

K. A. Bocking<sup>1</sup> and D. G. Fredlund<sup>2</sup>

## Use of the Osmotic Tensiometer to Measure Negative Pore Water Pressure

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**ABSTRACT:** The osmotic tensiometer was developed to provide a method of direct measurement of tension in the pore water of soils. A study was undertaken at the University of Saskatchewan to investigate the instrument's operational characteristics and its applicability to practical engineering problems. The study covered long-term stability, response time to changes in pore water pressure, and response to changes in ambient temperature. It was found that the internal prestress pressure tended to diminish with time, probably due to leakage of the confined solute through the semipermeable membrane. However, it was possible to individually calibrate each instrument to correct for this effect. Second, the pressure response of the osmotic tensiometers indicated that a transient flow process was occurring; the equilibration time of the device was primarily a function of the configuration and materials of the unit and the compressibility of the solution in the chamber. Third, it was found that changes in ambient temperature considerably affected the internal reference pressures. These results indicate that osmotic tensiometers may be useful to measure negative pore water pressures, providing that the temperature is controlled and the pore water pressure is constant. This may restrict their usefulness to research applications.

**KEY WORDS:** soil physics, instrumentation, pore water pressures, piezometers, suction

The pore water in natural and compacted soils is often in a state of tension; that is, its pressure is negative relative to atmospheric conditions. The geotechnical engineer is interested in knowing the magnitude of the negative pore water pressure and changes in it since they strongly influence the mechanical behavior of the soil. Soil scientists are also interested in the state of stress in the pore water since this affects the capability of the soil to support plant life. Consequently, researchers in both fields have been interested in the development of devices capable of measuring negative pore water pressure.

A number of such devices have been developed, including ceramic resistance blocks, conventional tensiometers, pressure plates, osmotic tensiometers, and thermocouple psychrometers. No one device has proven to be suitable for all possible applications, and some have severe limitations. To take a few examples, the relationship between the resistance of a ceramic block and

the negative pore water pressure of soil in contact with it is indirect and hysteretic; the use of conventional tensiometers is limited to pressures that are positive on an absolute pressure scale, for otherwise the fluid contained in the tensiometer will be subject to cavitation; and the pressure plate cannot be used for field measurements. In the context of these limitations the development of the osmotic tensiometer [1,2] was encouraging. Like conventional tensiometers it reads pore water pressures directly and is not subject to hysteresis. It is capable of measuring gage pressures at least as low as  $-1520$  kPa ( $-220$  lbf/in.<sup>2</sup>), and, subject to certain limitations, it can be used for continuous field measurements.

In 1969 an experimental study was commenced at the University of Saskatchewan to identify the operational characteristics of the osmotic tensiometer and study its applicability to practical engineering problems. Peck and Rabbidge [2] discussed a number of operational characteristics of the osmotic tensiometers. These included long-term reference pressure decay, response time, sensitivity to dissolved salts in the soil, and sensitivity to temperature changes. Several commercial osmotic tensiometers were purchased for the study. These were based on the Peck and Rabbidge [2] design and sold under the brand name "Aquatop." Due to the poor performance of the commercial gages, several larger scale devices were designed and built at the University of Saskatchewan and used in the research study. This paper summarizes the results of several years of experimental studies in terms of the theory of operation of the osmotic tensiometer [3,4].

### Apparatus and Theory of Operation

Design details of the osmotic tensiometers used in the study are shown in Fig. 1. The device involves the addition of a chamber (with a semipermeable membrane) to the end of a commercial strain gage-type pressure transducer. The chamber contains a solution of poly(ethylene glycol) (PEG) with a molecular weight of 20 000. The membrane is essentially impermeable to the PEG molecules.

A high reference pressure  $U_r$ , typically 1380 to 2070 kPa (200 to 300 lbf/in.<sup>2</sup>), is maintained in the chamber by osmotic forces. The reference pressure may be defined as the pressure of the solution within the chamber under equilibrium conditions at a standard temperature (20°C) when the device is immersed in distilled water at a gage pressure of 0. When an osmotic tensiometer, initially under reference conditions, is placed in contact with soil containing pore water under tension, a minute amount of water will flow out of the chamber through the semipermeable mem-

<sup>1</sup>Geotechnical engineer, Thurber Consultants Ltd., Victoria, B.C. V8V 3M8.

<sup>2</sup>Professor of civil engineering, University of Saskatchewan, Saskatoon, Sask. S7N 0W0.

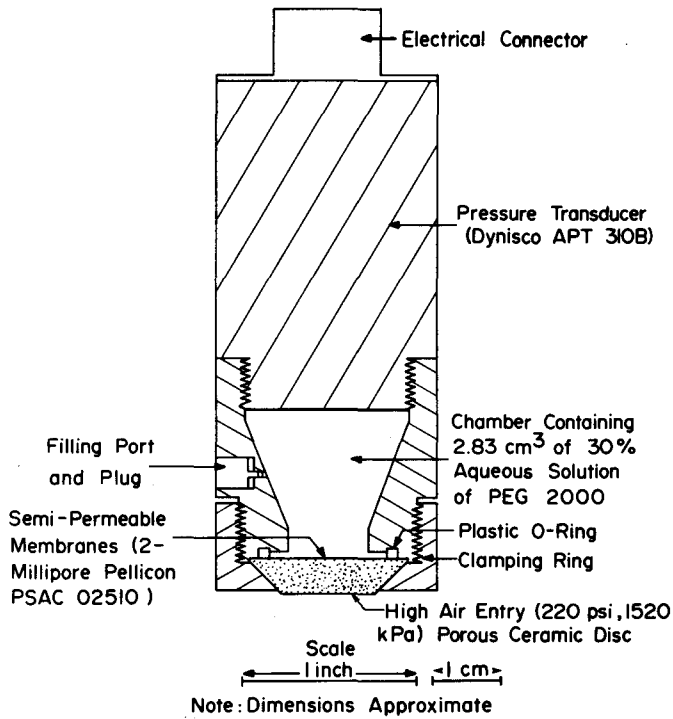


FIG. 1—Components and configuration of the University of Saskatchewan osmotic tensiometers.

brane. The pressure in the chamber will then be reduced by the amount of the pore water tension. Unless the pore water tension is greater than the reference pressure, the solution in the chamber will still be under a positive pressure that can be readily measured by the transducer without cavitation problems.

Two processes are involved in the operation of the osmotic tensiometers, osmosis and fluid flow. In the osmotic process, a solvent (for example, water) in contact with a solution through a semipermeable membrane (that is, one that is permeable to the

solvent but impermeable to the solute) will flow into the solution, tending to reduce its concentration. If the solution is confined, the flow will cause its pressure to rise. The pressurization of the confined solution will resist further solute flow. Ultimately an equilibrium will be reached and the solution pressure can be expressed as:

$$\pi = \Phi RTC_s \quad (1)$$

where

- $\pi$  = the solution pressure (that is, the osmotic pressure)
- $R$  = the universal gas constant
- $T$  = the absolute temperature
- $C_s$  = the molar concentration of the solution
- $\Phi$  = an osmotic coefficient

The osmotic coefficient depends on the solution concentration and on the nature of the solute and solvent molecules. Figure 2 shows the relationship between the osmotic pressure and concentration for aqueous solutions of PEG molecules of various molecular weights. The observed pressures correspond to values of the osmotic coefficient much greater than 1, a result of chemical interaction between solute molecules at higher solution concentrations.

The rate of flow of water through cellulose membranes into a confined solution of PEG can be described by the following equation [5]:

$$q = -K(\Delta p - \sigma\pi) \quad (2)$$

where

- $q$  = the rate of solvent (water) flow
- $K$  = a constant which for osmotic tensiometers is proportional to the areas and permeabilities of the porous stone and the membrane(s) and which is inversely proportional to their thicknesses
- $\Delta p$  = the amount by which the pressure of the confined solu-

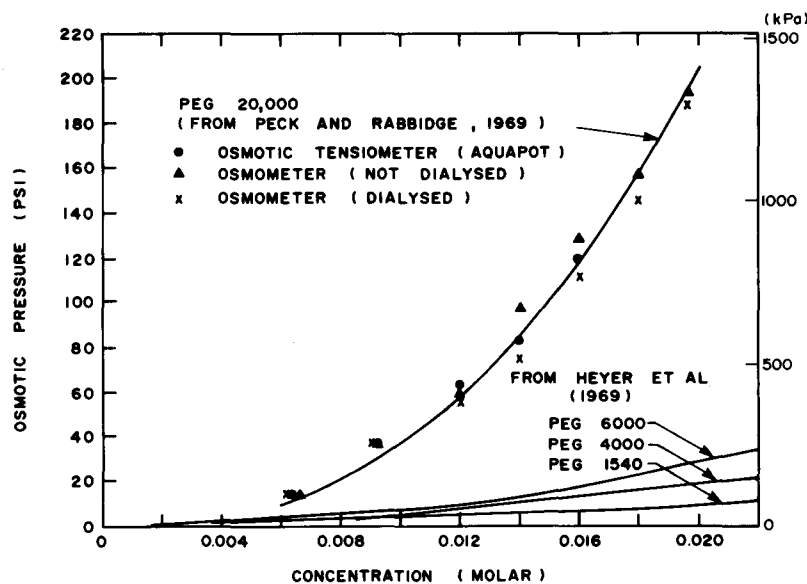


FIG. 2—Osmotic pressure of solutions of PEG.

tion  $u_c$  exceeds the pressure of the external solvent

$u_{ext}$   
 $\sigma =$  a reflection coefficient

The reflection coefficient accounts for deviations from ideal osmotic flow. For example, the membrane may be less than absolutely impermeable to the solute. Or, stratification of the solution may occur. Depending on the direction of the solvent flow, there may be a deficiency or "piling up" of solute molecules adjacent to the membrane.

Equation 2 illustrates the equilibrium condition between an osmotic tensiometer and the soil in which it is embedded. If  $u_c$  and  $u_{ext}$  are such that  $\Delta p$  equals  $\sigma\pi$ , there will be no flow and a state of equilibrium will exist. Should the value of one of the variables ( $u_c$ ,  $u_{ext}$  or  $\sigma\pi$ ) change, equilibrium will no longer exist. This will initiate flow of the solvent into or out of the chamber until a new state of equilibrium has been established.

Fredlund and Morgenstern [6] studied the rate of flow of water through a high air entry ceramic disc into the chamber adjacent to a pressure transducer. Their analysis can be adapted to the case of solvent flow into or out of an osmotic tensiometer.

Equation 2 can be expressed in terms of the volume of solvent  $\Delta Q$  flowing through the membrane in a time increment  $dt$  as follows:

$$\Delta Q = q \cdot dt = -K(u_c - u_{ext} - \sigma\pi)dt \quad (3)$$

If flow occurs into the confined chamber  $u_c$  will rise. As a result, the chamber will expand slightly and the fluid in the chamber will compress. The volume of water entering the chamber must equal the sum of the expansion of the chamber and the compression of the fluid. Therefore,

$$\Delta Q = \beta_f \cdot du_c / dt \cdot dt \cdot V_0 + \beta_c \cdot du_c / dt \cdot dt \cdot V_0 \quad (4)$$

where

$\beta_f =$  the compressibility of the fluid in the chamber

$\beta_c =$  the expansibility of the chamber

$du_c =$  the incremental change in fluid pressure over  $dt$

$V_0 =$  the original volume of the chamber

Combining and rearranging Eqs 3 and 4 gives the statement:

$$\frac{-K}{V_0(\beta_f + \beta_c)} dt = \frac{du_c}{(u_c - u_{ext} - \sigma\pi)} \quad (5)$$

The compressibility of the fluid and the expansibility of the chamber are taken to be constant with pressure. Fredlund and Morgenstern [6] demonstrated that if free air was present in a transducer chamber, the compressibility of the composite chamber fluid would be greatly increased and would be a function of pressure. The assumption of a constant chamber fluid compressibility appears justifiable for the osmotic tensiometer since the fluid will generally be under a pressure on the order of 1380 kPa (200 lbf/in.<sup>2</sup>). Any free air trapped in the chamber during assembly of the osmotic tensiometer should be forced into solution at this pressure level.

The constants on the left hand side of Eq 5 can be lumped together as a compliance factor  $C$ . By integrating and rearranging Eq 5, an expression for  $u_c$  as a function of time is obtained:

$$u_c = (u_{c0} - u_{ext} - \sigma\pi)e^{-Ct} + (u_{ext} + \sigma\pi) \quad (6)$$

where

$e =$  the base of natural logarithms

$u_{c0} =$  the initial chamber pressure

Equation 6 can be written in a dimensionless pressure form by dividing both sides by  $(u_{c0} - u_{ext} - \sigma\pi)$ . The pressure response can be written as:

$$U = (1 - e^{-Ct})100 \quad (7)$$

where  $U =$  the percent pressure response, defined as

$$1 - \left[ \frac{u_c - (u_{ext} + \sigma\pi)}{u_{c0} - u_{ext} - \sigma\pi} \right] 100$$

Theoretical plots of the percent response versus the logarithm of time are shown in Fig. 3 for various compliance factors. Although the equalization time is not a distinct point, it can be defined as the point of intersection between the extension of the straight line portion of the plot and the horizontal line after complete equalization.

The pressure response of an osmotic tensiometer due to dis-

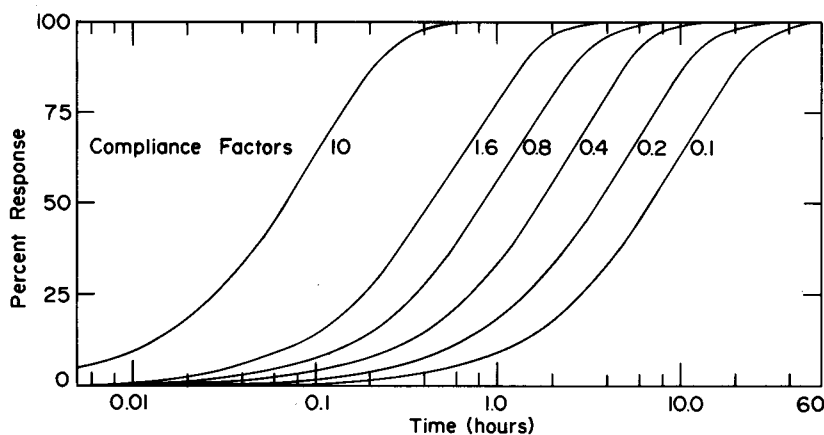


FIG. 3—Theoretical response curves for various compliance factors.

equilibrium may deviate from that predicted by Eq 7 for several reasons. First, the amount of flow may be large enough to significantly affect the pore water tension being measured. Second, the osmotic pressure may change during the period of flow because of a change in the osmotic coefficient, the molar concentration, or the temperature. Third, the compressibility of the fluid in the chamber and the expansibility of the chamber may not be constant. Fourth, flow may cause some solution stratification resulting in a change in the reflection coefficient [7].

When the osmotic tensiometer is placed in contact with the soil, the pressure response is also a function of the soil properties. In order for an osmotic tensiometer to register a change in pressure, a small but significant amount of water must flow through the pores of the adjacent soil towards or away from the instrument. Therefore, the response rate depends not only on the compliance factor of the instrument, but also on the permeability and compressibility of the soil.

Bishop and Henkel [8] discuss the response rate of a null indicator device measuring changes in pore water pressures for unsaturated soils with a specific set of flow boundary conditions. The solution shows that the response rate of the device and the adjacent soil is many times slower than that of the device alone (that is, than what would be measured by performing a pressure response test with the pressure-sensing element in contact with a reservoir of water). This conclusion can also be applied to the response rate of the osmotic tensiometer. In other words, the equalization time of a tensiometer-soil system would be much greater than that measured in the water reservoir response tests undertaken in this study.

### Performance of Osmotic Tensiometers

The following aspects of the performance of osmotic tensiometers were examined in the laboratory study: first, decay of the reference pressure with time; second, the speed with which the devices respond to changes in  $u_{ext}$ ; and third, their response to temperature changes.

#### Reference Pressure Decay

Figure 4 shows the reference pressures recorded for two osmotic tensiometers under equilibrium conditions in distilled water at 20°C over a period of 260 days. These results agree with

those of Peck and Rabbidge [2], indicating that the reference pressure decays with time at an approximately constant rate. The rate varied considerably from instrument to instrument.

According to Eq 1 the reference pressure decay is due to a decline in the value of either the solute concentration or the osmotic coefficient or both. Several factors could be involved in the change of the solute concentration over time. First, there could be diffusion of solute molecules into the "O" rings of the device. However, it is unlikely that the "O" rings could absorb enough solute to bring about the noted pressure losses of 25% or more. Second, there could be leakage of solute through the semipermeable membranes. There may be a wide range in both the size of pores in the membrane(s) and the size of the solute molecules. It may be possible for a small fraction of the number of solute molecules to pass through a small fraction of the pores in the membrane. Degradation of the membranes combined with solute breakdown would contribute to this leakage. Third, there could be flaws in the membrane(s). The variability in the rate of reference pressure loss from instrument to instrument may indicate that leakage is more controlled by random flaws in the membranes than by their average properties. Fourth, there could be damage to the membranes during service. The membranes used consisted of a thin semipermeable skin of unspecified nature supported by a porous cellulose substrate. It is notable that certain forms of cellulose are not wholly compatible with PEG and that cellulose is susceptible to biological attack [9], mechanical breakdown, and damage from contact with alcohol. Fifth, there could be a breakdown of the solute. Although PEG is relatively inert, it is susceptible to breakdown by mechanical [10] and biological [11] means. PEG also tends to break down chemically by autoxidation [12]. The breakdown of PEG molecules would not only affect the rate of leakage but may also affect the degree of interaction among solvent molecules and cause a decrease in the osmotic coefficient. A more complete understanding of the nature of this interaction is required. Sixth, the apparent decay in reference pressure could be caused in part by creep of the transducer strain gages under continuous load [2] and by drift in the readout device. Such effects would likely be insignificant.

#### Response Time

The response time of an osmotic tensiometer was determined

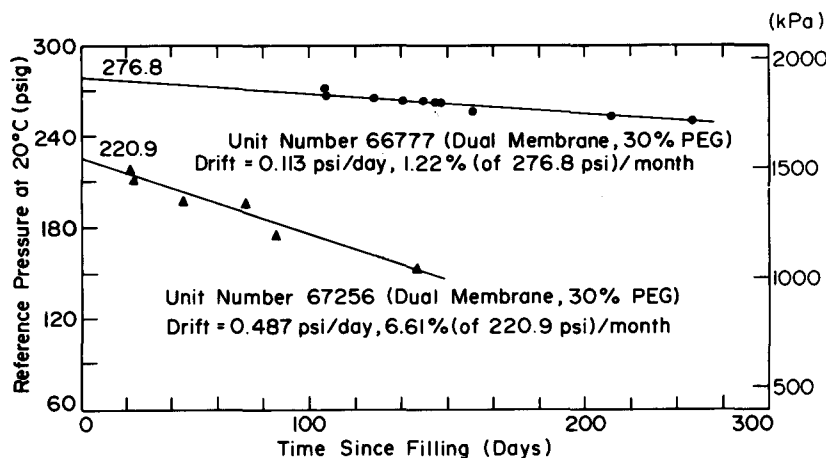


FIG. 4—References pressure drift of two University of Saskatchewan osmotic tensiometers.

by immersing the device in a water bath and allowing it to come to equilibrium. The pressure of the water bath was then quickly changed and the osmotic tensiometer chamber pressure response was monitored. This experiment was repeated several times and typical results are shown in Fig. 5. The instrument responded completely to each change in external pressure, with equilibration times between 20 and 37 h. When plotted on a semilogarithmic scale the response curves were S-shaped.

Curves based on Eq 6 can be fitted to the actual results at the median pressure by trial and error selection of a value of the compliance factor. The fit of the theoretical curves to the actual results is relatively poor if an attempt is made to best-fit the entire pressure range; the fit can be considerably improved by adjusting the value of  $u_{c0}$ . Such an adjustment is necessary because the change in  $u_{ext}$  causes an immediate instantaneous change in the chamber pressure. For example, a reduction in the external water pressure could cause an elastic expansion in the tensiometer case and a slight increase in chamber volume. The chamber pressure would be instantly reduced by an amount related to the relative compressibilities of the case and the fluid.

The agreement between the experimental curves and the best-fit theoretical curves obtained by using adjusted  $u_{c0}$  values is relatively good (see Fig. 5). The experimental curves are somewhat flatter than the theoretical ones in the later stages of the experiments. Consequently, the actual equilibration times were longer than the theoretical ones. Several possible causes of discrepancies between the actual and theoretical response curves were discussed above in the presentation of the theory. However, it is not known which factor(s) may be most significant in causing the observed discrepancies.

The compliance factors obtained from the pressure response experiments ranged from 0.22 to 0.28, with corresponding equilibration times ranging from 20 to 37 h. These responses were slower than those reported by Peck and Rabbidge [2]. Presumably, this difference relates to differences in the permeability of the porous ceramic disc and membranes.

### Temperature Response

Peck and Rabbidge [2] noted that "thermal transients result in differential expansion of the osmotic solution and its confined solution, which gives rise to spurious solution pressure changes." For this study, numerous tests were run to investigate the pressure response to temperature changes. One or more osmotic tensiometers were allowed to come to equilibrium at a constant temperature in a water bath. The water bath temperature was then changed, the change being substantially complete within 0.5 h. The chamber pressures were subsequently monitored until a new equilibrium was reached.

The pressure responses of two instruments to a temperature decrease are shown in Fig. 6. The change in pressure (beginning 0.5 h after the recording of the minimum pressures) is plotted against the log of time in Fig. 7. These results are typical; similar responses were noted for temperature changes as small as 1.6°C. The decrease in temperature caused a sharp drop in the pressures. Pressure readings were not taken continuously; therefore the magnitude of the maximum pressure drop is not precisely known. The decreased pressures caused a disequilibrium which caused water to flow into the instrument chambers until a new equilibrium was established at a higher pressure. The pressure response to temperature changes (see Fig. 7) is similar to that caused by changes in external pressure (see Fig. 5). The pressure response to temperature increases was the opposite of the response to temperature decreases; that is, a large pressure increase was noted followed by a gradual decrease in pressure until a new equilibrium was established at a final pressure lower than the initial.

Figure 8 shows the equilibrium reference pressure of two osmotic tensiometers as functions of temperature. These results were recorded under equilibrium conditions, indicated in each case by a series of essentially unchanged readings for several hours. The data were compiled from various experiments undertaken over a period of about 140 days and the results were cor-

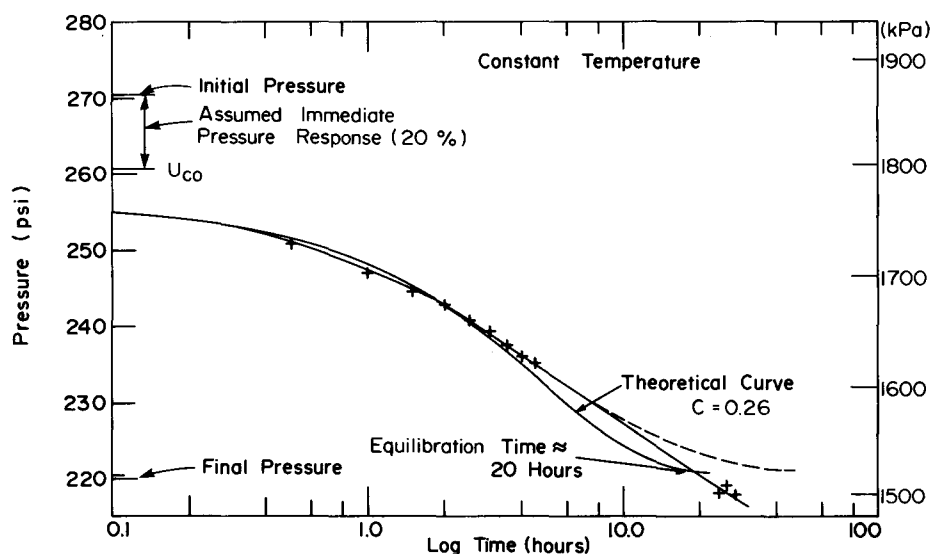


FIG. 5—Transient response of two osmotic tensiometers to a step change in pressure.

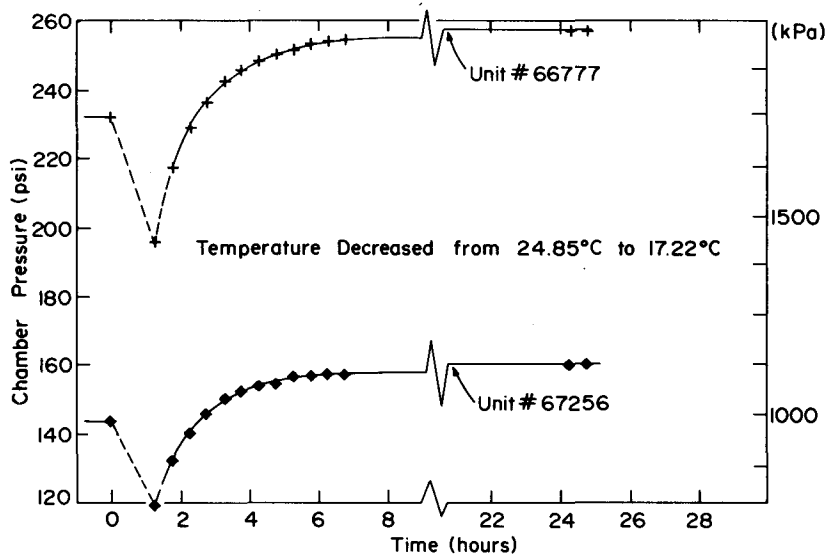


FIG. 6—Transient response of two osmotic tensiometers to a rapid temperature decrease.

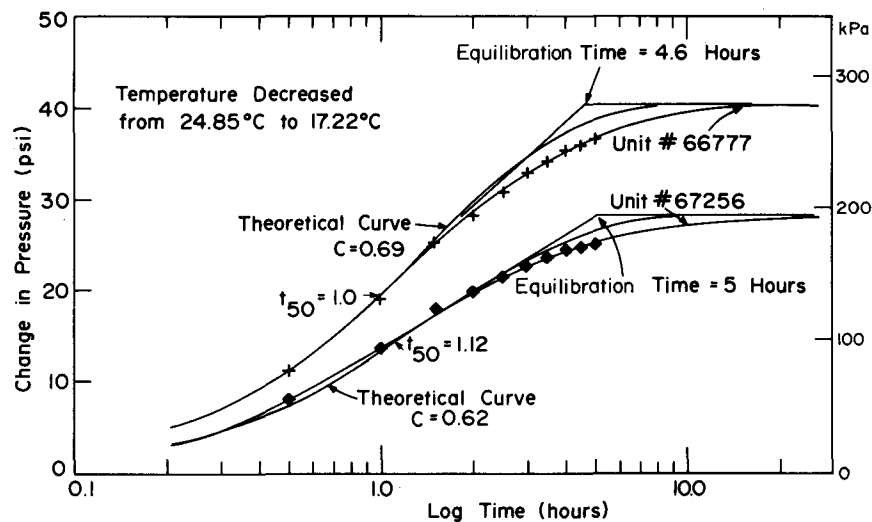


FIG. 7—Logarithmic plot of the transient response of two osmotic tensiometers to a rapid temperature decrease.

rected for reference pressure decay on the basis of results shown in Fig. 4.

The linear regression analyses of these results show equilibrium temperature sensitivities of  $-24.8 \text{ kPa}/^\circ\text{C}$  ( $-3.59 \text{ lbf}/\text{in.}^2 \text{ per } ^\circ\text{C}$ ) and  $-18.6 \text{ kPa}/^\circ\text{C}$  ( $-2.70 \text{ lbf}/\text{in.}^2 \text{ per } ^\circ\text{C}$ ) for the two instruments. The percent change from their original reference pressure at  $20^\circ\text{C}$  is  $-1.30\%$  and  $-1.24\%$ , as compared to the value of approximately  $-1.5\%$  obtained by Peck and Rabbidge [2]. Although there is considerable scatter in the results, it appears that the equilibrium temperature sensitivity is nonhysteretic, not significantly affected by reference pressure decay with time, and relatively constant throughout the range of temperatures studied ( $6$  to  $25^\circ\text{C}$ ). It is apparent from Eq 1 that the osmotic coefficient is a function of temperature. The reason for this is not completely clear, but it may be that the chemical interaction that occurs between the solute molecules is temperature-related.

### Summary

The following four performance characteristics of osmotic tensiometers have been examined: the decay of the reference pressure with time; the effect, under equilibrium conditions, of changing temperature on the reference pressure; the slow response of osmotic tensiometers to changes in pore water pressure; and the transient effect of temperature changes on the reference pressure. All of these characteristics present difficulties to the successful use of these devices to measure negative pore water pressures.

The rates of reference pressure decay that were measured are such that it would be inaccurate to use these devices over extended time periods (more than several weeks) without periodic determinations of the current reference pressure. Experimental results indicate that the decay rates vary considerably from unit to unit; however, they are linear with time. Similarly, the effect

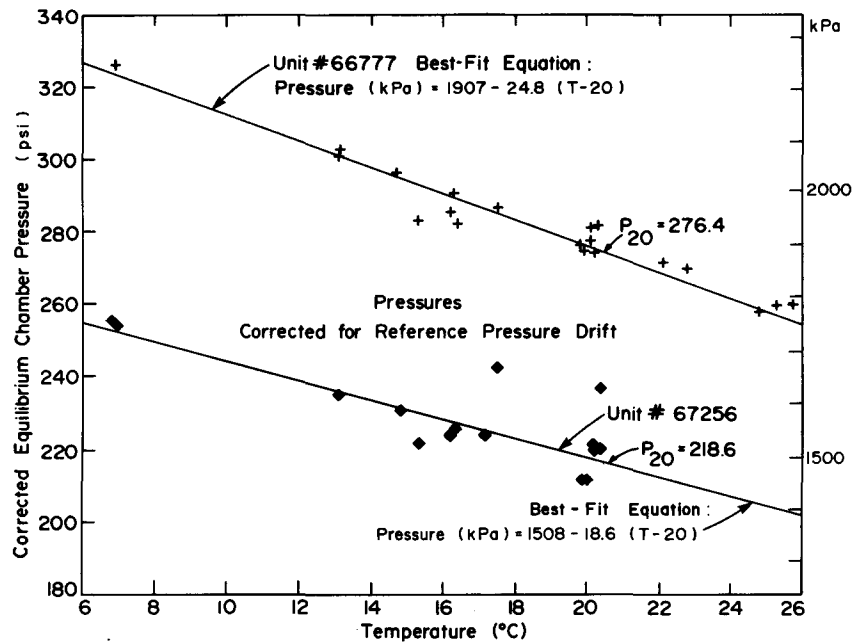


FIG. 8—Equilibrium chamber pressure versus temperature.

of temperature changes on the reference pressures at equilibrium varies from unit to unit, but is still linear. It is possible to correct the output of osmotic tensiometers for these two effects using the following equations:

$$u_{ext} = (u_c - U_r') \quad (8)$$

$$U_r' = U_r - m(t - t_0) - n(T - T_0) \quad (9)$$

where

- $U_r$  = reference pressure at  $t_0$  and  $T_0$
- $U_r'$  = corrected reference pressure
- $t, t_0$  = present and initial times, respectively
- $T, T_0$  = actual and standard temperatures, respectively
- $m$  = the slope of the plot of reference pressure versus time (positive)
- $n$  = the slope of the plot of equilibrium reference pressure versus temperature (positive)

To evaluate  $m$  and  $n$  it is necessary to run two series of calibration tests for each unit. The reference pressure must be measured at the standard temperature over a period of several months and under equilibrium conditions at various temperatures.

The rate of response of the osmotic tensiometers studied to changes in external water pressure was very slow. This imposes an important constraint on the use of these devices. If they are to be used to measure continuously changing negative pore water pressures, the period of these changes must be slow enough that an osmotic tensiometer can maintain equilibrium. Because the response of the tensiometer-soil system would be even slower than that of the tensiometer itself, the period of pore water pressure changes would have to be on the order of several days at least. If accurate measurements of this sort were required it would be necessary to establish the system equilibration period beforehand. This would require testing of the unit to be used with the

particular soil to be studied using externally controlled pore water pressure changes.

It has been shown that a change in temperature initiates a flow process which is essentially the same as that caused by a change in external pore water pressure. Therefore, accurate results can only be obtained if the temperature is controlled, or if the period of temperature changes exceeds the tensiometer-soil system equilibration period discussed above. The required degree of temperature control is not known, except that it is less than  $1.6^\circ\text{C}$ .

In conclusion, the osmotic tensiometer provides a means of accurately measuring negative pore water pressures over a substantial pressure range under certain conditions. It may be used to measure constant pore water pressures at stable temperatures providing the reference pressure is corrected for drift and for nonstandard temperatures. Also, it can be used under conditions of changing pore water pressure and temperature providing the period of these changes exceeds the equilibration time of the osmotic tensiometer-soil system. In this case it would be necessary to both correct the reference pressure and experimentally determine the system equilibration time. Considering the difficulties involved under the latter conditions, it is unlikely that the osmotic tensiometer will be used other than in research applications where the temperature and pore water pressure are constant.

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