A Device for Measuring Tensions in Water

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The measurement of negative pore water pressures in soil systems is important in both research and design studies on precompressed saturated clays and partially saturated compacted clays. To date, no equipment that can measure water tensions below absolute zero pressure under conditions of changing external stress has been available. This paper describes such equipment.

In the device described here, the sensing element contacting the soil is a fine-grained ceramic stone, which is connected by a closed water system to a flexible steel membrane. Tension is controlled by externally adjusting the membrane deflection. The absence of a free water surface prevents cavitation.

Calibration data demonstrate that the pore pilot can indeed measure water tensions below absolute zero pressure.

● THIS PAPER describes a tensiometer capable of measuring water tensions of large magnitudes. The absence of a free water surface within the system prevents cavitation of the water at pressures below absolute zero pressure. The device was calibrated by application of pressures and vacuums of known magnitudes. Computed osmotic pressure differences were used for calibration in the high tension range. The calibration results demonstrate that the device can indeed accurately measure water tensions as large as 90 psi (all pressures referred to in this paper are gage pressures).

This device was developed at the Soil Engineering Division, Department of Civil and Sanitary Engineering, Massachusetts Institute of Technology, as the first phase of a doctoral research program on the properties of compacted clays. The research program is under the supervision of Dr. T. William Lambe, Head of the Soil Engineering Division.

THE IMPORTANCE OF WATER TENSION MEASUREMENTS IN SOILS

The importance of "effective" or "intergranular" stresses in the determination of the properties of soils has long been recognized in soil mechanics. The effective stress concept was first formulated by Terzaghi (12). The validity of this concept for saturated soil systems has been demonstrated experimentally (1, 2).

In saturated clays appreciable negative pore water pressures can be developed: During the undrained shear of over-consolidated clays; upon removal of overburden and desiccation; and during sampling. Hansen and Gibson (7) have presented a detailed theoretical treatment on the effects upon shear strength caused by the change of stress a clay undergoes during sampling; however, lack of instrumentation for the measurement of the induced negative pore water pressures allowed only qualitative conclusions.

The measurement of water tensions is of prime importance in the study of partially saturated, compacted clays. It is felt by many that the strength of compacted clays is due primarily to the negative pore water pressures developed during compaction. Hilf (8) measured a water tension of 13.8 psi in a clayey silt compacted at optimum water content by Standard Proctor compaction. It cannot be assumed that water tensions in compacted soils are equivalent to negative pore water pressures as used in the effective stress concept, as this concept applies only to saturated systems. The degree of discrepancy will depend upon many factors, the two main factors being the degree of saturation and the compressibility of the soil. Much experimental work remains to be done in this area.

REQUIREMENTS FOR WATER TENSION MEASUREMENTS IN SOILS

Needed for research on compacted clays is a device that can measure moderately large water tensions in both saturated and partially saturated soils systems under conditions of changing external stress. The equipment should require no moisture transfer between soil and device and should have a negligible time lag. Such a device has been developed and is described herein.

Table 1 summarizes available methods for determining water tensions in soils together with the tension range for which the methods are suited (4, 5, 11).

As normally performed, all of the above techniques involve moisture transfer with a concomitant time lag to equilibrium. The tensiometer and pressure membrane methods can be modified so that they are "no flow" devices. Hilf's device (8) for measuring pore pressures in compacted clays is basically a combined tensiometer-pressure membrane system modified to operate as a "no flow" device. However, his device is still limited to a tension of 0.8 atm, and the air pressure applied in the pressure membrane method precludes other possible changes in external stress.

DESCRIPTION OF DEVICE

Basic Principles

The device described below is basically a tensiometer so modified as to operate under "no flow" conditions, with the tension range greatly extended beyond 0.8 atm. Tensions below absolute zero pressure are possible because there are no free vapor-liquid surfaces present in the system. A schematic of the device is shown in Figure 1. It measures the pressure or tension necessary to prevent the flow of water out of or into the soil mass. The sensing element which is in contact with the soil consists of a porous ceramic cylinder and is connected by a continuous closed water system to a chamber above a steel membrane. The membrane is initially prestressed from below by air pressure. Water movement toward or away from the ceramic stone is indicated by movement of a mercury null slug in a capillary bore section of lucite tube between the stone and the steel membrane. The change in air pressure necessary to prevent water movement out of or into the soil can be interpreted as a tension or a pressure in the pore water.

TABLE 1

METHODS FOR DETERMINING SOIL WATER TENSIONS

After Aitcheson (1)

Method	Tension Range, Atmospheres
Tensiometer	0 - 0.8
Tension Plate	0 - 0.8
Pressure Membrane	0.1 - 20
Gypsum Block	0.5 - 50
Sorption (Vacuum Desiccation)	10 - 10.000

It can be shown by thermodynamics that a liquid, when sealed in a closed system without a free surface, may be tensioned well below its vapor pressure without boiling. The fact that water can withstand considerable tension has also been demonstrated experimentally. Green (6) has summarized the work of Berthelot (1850), Dixon (1909), Meyer (1911), Vincent and Simmonds (1943), and Temperley and Chambers (1946). In these experiments, the researchers sealed a section of capillary tube in which a small bubble of air was purposely entrapped in the water-filled tube. The tube was gently heated until the bubble disappeared and then was allowed to cool. In all cases the temperature at which the bubble reappeared was considerably below the disappearance temperature. Computation of the contractions during cooling led to the value of induced water tension. There was general agreement that water containing air in solutiong could withstand a tension of 40 atm in a closed vessel. In 1951 Green (6) performed a modified Berthelot experiment. He vacuum-distilled his water, completely de-airing it. A bubble of water vapor was entrapped instead of an air bubble. Water tensions were obtained upon cooling of 190 atm. These experiments clearly demonstrate that in the absence of a free surface water can withstand considerable tension without cavitation.

Design Details

The device was designed for a maximum range of approximately 10 atm of tension. A schematic of the device is shown in Figure 1. The membrane chamber was constructed of stainless steel. All other fittings are soft brass, joined by $^1/_8$-in. copper tubing. The null section consists of a $^3/_4$-in. lucite tube with a 0.040-in. bore, screwed by means of $^3/_8$-in. pipe threads into brass fittings. Pipe threads were used throughout. The copper tubing is connected to other fittings by means of standard compression sleeve fittings. The five valves used in the apparatus were specially constructed piston type plug valves similar to those described by Bishop and Henkel (3). Sealing between the piston and bore is accomplished by "0" rings.

The steel membrane design was a compromise between flexibility for adequate displacement sensitivity at the null section and rigidity for adequate strength under the prestress air pressure. The membrane was treated as a circular plate with clamped edges, (13), and designed for a prestress air pressure of 200 psi. The final design dimensions are shown in Figure 2. The critical seal between the top and membrane sections was accomplished by use of an inset lead gasket.

Temperature changes cause unequal expansion (or contraction) of the steel chamber and the enclosed water. Calculations show that the pressure-temperature response of the device is + 1.1 psi per deg F. As ambient temperature can be controlled within a degree during the duration of most tests and the precision of the pressure gage used is ± 1 psi, it is felt that this effect is minor.

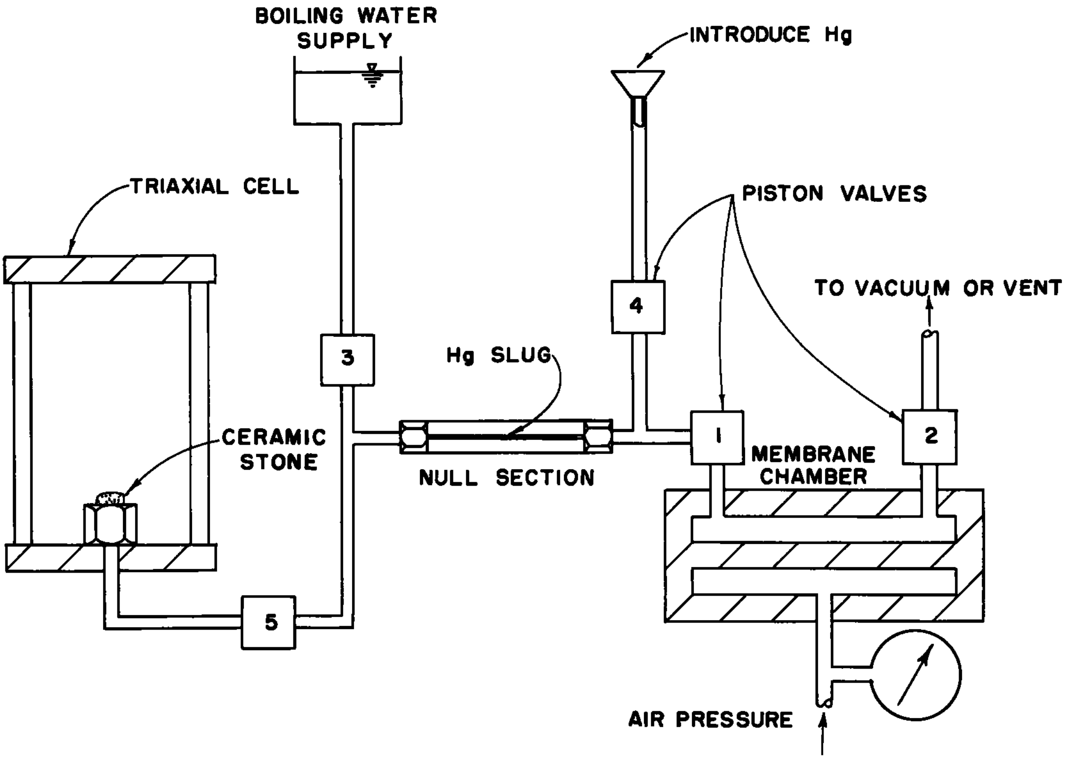

Figure 1. Schematic of device.

The ceramic stone used is a 0.5 in. diameter by 0.9 in. long cylinder of Linde alumina, fired at 1,000 C. The stone was prepared by the Ceramics Division, Department of Metallurgy, Massachusetts Institute of Technology. The stone is attached to the system by means of a "Flex" fitting, consisting of a compression fitting acting on a rubber compression sleeve.

A major construction problem to be overcome was the possible entrance of air into the system through valves, fittings, construction joints, and the pores of the ceramic stone. Such entrance of air would immediately cause cavitation in the tensioned water system.

All joints are water-filled during preparation for testing. Tight joints will act as two-dimensional capillaries. They will not drain in the presence of air until the pressure differences across them exceed their capillary head. Assuming the surface tension of water as 0.075 gm/cm, it can be shown that the joints will exclude air under a water tension of 10 atm if the joint width is less than 6 micro-in. The same reasoning applies to the maximum permissible radius of continuous pores in the ceramic stone. These dimensions cannot be measured; satisfactory joint design can only be proven during calibration of the equipment. Nonetheless, joints of maximum possible tightness remained as a prime requirement.

Preparation of the Device for Testing

It is essential that the device be completely filled with de-aired water. Because the presence of the smallest air or water vapor bubble will allow cavitation to occur, extreme care must be taken in filling the device. A step-by-step preparation procedure is outlined in Table 2. Valve numbers refer to Figure 1.

CALIBRATION

If the water and the device itself were perfectly incompressible, the induced tension in the water would be exactly equal to the reduction in the air pressure acting upon the membrane. However, because volume changes occur in the device with changes in pressure, the membrane will deflect somewhat, even though the mercury slug is maintained stationary. As the steel membrane is very stiff, this small deflection due to volume changes results in a water tension smaller than the drop in air pressure. If a 1 to 1 correspondence between air pressure drop and induced tension is defined as an

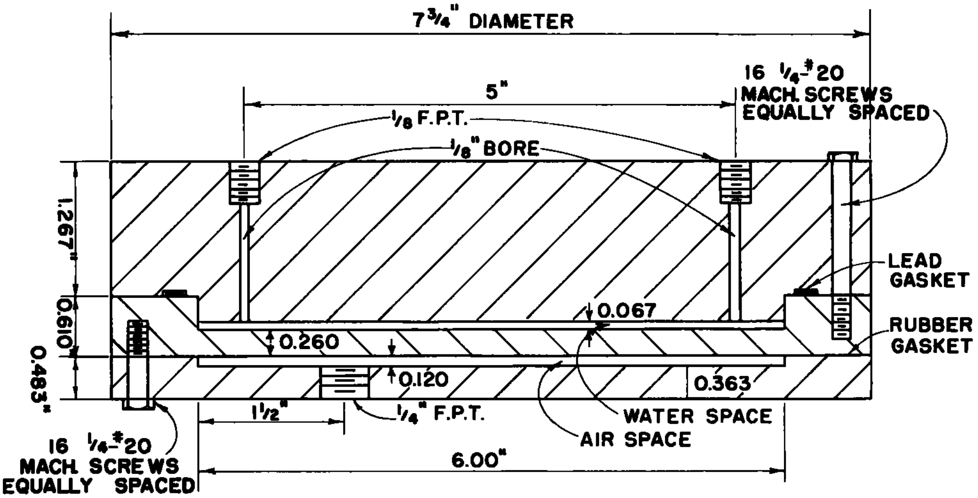

Figure 2. Steel membrane details.

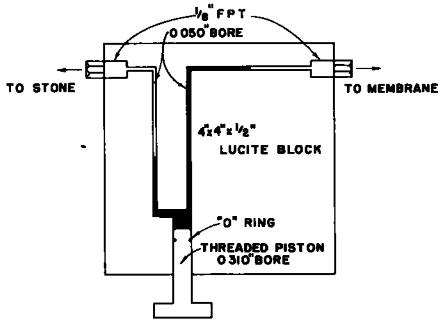

Figure 3. Modified null section.

efficiency of 100 percent, calculations show that the compressibility of the water alone will reduce the efficiency to 95 percent. Compression of fittings, valves, gaskets, etc., will reduce the efficiency still more. Just how much must be determined by calibration tests.

The deflection behavior of the steel membrane was investigated to determine whether it was operating within its elastic range. If not, fatigue and plastic deformations would preclude any consistent calibration of the device. The device was prepared in the usual manner except that the stone was left out and valve 5 remained closed. Before air pressure was applied to the membrane, valves 1 and 3 were opened; all other valves remained closed. The displacement of the mercury null versus applied air pressure was measured up to a maximum air pressure of 200 psi. The air pressure was decreased by steps to zero. This process was repeated several times. It was found that the null movement was perfectly reversible, so that the membrane operates within its elastic range. The flexibility constant of the membrane was found to be 3.7×10^{-4} in.^{3}/psi, which compares favorably with the theoretical design value of 3.1×10^{-4} in.^{3}/psi.

Because of the compressibility of the system between the null section and the ceramic stone, the system is not truly a "no flow" device when the mercury slug is maintained in a constant position in the null section. The resulting time lag to equilibrium pres-

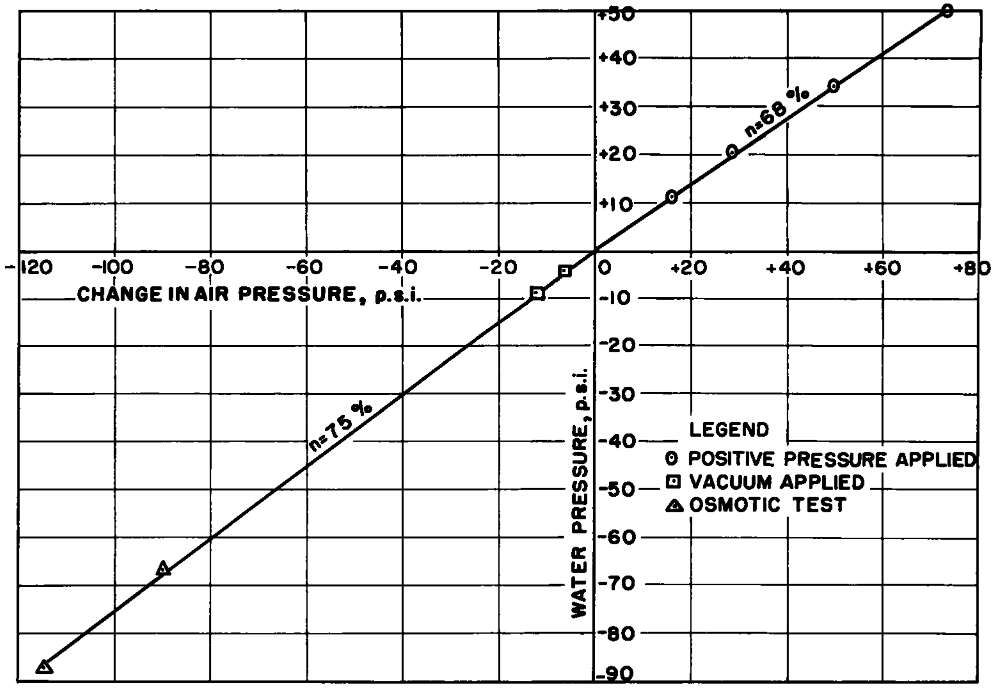

Figure 4. Calibration data.

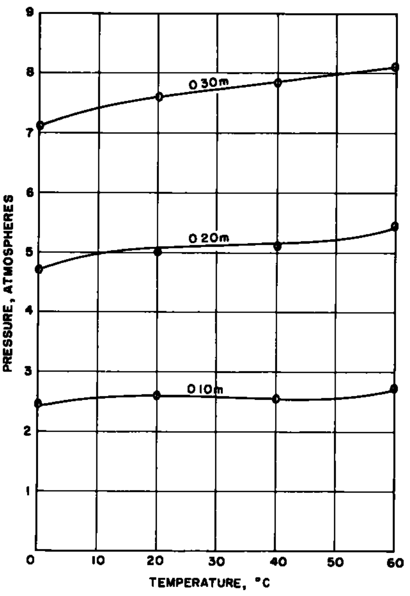

Figure 5. Osmotic pressures (after Berkeley, Hartley, Morse, and Frazer).

sure depends upon the system compressibility and the conductivity of the stone—the ease with which the stone allows water movement under pressure. The stone conductivity was measured by preparing the device in the usual manner described in Table 2. The porous stone assembly was inserted in a triaxial chamber filled with water. An air pressure was applied to the triaxial chamber, and valve 1 closed and valves 4 and 5 opened. The time-displacement of the mercury null slug was observed (this is basically a constant head permeability test). The conductivity of the stone was 0.0051 cc/atm-min. This relatively low conductivity value led to a noticeable time lag to equilibrium pressure in the over-all calibration tests described later. A modified null section that will eliminate this undesirable time lag is now under construction (Fig. 3). While the mercury slug will be maintained in a fixed position as before, an adjustable piston will allow control of the volume of the system between the fixed mercury slug and the ceramic stone, thereby compensating for the compressibility of that part of the system.

The air-entrance pressure of the ceramic stone—the air pressure applied to the water-saturated stone at which air will displace water from the pores—is of critical importance when measuring water tensions in partially saturated soils. When the

TABLE 2

PREPARATION PROCEDURE

1. All valves closed.
2. Open valves 1 and 2; evacuate system with vacuum pump attached at valve 2.
3. Attach boiling distilled water supply at valve 3.
4. Close valve 1; open valve 3; after several minutes open valve 5.
5. When porous stone compression fitting is overflowing with water, insert stone (previously boiled in distilled water) and screw on compression fitting. Close valve 5.
6. Open valve 1. After water flow through the system has occurred for 10 minutes, close valve 2 and remove vacuum pump.
7. Allow 10 minutes for the hot water under positive head to fill system, collapsing any vapor pockets left by the vacuum.
8. Open valve 4, filling hose up to funnel. Close valves 4 and 3, remove water supply hose at 3.
9. Allow system to cool to room temperature.
10. Introduce slug of mercury through funnel, open valve 4.
11. Partially open valve 3, letting out sufficient water until mercury slug appears in lucite null section.
12. Close valve 3, then 4.
13. Open valve 2 and apply desired prestress air pressure to bottom of membrane.
14. Close valve 2.

The system is now ready for operation.

measured tension exceeds the air-entrance pressure, air can enter the system through the stone and cause cavitation. The air-entrance pressure of the stone was measured by assembling the device as described in the above paragraph and then applying air pressure directly to the saturated stone (a pressure membrane technique). The air pressure was increased in 5 psi increments. There was no noticeable movement of the mercury null until an air pressure of 35 psi was reached. At that point the air overcame the capillary head of the stone, and the mercury null moved at a slow, constant rate away from the stone.

The air-entrance pressure of the ceramic stone is small compared with the design range of the device. However, there are ceramic stones available with much larger air-entrance pressures. Kemper (9) has experimentally determined air-entrance pressures of 9 atm in some commercially produced ceramic stones.

The over-all calibration of the device was a relatively simple matter in the pressure range from -12 to +80 psi. Under test conditions the mercury null is held in a constant position by adjusting the membrane air pressure. Therefore, it is only the compressibility of the system from the null slug back towards the membrane that influences the calibration of the system. The ceramic stone was removed and a pressure (or vacuum) line was attached at valve 5 (Fig. 1). Different magnitudes of pressure and vacuum were applied at valve 5, and the membrane air pressure change necessary to prevent movement of the mercury null was recorded. These data are plotted in Figure 4.

It was necessary to find some method for calibrating the device in the range of moderately large tensions. Some means of obtaining large tensions of known magnitude was required. The phenomenon of osmosis was finally decided upon (a more detailed description of the phenomenon can be found in (10)).

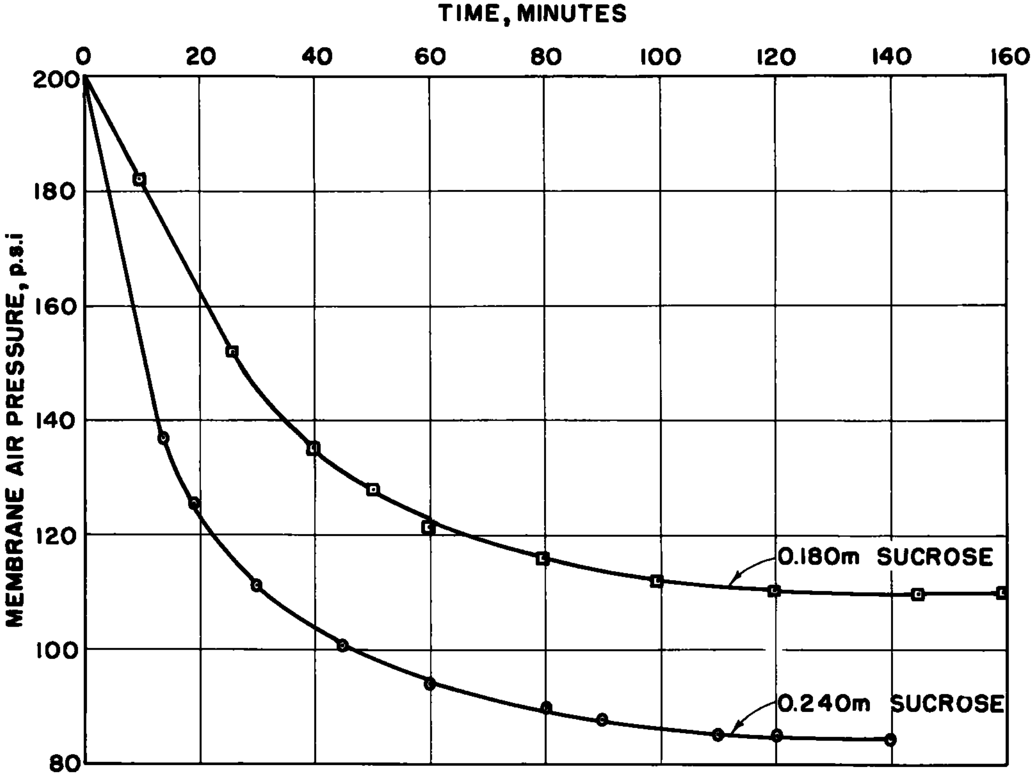

Figure 6. Time lag, osmotic calibration tests.

If a chemical solution is separated from a supply of pure water by a semi-permeable membrane—permeable to water but impervious to the chemical solute—there is a tendency for the solution to dilute itself to a uniform concentration throughout. As the solute cannot pass the membrane, the distilled water tends to flow through the membrane into the solution. If the movement of water is prevented by mechanical means, the resulting pressure P acting across the membrane is referred to as the osmotic pressure.

For dilute solutions the magnitude of osmotic pressure can be predicted accurately by van't Hoff's equation:

$$PV = nRT$$

where P = osmotic pressure
V = volume of solution
n = number of molecules of solute
R = gas content
T = absolute temperature.

For relatively concentrated solutions the van't Hoff equation loses some of its accuracy in the same manner that the ideal gas law ceases to apply at large pressures. Osmotic pressures then become a matter for experimental determination.

Osmotic pressures were first measured with some degree of accuracy by Pfeffer in 1877. More accurate determinations were made between 1901 and 1923 by Berkeley, Hartley, Morse, and Frazer (12). Their results with aqueous sucrose solutions are shown in Figure 5. It can be seen that there is a small temperature dependence, as would be expected from the van't Hoff equation. At 20 C, their results can be expressed empirically as:

$$P = 25.3\ m$$

where P = osmotic pressure, atm.
m = molarity, gram formula wt/1000 g H_2O.

In the above experiments positive pressures were measured; that is, the pressure applied to the solution to prevent water inflow through the semi-permeable membrane. In the calibration of the device, negative pressures were measured—the necessary tension applied to the distilled water to prevent inflow into the semi-permeable membrane.

It must be admitted that the ceramic stone is not a perfect semi-permeable membrane. It was felt, however, that diffusion of sucrose molecules through the stone in the relatively short time to equilibrium would be negligible—this was borne out by determinations of the "down-stream" sucrose concentrations after the tests.

Two osmotic calibration tests were run with aqueous sucrose solutions of 0.180 m and 0.240 m respectively. The system was filled with de-aired distilled water as described previously. The porous stone was inserted into a triaxial chamber which was filled with 2 liters of the sugar solution. The membrane air pressure was regulated to prevent movement of the mercury null towards the stone. A plot of air pressure versus time is shown in Figure 6. There is a pronounced time lag due to the low conductivity of the porous stone and the compressibility of the system. After completion of the tests, samples of the originally distilled water below the stone were tested for sugar content by evaporation. The sugar concentration was less than 0.001 m.

The predicted osmotic pressures based on the data shown in Figure 5 are plotted versus membrane air pressure change in the calibration curve of Figure 4.

CONCLUSIONS

Examination of Figure 4 shows two linear calibration regimes: one for positive pressures corresponding to an efficiency of 68 percent, and one for negative pressures corresponding to an efficiency of 75 percent. Because all of the fittings are tapered pipe threads or tapered copper compression sleeves, it is not surprising that the system is less compressible under water tensions. The fact that the negative pressures determined by the direct application of vacuum are consistent with the negative pressures determined by osmotic calibration is an indication of the validity of the calibration method.

In conclusion, it has been demonstrated that the device described can accurately measure water tensions to a magnitude of 90 psi in saturated systems. The limiting tension of the device when used with partially saturated soils is the air-entrance pressure of the ceramic stone.

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