The water in the circular space between the external ring and the sample ring of the oedometer was warmed up by a circular heater, which increased the temperature of the soil sample. The calibration tests showed that about 18 minutes was the average time required for a given temperature in the circular space to reach the midpoint of the sample. Consequently, the target temperature should be maintained for at least 20 minutes before starting any experiment.

2.5 Laboratory test using modified oedometer for SWCC tests

Before conducting any tests using the modified oedometer, it is essential to control calibration of the modified oedometer system, the water leakage, and the permeability of the ceramic disk. The overall process of the test performance using the modified odometer is presented in the flow chart given in Fig. 8. The basic properties of the residual granite soil employed in the study are given in Tab. 2 (Kholghifard et al., 2014). The soil samples were prepared with a thickness of 20 mm and a diameter of 75 mm and then were fully saturated for 24 hours. To define the SWCC of the unsaturated soil, the saturated samples were subjected to several prearranged suction steps in both the drying and wetting paths using the axis translation technique. For the drying tests, the suction pressure was increased from zero (saturated) to 700 kPa in steps of 5, 10, 25, 50, 100, 200, 400, 500 and 700 kPa. For the wetting tests, the suction pressure was firstly increased up to 700 kPa and then decreased in steps of 450, 200, 100, 50, 25, 10 and zero kPa. To maintain a constant temperature during the SWCC tests, a water compartment between the external ring and internal ring of the oedometer with a digital heater-temperature controller was used. To examine the problem connected to the water condensation, the values of the volumetric water content of the soil were also directly obtained by weighing the samples at the end of the experiment in two ways, i.e., with and without a heating system.

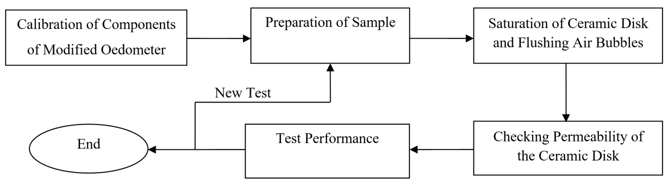

Fig. 8 *Flow chart of performance of test using the modified odometer*

Tab. 2 *Granite residual soil properties*

Indices	Value
LL (%), Liquid limit PL (%), Plastic limit PI (%), Plasticity index	68 35 33
Properties	
OMC (%), Optimum moisture content MDD (Mg/m^3), Maximum dry density G_s Specific gravity γ_d, Natural dry density (Mg/m^3) w_n(%), Natural water content, k_{sat} (m/sec)	30 1.42 2.67 1.21 27 0.51 * 10^{-6}

To verify the results obtained from the modified oedometer, the SWCC of the soil was also defined using a pressure plate device made by Soil Corp.® (Fig. 9). The soil specimens were placed on the cellulose membrane and saturated with water for 48 hours to achieve a fully saturated condition. After the saturation process, the soil samples (fifteen rings with 75 mm in the inner diameter and a 20 mm height) were placed in five different pressure plates of the Soil Corp.® pressure plate (Capacity: 15 bars). The sample rings were located on a saturated cellulose membrane exposed to the atmosphere as shown in Fig. 9-a. After assembling the chamber, the designed suction (from zero to 700 kPa) was applied to the samples by regulating the air pressure at specific pressures as shown in Fig. 9-b.

a)

b)

Fig. 9 ***a)*** *Sample preparation* ***b)*** *Pressure plate test setup*

3 RESULTS AND DISCUSSION

3.1 SWCC results

Fig. 10 shows the SWCCs, which were obtained on the basis of the amount of the water flow during a drying-wetting cycle for the soil samples. The unsaturated parameters of the soil samples (such as the saturated volumetric water content, θ_s, the residual volumetric water content, θ_r , and the air entry value, s_{ae}, were determined from the SWCCs as shown in Tab. 3. Due to the air trapped in the pores, the volumetric water content values at the saturation point in the wetting curves were lower than those in the drying curves at the same point. This indicates a hydraulic hysteresis phenomenon of the SWCC for the residual granite soil. A similar hydraulic hysteresis phenomenon for the residual soils was reported by Kassim (2011) when confirming the modified oedometer results. Based on the SWCC, he reported values of 49% for the saturated volumetric water content, 7 kPa for the air entry value, and 34% for the residual water content of the soil. These values are close to the SWCC parameters of this soil sample.

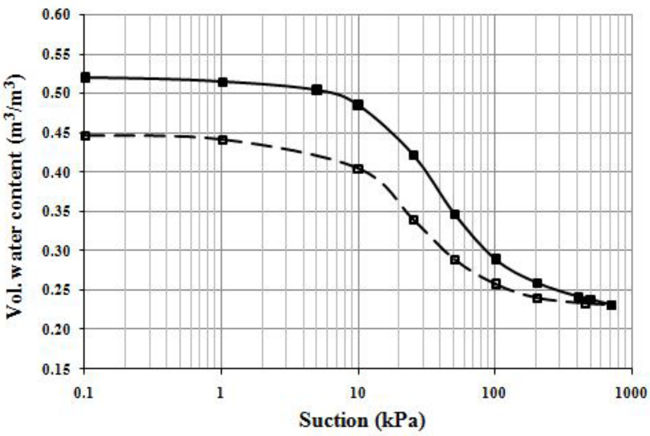

Fig. 10 *SWCC obtained from the modified oedometer*

Tab. 3 *SWCC parameters for the LS and DS soils*

SWCC parameter	Amount
θ_s (%), Saturated Vol. Water Content	51.9
s_{ae} (kPa), Air Entry Value	11
s_{ex} (kPa), Air Expulsion Value	7
θ_r (%), Residual Water Content	27.6
s_{res} (kPa), Residual Suction	88

The SWCC of the residual soil were also obtained using a pressure plate device. Fig. 11 shows the SWCCs of the soil samples, which were established by fitting the average value from a group of pressure plate extractors and modified oedometer tests. Comparing the results, the range of differences for both SWCCs are between 0.8% and 7.74%. The test performed using the pressure plate required several samples; the device should be dismantled several times during the test for weighing the samples. Evaporation of the water therefore causes more errors during the water content determination process. On the other hand, the modified oedometer is capable of obtaining data points to develop the SWCC using the same sample without dismantling the cell. Hence, the values of the water content obtained using the modified device should be more accurate than those collected based on the pressure plate.

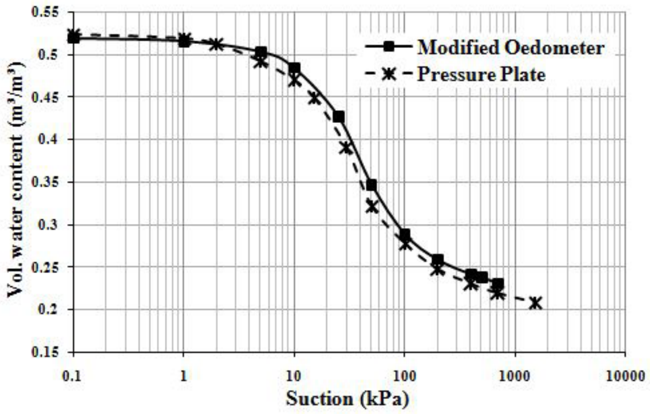

Fig. 11 *SWCCs of the soil (modified oedometer and pressure plate)*

3.2 Evaluation of the Water Condensation on the Cell Walls of the Modified Oedometer

To examine the problem linked to the water condensation, the volumetric water content values of the soil were also directly obtained by weighing the samples at the end of each experiment in two ways: with and without the heating system. The SWCC test was repeated using the modified oedometer with a temperature control system. The SWCC envelopes obtained from the results with and without the heating control system are presented in Fig. 12. The difference between the volumetric water content obtained from the volume change indicator readings and the direct calculations at the end of the test without the heating system was around 3.42%. On the other hand, with the application of the heating controller, the difference was reduced to 1.12%.

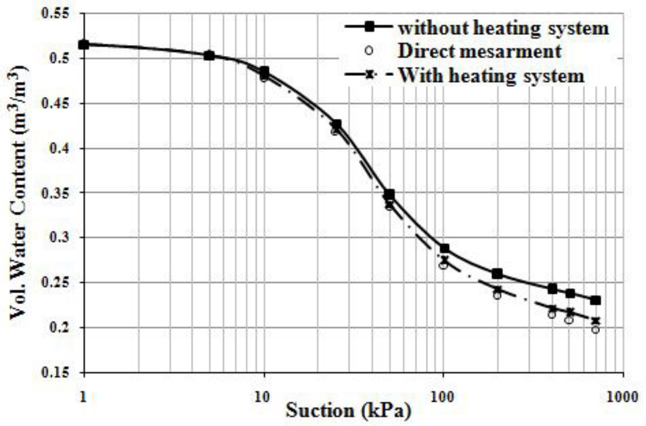

Fig. 12 *SWCC of the soil*

Fig. 13 shows the sample rings upon completion of the SWCC tests with and without the heating system. As can be seen from the figure, there is no water condensation on the ring wall at the end of the test with the heating controller. This caused a reduction in errors in the volumetric water content measured due to removal of the water condensation in the cell with maintenance of the temperature during the test. These results indicate that the difference between the volumetric water content obtained from the directly calculated and volume change indicator readings was significantly reduced. Nevertheless, the heating system with a temperature controller significantly decreased the cell condensation problems for the SWCC tests.

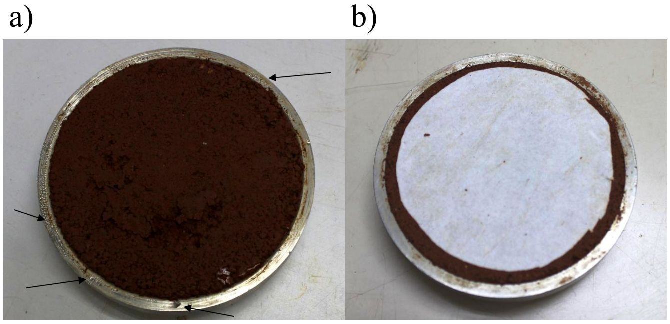

Fig. 13 *Ring, including the sample at the end of the SWCC tests a) without and b) with the heating system*

4 CONCLUSION

In comparison to the pressure plate, the modified oedometer results showed distinct characteristics, some of which are highlighted as follows:

A complete SWCC test can be conducted on a single specimen without dismantling the modified oedometer. It also allows for a combination of controlled suction and the temperature to obtain a SWCC and consolidation test on an unsaturated soil sample.

Two application tests, i.e., the SWCC and consolidation tests, were conducted under the saturated and unsaturated conditions.

The body was composed of two cells, i.e., internal and external. A water compartment was designed so that heated water covered all around the internal air tight cell. A digital temperature controller was then used to maintain a constant temperature all around the cell. As a result, the temperature was indirectly applied to the soil sample, thereby causing a uniform temperature for the soil sample. Consequently, the water volume errors involving condensation were reduced.

The device can also be employed to study the hydro-mechanical behaviour under a different range of temperatures.

The total change in volume, the change in the water volume, and the vertical deformation can be monitored during the test. Furthermore, the device can be employed to study potential collapses, the compression index, and the yield stress of unsaturated soil (Kholghifard and Ahmad, 2021).

Finally, a conventional oedometer was modified and successfully developed for unsaturated soils at a low cost. Therefore, the device allows for conducting one-dimensional consolidation tests on saturated and unsaturated soil samples.

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