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# Air Volume Change Measurement in Unsaturated Soil Testing Using a Digital Pressure-Volume Controller

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**ABSTRACT:** One of the challenges associated with the testing of unsaturated soils is the measurement of air volume change induced by stress changes. This paper reports the results of an evaluation of a digital pressure-volume controller as an air volume change indicator. Effects of temperature, confined volume, and precompression of the measurement medium on the $p$-$V$ characteristics and the device response were determined. The device was also used to measure air volume changes of unsaturated soil specimens undergoing isotropic consolidation and axial loading in constant water content tests in a triaxial cell. The results show that the controller performs satisfactorily as an air volume change measurement device. It also permits measurement of air volume change simultaneously with the implementation of the axis-translation technique, making it a versatile device in the testing of unsaturated soils.

**KEYWORDS:** air volume change measurement, unsaturated soil testing, digital pressure-volume controller, air pressure control

The pore space of soils found near the ground surface generally contains air and water. The presence of air, in addition to water, within the pores of a soil renders it unsaturated. This unsaturated state alters the behavior of the soil as compared with a saturated soil.

Several soil testing procedures have been used to investigate the shear strength and volume change behavior of a soil. While some of the procedures used for testing *saturated* soils have been found applicable to unsaturated soil, further methods to measure pore-air volume changes in unsaturated soil specimens are required.

An important behavior of an unsaturated soil under loading is its deformation in response to applied stress. Volume change occurs as a result of changes in pore volume since the mineral soil particles are essentially incompressible. Volume changes are primarily due to inward or outward flow of pore-water and pore-air fluids when an external stress is applied. There can also be volume changes associated with shear between the particles, which results either in dilation or compression.

It is common practice to measure the overall and/or pore-water volume changes. During triaxial testing of an unsaturated soil specimen, the air volume change can be computed as the difference between the overall and water volume changes (Fredlund and Rahardjo 1993). The reason for using this procedure is related to the difficulty in measuring air volume. Air is highly compressible and sensitive to temperature changes. It is common practice in triaxial testing to measure water volume change using the conventional twin burette volume change indicator. The measurement of overall volume change, on the other hand, is more difficult. Arrangements for overall volume change measurement have involved the use of mercury (Bishop and Henkel 1962), double-walled triaxial cells (Wheeler and Sivakumar 1992), noncontacting transducers located around the specimen (Cole 1978; Khan and Hoag 1979; Drumright 1987), or Hall effect transducers to measure axial and radial deformation in triaxial specimens (Clayton and Khatrush 1986).

There remains a need to improve the measurement of overall and air volume changes. Bishop and Henkel (1962) and Matyas (1967) used two burettes to measure air volume change under atmospheric pressure conditions. The apparatus was cumbersome and limited to measuring at atmospheric conditions; however, it has its merits. Other problems ascribed to air volume measurement (apart from temperature sensitivity and compressibility) are leakage and diffusion. All of these aspects must be properly addressed in an air volume measurement device. This paper presents the results of an evaluation of a digital pressure-volume controller described by Menzies (1988) as an air volume change measuring device.

## Theory of Air Volume Change Measurement

### *Ideal Gas Law*

The behavior of a gas is governed by an equation of state relating its pressure, volume, and temperature and is given by

$$pV = kT \qquad (1)$$

where

$p$ = absolute pressure, Pa,
$V$ = volume, m$^3$,
$T$ = temperature, K,
$k = nR$, J·K$^{-1}$,
$R$ = universal gas constant (8.314 41 J mol$^{-1}$ K$^{-1}$), and
$n$ = amount of gas, mol.

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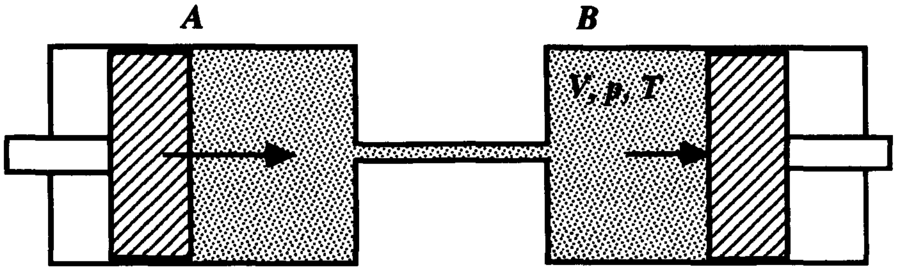

FIG. 1—*Two cylinders connected in series; the confined air space (shaded) has volume* V, *pressure* p, *and temperature* T.

The equation of state can be applied to a confined volume of air in order to determine volume changes resulting from pressure or temperature changes.

Consider a volume of air confined within two cylinders, A and B, connected in series via a tube as shown in Fig. 1. Figure 1 could also represent the connection between the air space in a soil specimen (Cylinder A) and a volume change measurement device (Cylinder B). Under equilibrium conditions, the confined air is under a pressure, $p$, temperature, $T$, and has a total volume, $V$, comprising the air within both cylinders and the connecting tube. The confined air can be compressed or expanded by the movement of either Piston A or B or by changes in temperature. When either of these occurs, the state equilibrium is disturbed, and reactions occur so as to restore equilibrium.

Suppose Piston B is fixed. A displacement of Piston A to the right will cause compression of the confined air and an accompanying pressure increase, $\Delta p_c$, and volume decrease, $\Delta V$. A pressure increase, $\Delta p_t$, can also be imposed on the confined air if its temperature increases.

The volume change due to changes in pressure and temperature can be determined using Boyle's and Charles' laws, respectively:

Isothermal conditions $$\Delta V_p = \frac{kT}{\Delta p_c} \qquad (2)$$

Isobaric conditions $$\Delta V_t = \frac{k}{p}\Delta T \qquad (3)$$

where

$\Delta V_p$ = air volume change caused by a pressure change at constant temperature,

$\Delta V_t$ = air volume change caused by a temperature change at constant pressure, and

$\Delta p_c$ = pressure change induced by compression or expansion.

The pressure change due to a change in temperature is given by:

Isomeric conditions $$\Delta p_t = \frac{k}{V}\Delta T \qquad (4)$$

where $\Delta p_t$ = pressure change induced by a temperature change.

Thus, pressure changes induced by compression, expansion, or temperature changes can be related to volume changes using Eqs 2 to 4. For example, a volume change device can be designed such that an induced pressure change, $\Delta p_c$, can be translated into a volume change (Eq 2). In this arrangement, an increase in pressure is transmitted to the device that responds by increasing its volume to maintain the pressure constant. This is the operating principle of the digital pressure-volume controller used in this study.

### *Compressibility of Fluids*

The isothermal compressibility of a fluid such as air, $C \geq 0$ ($\text{Pa}^{-1}$), is defined as the volume change of a fixed mass of the fluid with respect to the pressure change per unit volume at a constant temperature and is expressed as:

$$C(V) = -\frac{1}{V}\cdot\frac{\Delta V}{\Delta p} \qquad (5)$$

Rearranging Eq 5, the pressure change induced by an incremental volume change is inversely proportional to the compressibility and the volume of the confined air $V$ (Eq 6)

$$\Delta p = -\frac{1}{C(V)\cdot V}\Delta V \qquad (6)$$

so that an incremental change in volume $\Delta V$ with air as the operating fluid will induce a substantially smaller pressure change $\Delta p$ than an identical volume change with water (which is essentially incompressible) as the operating fluid.

## Digital Pressure-Volume Controller

The digital pressure-volume controller is a multipurpose device designed for the precise control and measurement of liquid volume and pressure changes (Menzies 1988). In this paper we report the results of tests conducted to evaluate the suitability of the controller for measurement of air volume changes.

A schematic layout of the controller is shown within each of the dashed boxes in Fig. 2. The controller operates in either a manual (stand-alone) or a computer-control mode. It regulates and measures pressure and volume through a microprocessor-controlled hydraulic actuator, B. The actuator piston is driven through a 200-mL steel cylinder that will withstand pressures from −100 kPa to a maximum 2000 kPa. The device is specified for operation in ambient temperatures between 10 to 30°C. With water as the working fluid, it has a thermal drift of 0.025%/°C of the measured value during a pressure measurement and 0.025%/°C of the measured value (plus 0.2% of volume of water in the cylinder) during a volume change measurement. With air having a coefficient of thermal expansion approximately 17 times that of water, one can expect a thermal drift of about 0.4%/°C. The characteristic error for water pressure measurement is 0.1% of full range (plus 0.05% of measured value) and 0.25% of the measured value for water volume change measurement. Resolution for liquid pressure and volume is 0.2 kPa and 1 $\text{mm}^3$, respectively.

The controller can be programmed to keep its confined fluid at either constant pressure or constant volume. If programmed to control pressure at some constant value, say $p^*$, any pressure change, $\Delta p$, induced in the confined fluid is translated into a

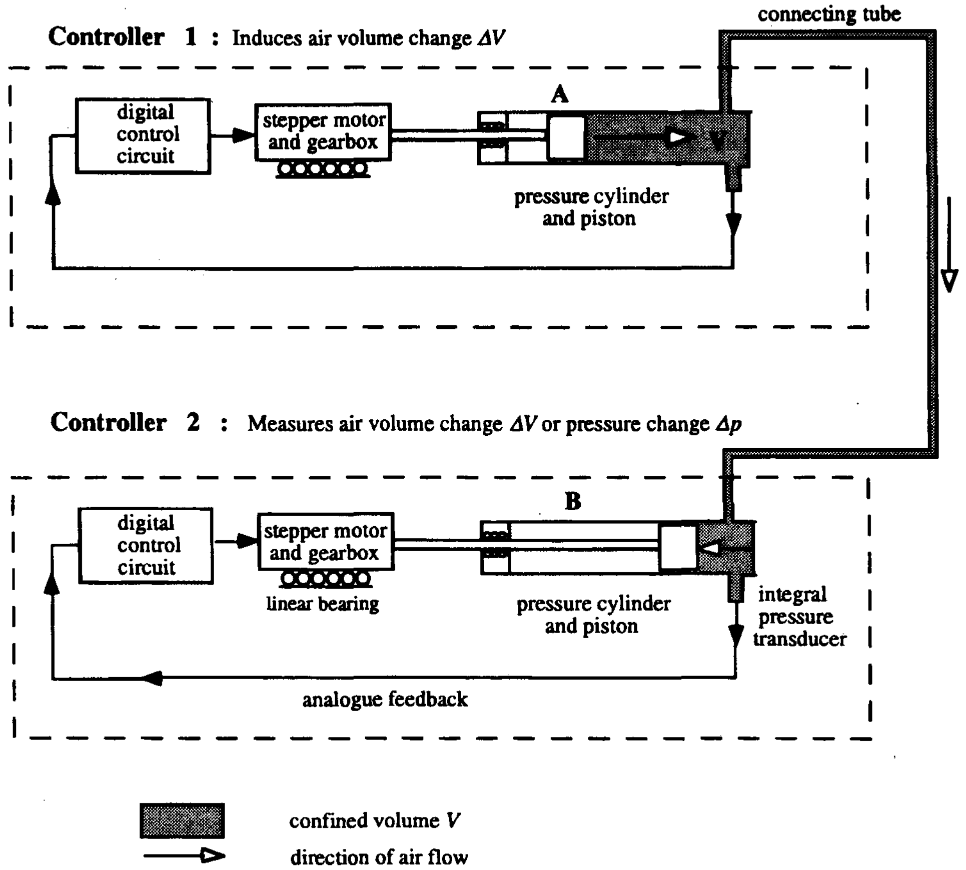

FIG. 2—*Schematic of the two digital pressure-volume controllers (in dashed boxes) connected in series; Controller 1 induces a target volume change,* ΔV, *by a displacement of Piston A; Controller 2 is set in either constant volume mode to measure pressure change or in constant pressure mode to measure volume change.*

volume change, ΔV. Pressure change is sensed and measured by a pressure transducer (Fig. 2). To restore equilibrium, a feedback mechanism allows the sensed pressure change to be adjusted by activating the stepper motor such that it repositions Piston B. The pressure control algorithm seeks a pressure within 1 kPa of the targetted pressure (this avoids "hunting" or oscillation of piston movement). The microprocessor calculates volume change as the product of piston displacement and the bore. A reducing stroke (movement of Piston B to the left) means the device is responding to pressure above the set constant pressure, $p^*$, induced on the confined air, which occurs when the confined air is compressed (negative volume change). An increasing stroke (movement of Piston B to the right) means the confined air pressure has been reduced below $p^*$ by expansion, so Piston B must make up for this by repressurizing the air to the set constant pressure, $p^*$. In so doing, the movement of Piston B indicates a positive volume change. The pressure and volume measurements are made available to a host computer via an IEEE interface.

## Evaluation of the Controller as an Air Volume Change Measurement Device

To investigate the controller for air volume change measurement in unsaturated soil testing, the testing program consisted of several series of experiments. Since the controller is programmed to measure volume change in direct response to pressure changes, the effect of factors that affect pressure changes (i.e., absolute pressure, temperature, and volume of the confined space) were investigated. Experiments were performed to determine the effects of temperature, initial confined volume, and precompression of the air space on the $p$-$V$ characteristics of the device. The response of the device to ramped air volume changes was also investigated. Several tests were then conducted to measure air volume changes of soil specimens loaded in a triaxial cell.

The testing procedures and results are presented below.

## Pressure-Volume Characteristics

The cylinders of two controllers were connected as shown in Fig. 2 to form a confined air space (shaded region $V$) in which volume changes were induced and measured. Controller 1 was used to induce volume changes, and Controller 2 was used to measure the change. Air leakage was prevented by sealing all fittings at external connection points. The manufacturers had earlier conducted tests over several days and were able to report that the device itself was airtight. Our experience with the controller showed that because of the sensitivity of air to temperature changes, fluctuations greater than ±2°C in ambient temperature can significantly affect the device output. Tests were therefore conducted under isothermal conditions in a controlled environment room at a relative humidity of 50%.

To determine the device $p$-$V$ characteristics, Controller 1 was used to induce a volume change, while Controller 2 was set in constant volume mode and used to measure the resulting pressure change in the confined volume. Piston A was placed at the beginning of its stroke (i.e., to the far left) and Piston B at the end of its stroke (i.e., to the far right) before commencement of measurements. This resulted in an initial volume of about 213 mL, consisting of the cylinder volume of 200 mL plus an additional 13 mL enclosed by the connecting tube (7 mL) and the dead volumes (i.e., the minimum volume remaining when the piston is at the outlet end of its stroke) of both controllers (3 mL each). The experiment was repeated with initial confinement pressures of 0 and 50 kPa (gage) and at three temperatures (15, 20, and 26°C). One other experiment was conducted with an initial confinement volume of 138 mL and a 50-kPa precompression pressure.

Figure 3 shows the effect of precompression on the pressure-volume relationship. For an identical initial confined volume of 213 mL, higher pressure increases were observed for a space that was precompressed before measurements were taken. Figure 4 shows that measurements taken in a smaller space also produce higher pressure changes. Compressibility versus pressure based on Eq 5 for these data is presented in Fig. 5. Conditions that provide higher pressure increases (i.e., precompression and a smaller confined volume) will tend to reduce the effect of air compressibility and produce better measurements. Temperature had negligible effect on the $p$-$V$ characteristics.

## Response of the Device to Known Volume Changes

In these experiments Controller 1 was used to induce a known volume change, and Controller 2 was set in constant pressure mode and used to measure the volume change (Fig. 2). The initial volume of the confined space was set to about 213 mL. A 5-mL volume reduction in the confined space was induced by displacement of Piston A. Controller 2 was allowed to respond, and on attaining equilibrium, its volume reading was recorded. Additional 5-mL volume reduction increments were applied and measured up to a total of 60 mL. Tests were repeated at temperatures of 15, 20, and 26°C.

Additionally, the time responses of the device (Controller 2) to 5, 30, and 60 mL ramps induced by Controller 1 were obtained. To investigate the effect of precompression on the response, experiments were carried out with the confined space subjected to precompression pressures of 0 (i.e., no precompression), 50, and 100 kPa (gage) prior to making air volume change measurements. The initial volume of the confined space was set to 213 mL. Precompression was achieved by repositioning the controller piston to obtain an initial confined volume $V_0$ corresponding to the desired initial pressure (determined from the controller $p$-$V$ relationship).

### *Effect of Temperature on Measurement Accuracy*

Figure 6 shows the effect of temperature on the volume change indicated at the device versus input volume changes over a 60-mL range. There was little difference in the readings taken at all the temperatures. Cumulative errors at 60 mL total volume change were all within 0.63%.

### *Effect of Precompression on the Time Response*

The time responses of the device to a 5-mL air volume change induced on the confined space are shown in Fig. 7. Higher precompression pressures improved the measurement accuracy and response speed as the effect of air compressibility was reduced. The steady-state measurement errors were 12, 5.8, and 0.22% with 0, 50, and 100 kPa precompression, respectively. In all cases, the device attained 95 to 100% of its final reading within 5 min. The stepper motor adjustment for the final 0.05 to 0.1 mL of volume change is much slower while the pressure seek algorithm attempts to approach the target pressure in a stable manner. Recording the volume reading prior to the sensing of this minute volume for a 60-mL volume change introduces 0.08 to 0.17% error, whereas, for a 5-mL volume change, an error of 1 to 2% is introduced. The manufacturer has agreed to modify the pressure control algorithm

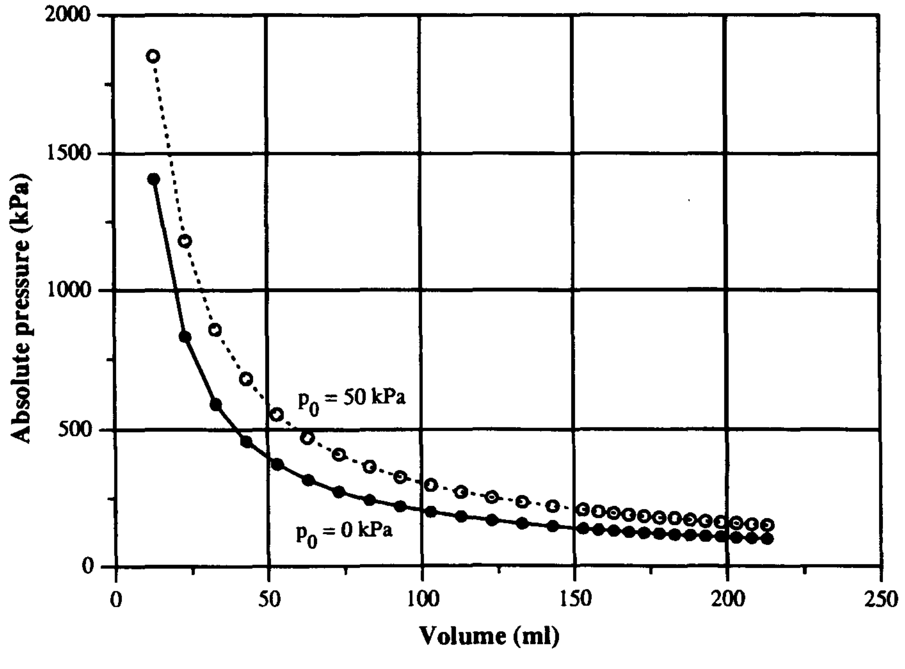

FIG. 3—*Effect of precompression pressure on the controller pressure-volume relationship (213-mL initial confined volume).*

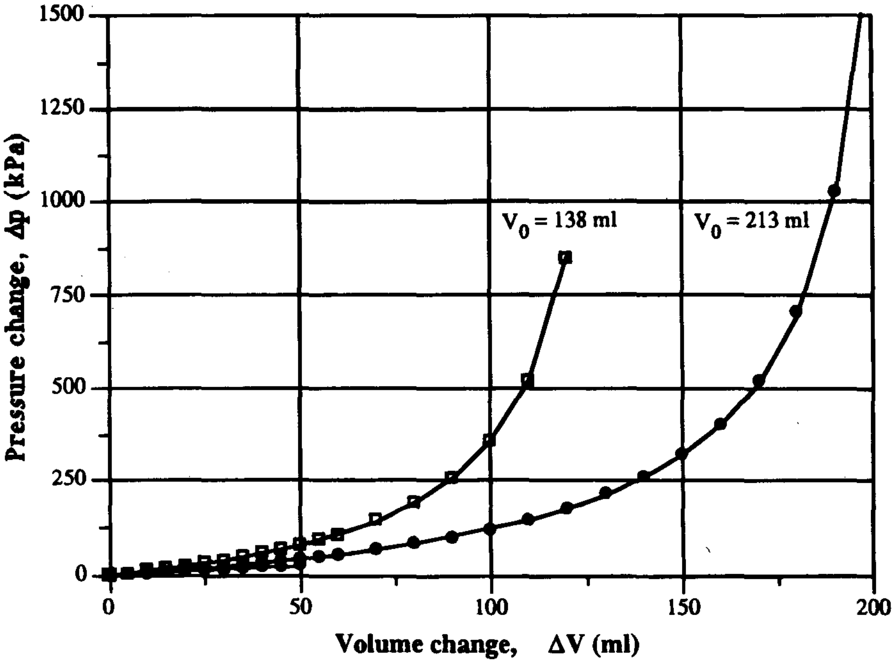

FIG. 4—*Effect of initial confined volume on the controller* Δp-ΔV *relationship (50 kPa precompression pressure).*

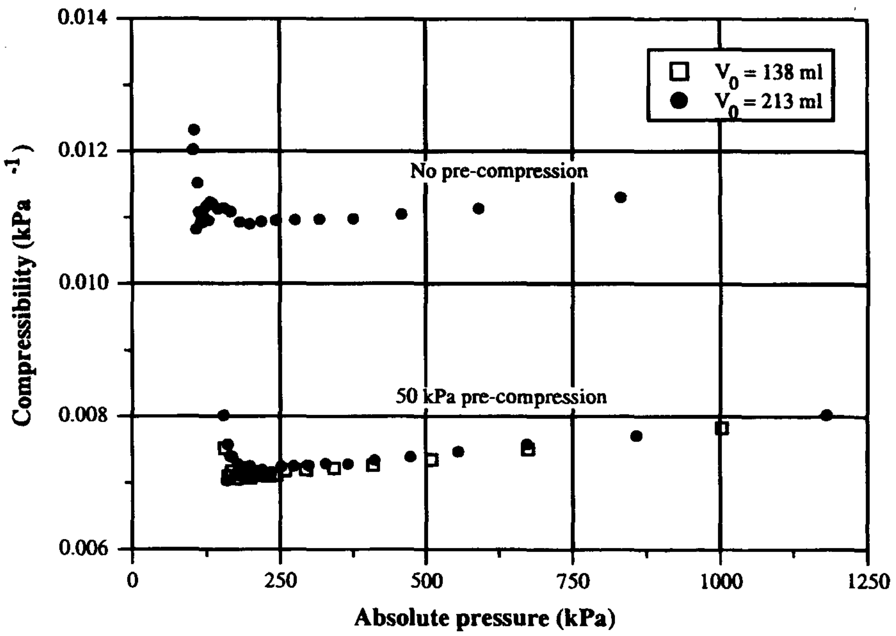

FIG. 5—*Effect of precompression on compressibility characteristics of controller with air as the working fluid.*

to make the device more suitable for controlling low air pressures by reducing the dead zone (i.e., the band of pressure within which the controller accepts that it has achieved the set target pressure).

Measurements of small volume changes in a large uncompressed air space are prone to greater error because of air compressibility, system compliance, and friction. Near the beginning of the stroke (i.e., for low-volume changes), the system responds sluggishly as it is operating in or near the dead zone. Precompression increases sensitivity of the device to subsequent small volume changes and reduces the effect of system compliance and a threshold volume. At higher pressures, the effects of friction become negligible, which may partially explain the apparent gradual increase in compressibility (Fig. 5).

### *Response of the Controller to Larger Air Volume Changes*

Figure 8 shows the response of the device to larger volume changes without precompression of the confined space at 26°C. The results indicate improved measurement accuracy for larger volume changes as the confined volume decreased. After 10 min, the device indicated 90.1, 98.6, and 99.6% of the input volume

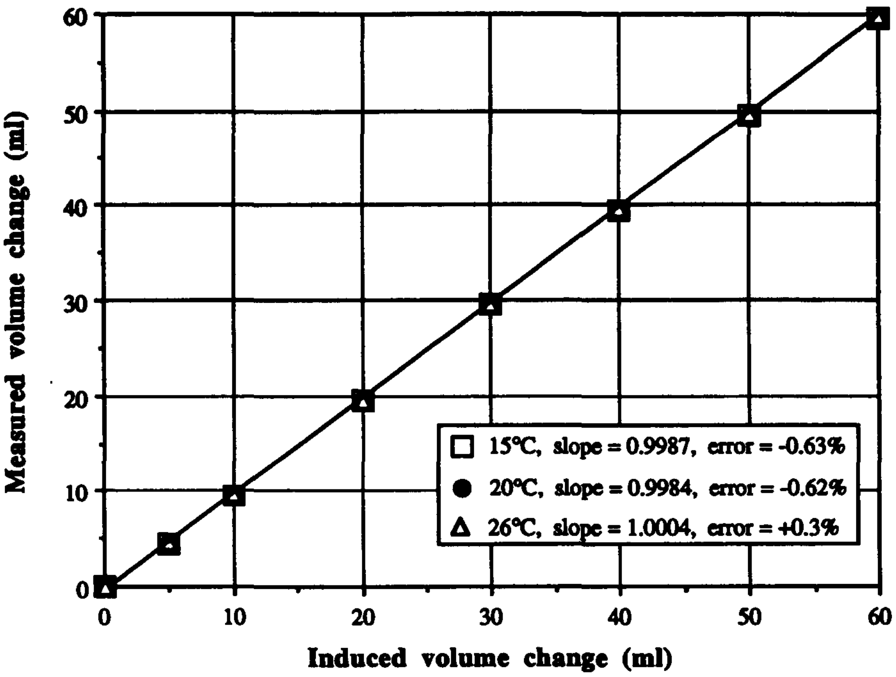

FIG. 6—*Air volume measurement at 15, 20, and 26°C cylinder temperatures without precompression and with 213 mL initial confined volume; cumulative measurement errors at 60 mL are indicated.*

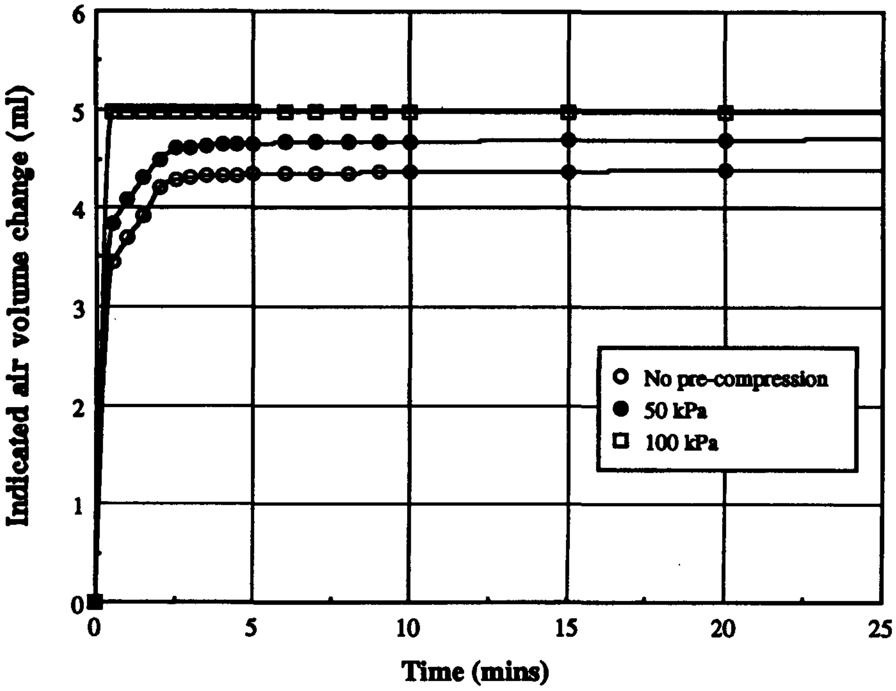

FIG. 7—*Effect of precompression of control volume on controller response to a 5-mL air volume change at 20°C cylinder temperature, 213 mL initial confined volume.*

changes of 5, 30, and 60 mL, respectively. Even though we loaded at a rate of 30 mL/min (the maximum drive train speed), there was a limit on the response rate of about 12 mL/min under pressure control mode (the system is suitable for "static," i.e., slow rate, testing).

## Air Volume Change Due to Deformation of a Soil Specimen

Unsaturated cylindrical soil specimens (70 mm diameter, 140 mm length, 1.2 Mg $m^{-3}$ bulk density) were compacted at two different water contents (16 and 19%), resulting in specimens with different fabrics and strengths. The soil is classified as a clay loam (47.5% sand, 24.2% silt, 28.3% clay). The controller was connected to a specimen in a triaxial cell as shown in Fig. 9. As before, volume change measurements were taken in a confined air space. The confined air space here is the space that links the soil air voids through a corundum disk (placed on top of the specimen) and a tube to the controller cylinder. Pore-water volume change was measured using a burette.

Constant water content tests (i.e., shearing with the pore-air

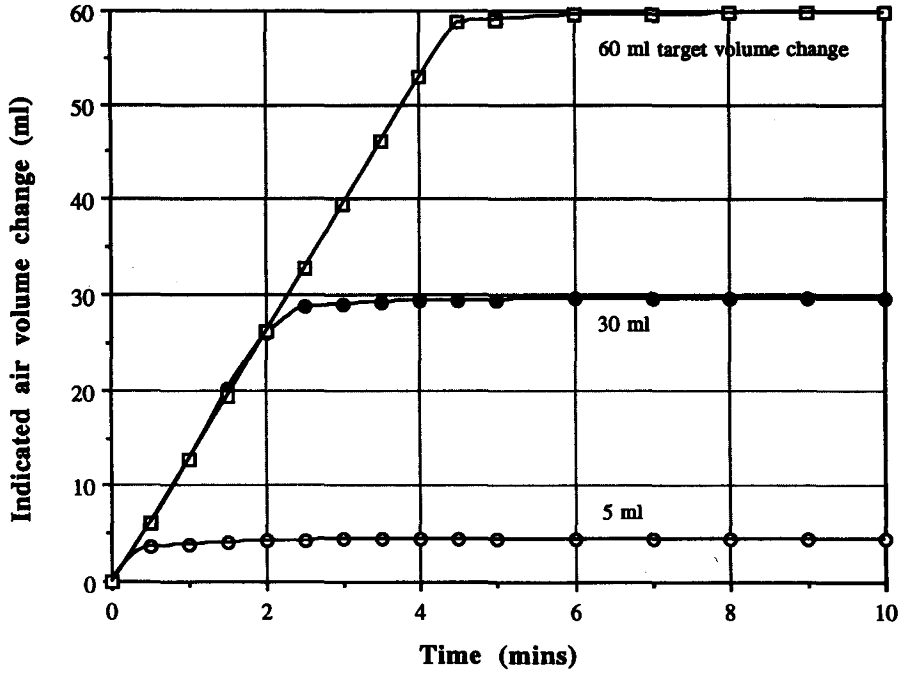

FIG. 8—*Response of controller to 5, 30, and 60 mL total input volume changes ramped at 30 mL/min with no precompression and 213 mL initial confined volume.*

FIG. 9—*The controller connected to an unsaturated soil specimen in a triaxial cell: (1) digital pressure-volume controller for pore-air volume change measurement, (2) temperature monitor, (3) triaxial cell, (4) connecting tube, (5) data acquisition and signal conditioning unit, (6) host computer; (7) burette for pore-water volume change measurement.*

phase drained and pore-water phase undrained such that the gravimetric water content remains constant) were carried out on specimens compacted at 19% water content after having been consolidated under confining pressures of 200, 250, 300, and 400 kPa and a constant specimen matric suction of 50 kPa. One other constant water content test was conducted on a specimen compacted at 16% water content under a confining pressure of 200 kPa. To obtain the desired matric suction, the controller was programmed to maintain a constant air back pressure of 50 kPa (an artificial atmospheric gage pressure). In this mode, the device subsequently measures the air volume changes that occur within the specimen as it undergoes stress changes. This arrangement, which is termed the axis-translation technique (Hilf 1956), allows the pore air to drain into the artificial atmosphere maintained by the device while the pore-water line drains to ambient atmospheric conditions (i.e., 101.3 kPa absolute).

The triaxial tests were conducted at temperatures between 25 to 27°C. At these temperatures the coefficient of solubility of air in water is about 2% times the volume of water in the specimen. For specimens with a low-water content, the effect of air going in and out of solution was therefore considered negligible. However, for specimens tested at high water contents, the air voids within the water should be included as part of the overall volume.

### *Results*

Figure 10 shows the effect of confining pressures on pore-air volume change for the specimens at a water content of 19% during isotropic consolidation. Greater air volume changes were experienced by specimens subjected to higher confining pressures. Higher confining stresses cause greater compression of the pore voids and more pore air to be squeezed out of the specimens.

Figure 11 shows less air volume change in specimens subjected to higher confining pressures (300 and 400 kPa) during the shearing stage of constant water content tests as the pore-air volume in these specimens had already been drained to a large extent during the consolidation stage of the test. Specimens under lower confining pressures (200 and 250 kPa), on the other hand, experienced larger pore-air volume change during shearing.

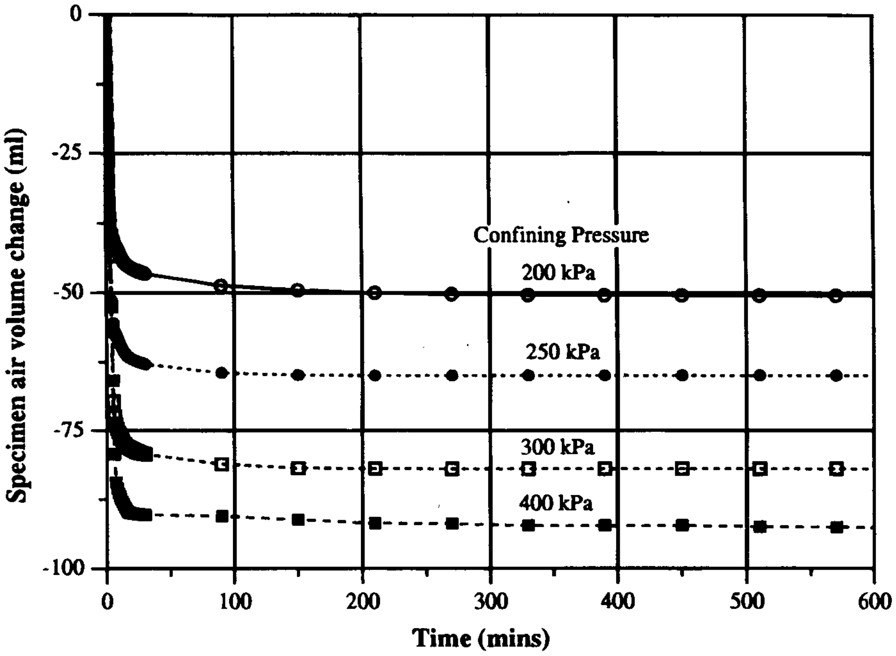

FIG. 10—*Air volume changes during isotropic consolidation of specimens at 19% water content under different confining pressures.*

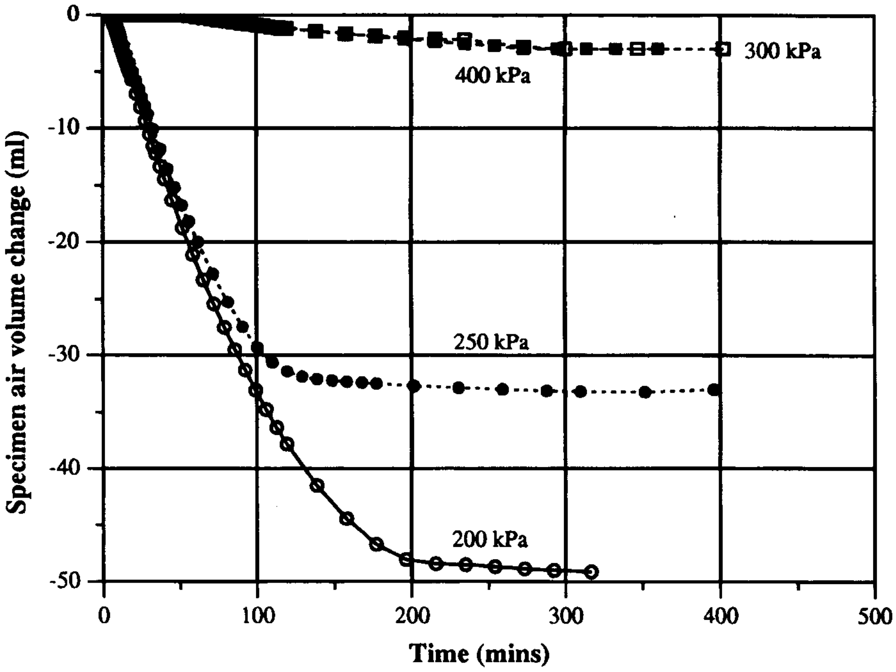

FIG. 11—*Air volume changes during constant water content shearing of specimens at 19% water content under different confining pressures.*

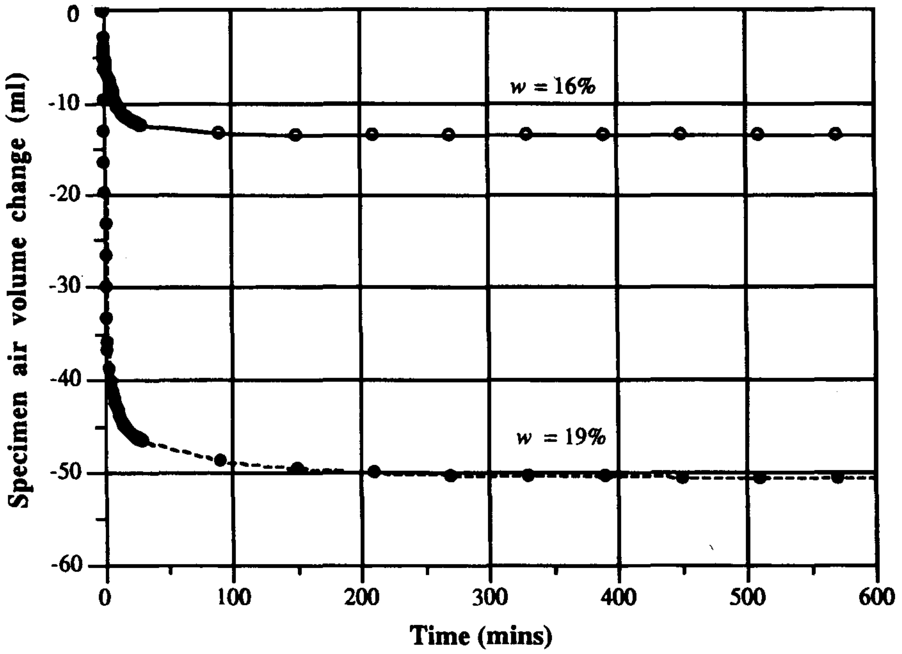

FIG. 12—*Air volume changes during isotropic consolidation of two specimens at different water contents at 200 kPa confining pressure.*

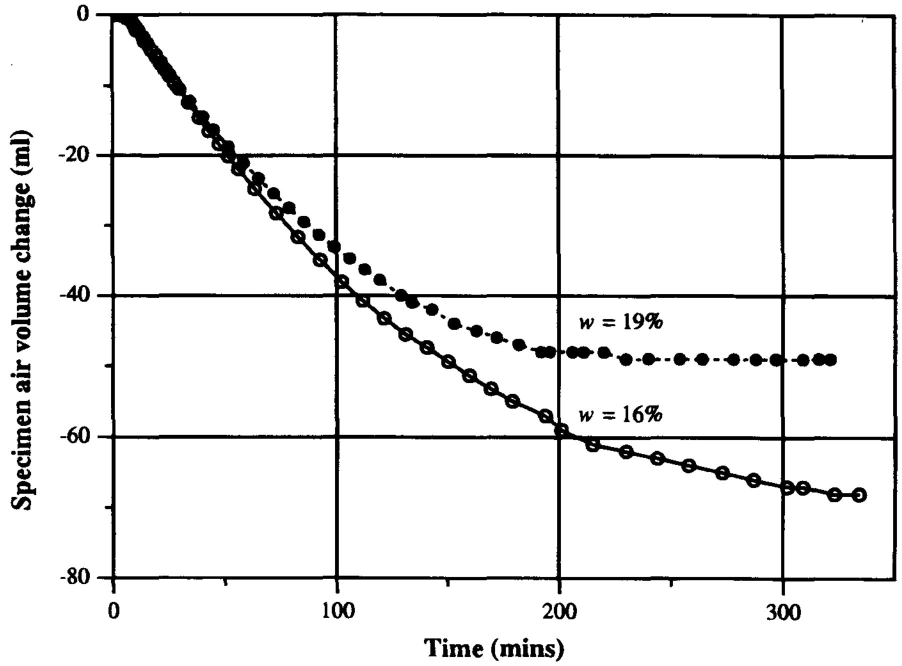

FIG. 13—*Air volume changes during constant water content shearing of two specimens of different water contents and 200 kPa confining pressure.*

Figures 12 and 13 show the volume change behavior during consolidation and shearing stages of constant water content tests on two specimens at different water contents, respectively. Figure 12 shows more air being expelled from the wetter specimen due to its higher compressibility. Drier soil specimens have higher strengths (Koolen and Kuipers 1983; Gan et al. 1988; Horn et al. 1994), providing greater resistance to compression. Figure 13 shows that the drier specimen, with its larger volume of air-filled voids, experienced greater pore-air expulsion than did the wetter specimen during the shearing stage. This is because a larger volume of pore air was expelled from the wetter specimen during the consolidation stage, leaving a smaller volume of air at the start of the shearing phase.

## Conclusions

By taking adequate precautions such as maintaining essentially isothermal conditions, preventing leakage at connecting points, precompressing the confined air space, and minimizing the total volume of the air confined space, the digital pressure-volume controller was found to be an excellent device for measuring air volume changes. The *p*-*V* response of the controller can be used to set the controller precompression pressure and initial confinement volume for optimum system performance. The time response of the controller is acceptable for slow strain rate testing of soils. The device also permits the implementation of the axis-translation technique, making it a versatile apparatus in the testing of unsaturated soils.

## Recommendations

The following recommendations are made relative to the use of the digital pressure-volume controller as an air volume change device:

1. The controller should be used under essentially isothermal conditions (±2°C). This requires the insulation of the cylinder or, preferably, operation within a controlled environment.
2. Precompression of the air in the controller cylinder should be used to minimize measurement error and improve response time.
3. The total volume of the confined air space undergoing volume change should be kept as small as possible, particularly if small volume changes are anticipated. This can be achieved by appropriate positioning of the controller piston before measurements are started.

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## References

Bishop, A. W. and Henkel, D. J., 1962, *The Measurement of Soil Properties in the Triaxial Test,* 2nd ed., Edward and Arnold Publishers, London, England.

Clayton, C. R. I. and Khatrush, S. A., 1986, "A New Device for Measuring Local Strains on Triaxial Specimens," *Geotechnique,* Vol. 36, No. 4, pp. 593–597.

Cole, D. M., 1978, "A Technique for Measuring Radial Deformation during Repeated Load Triaxial Testing," *Canadian Geotechnical Journal,* Vol. 15, pp. 426–429.

Drumright, E., 1987, "Shear Strength for Unsaturated Soils," Ph.D. dissertation, University of Colorado, Fort Collins.

Fredlund, D. G. and Rahardjo, H., 1993, *Soil Mechanics for Unsaturated Soils,* John Wiley & Sons Inc., New York.

Gan, J. K. M., Fredlund, D. G., and Rahardjo, H., 1988, "Determination of the Shear Strength of Unsaturated Soils," *Canadian Geotechnical Journal,* Vol. 25, pp. 500–510.

Hilf, J. W., 1956, "An Investigation of Pore-Water in Compacted Cohesive Soils," Ph.D. dissertation, Technical Memo. No. 654, U.S. Department of the Interior, Bureau of Reclamation, Design and Construction Division, Denver, CO.

Horn, R., Taubner, H., Wuttke, M., and Baumgartl, T., 1994, "Soil Physical Properties Related to Soil Structure," *Soil & Tillage Research,* Vol. 30, pp. 187–216.

Khan, A. H. and Hoag, D. L., 1979, "A Non-Contacting Transducer for Measurement of Lateral Strains," *Canadian Geotechnical Journal,* Vol. 16, pp. 409–411.

Koolen, A. J. and Kuipers, H., 1983, *Agricultural Soil Mechanics,* Advanced Series in Agricultural Sciences 13, Springer-Verlag, New York.

Matyas, E. L., 1967, "Air and Water Permeability of Compacted Soils," *Permeability and Capillary of Soils, ASTM STP 417,* American Society for Testing and Materials, pp. 160–175.

Menzies, B. K., 1988, "A Computer Controlled Hydraulic Triaxial Testing System," *Advanced Triaxial Testing of Soil and Rock, ASTM STP 977,* American Society for Testing and Materials, pp. 82–94.

Wheeler, S. J. and Sivakumar, V., 1992, "Critical State Concepts for Unsaturated Soil," *Proceedings,* Seventh International Conference on Expansive Soils, Dallas, TX, Vol. 1, pp. 167–172.