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Automated Humidity System for Measuring Total Suction Characteristics of Clay

ABSTRACT: A computer-automated experimental system for determining total suction characteristic curves using relative humidity control is described. The system is applicable in the relatively high suction range important for fine-grained materials (7000 to 700 000 kPa). The new system has several advantages over existing suction measurement techniques; most notably, it is fully automated, has a much broader measurement range, is capable of determining both wetting and drying characteristics in significantly less time, and requires only one undisturbed sample for testing. Tests are conducted to evaluate the system response and illustrate its use in practice. Total suction characteristic curves are determined for four types of clay, ranging from highly expansive smectite to non-expansive kaolinite. Concurrent characteristic curves are determined using the filter paper method for comparison. Practical applications are demonstrated in two ways. First, select results are analyzed to assess the swelling potential of the four clays using an existing methodology based on total suction testing. Second, aspects related to the adsorption kinetics of expansive soils are evaluated by analyzing the results with a first-order kinetic model.

KEYWORDS: unsaturated soils, suction, relative humidity, soil-water characteristic curves, expansive soils, adsorption kinetics, automated testing

Soil suction is a fundamental physical property of unsaturated soils describing the potential with which a given soil at given water content adsorbs and retains pore water. *Total* soil suction (Ψ_t) is comprised of two components: a *matric* component (Ψ_m) associated with interparticle capillary menisci and particle surface hydration mechanisms, and an *osmotic* component (Ψ_o) arising from the presence of dissolved solutes in the pore fluid. Moisture-suction characteristic curves, often referred to as "soil-water characteristic curves," or "suction characteristics," describe the constitutive relationship between moisture content and suction. Typically, this relationship is described either in terms of the matric component of suction (e.g., "matric suction characteristic curves") or in terms of total suction (e.g., "total suction characteristic curves").

It is well established that determination of matric and/or total suction characteristic curves is necessary in order to fully characterize numerous phenomena in unsaturated soil behavior. For example, in problems associated with unsaturated fluid flow, measurement or modeling of *matric* suction characteristics is usually required. Historical applications in this arena include vadose-zone contaminant transport studies, groundwater infiltration and evaporation studies, capillary barrier evaluations, and containment facility design for landfills or mine waste (Barbour 1998). Other important applications include the estimation of particle surface area (Keren and Shainberg 1975), pore size distribution (Lowell 1979), or permeability (Brooks and Corey 1964).

More recently, the important role of *total* suction characteristics in assessing unsaturated soil behavior has attracted increasing attention. For example, it has been shown that the "slope" of the total suction characteristic curve may be used to qualitatively classify the relative swelling potential of expansive soils, e.g., as "low," "moderate," "high," or "very high." (McKeen 1992). Several empirical correlations based on total suction testing have been developed for quantitative heave prediction under field conditions (Johnson and Snethen 1979; McKeen 1992).

This paper introduces a new type of experimental system for determining total suction characteristic curves using relative humidity (RH) control. The system has several advantages over existing total suction measurement techniques. The new system is fully computer-automated, has an extremely wide measurement range, and is capable of generating complete characteristic curves (i.e., wetting and drying loops) in much less time. Unlike the existing techniques, which typically require independent measurements of suction for numerous individually prepared sub-samples, the new system allows continuous characteristic curves to be determined from a single undisturbed sample. Measurement uncertainties associated with sample sub-splitting and mixing procedures (i.e., disturbance) are avoided. The new system is applicable for suction ranging from approximately 700 000 to 7000 kPa, a range unattainable by established techniques and well covering the wide range of interest for the characterization of clayey and potentially expansive soils.

Total Suction and Relative Humidity

In thermodynamic terms, total soil suction may be described in terms of the free energy state of the soil pore water, which may be measured in terms of its partial vapor pressure (u_v) or relative humidity (*RH*) at local equilibrium. The relationship between total suction Ψ_t (kPa) and relative humidity of water vapor is described by Kelvin's equation (Sposito 1981):

$$\Psi_t = -\frac{RT}{v_{wo}\omega_v} ln\left(\frac{u_v}{u_{v0}}\right) = -\frac{RT}{v_{wo}\omega_v} ln\,(RH) \qquad (1)$$

where u_v is the partial pressure of water (e.g., soil pore-water) vapor (kPa), u_{v0} is the saturation pressure of pure water vapor (kPa), R is the universal gas constant (8.31432 J mol^{-1} K^{-1}), T is

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absolute temperature (K), v_{wo} is the specific volume of water (i.e., reciprocal of density, m³/kg), and ω_v is the molecular mass of water vapor (18.016 kg/kmol). Figure 1a shows a plot of Eq 1 for $T = 1$, 20, and 50°C.

Psychrometer and Filter Paper Methods

Two techniques have been most commonly used for measuring total suction and total suction characteristic curves: thermocouple psychrometers (Spanner 1951) and "non-contact" filter paper methods (Houston et al. 1994). Both techniques rely on determining the

relative humidity of the pore-water vapor and converting the measurement to total soil suction using Kelvin's equation (Eq 1).

In the former technique, humidity is measured directly. Psychrometers work in either "wet bulb" or "dew point" modes by relating the evaporation-induced signal response at a Peltier-cooled thermocouple junction to relative humidity. The filter paper technique, on the other hand, relies on indirect measurement of relative humidity. Filter papers are used as "sensors" under the assumption that their water content in a closed environment will achieve equilibrium with the relative humidity of soil pore-water vapor. For total suction measurements, an initially dry paper is
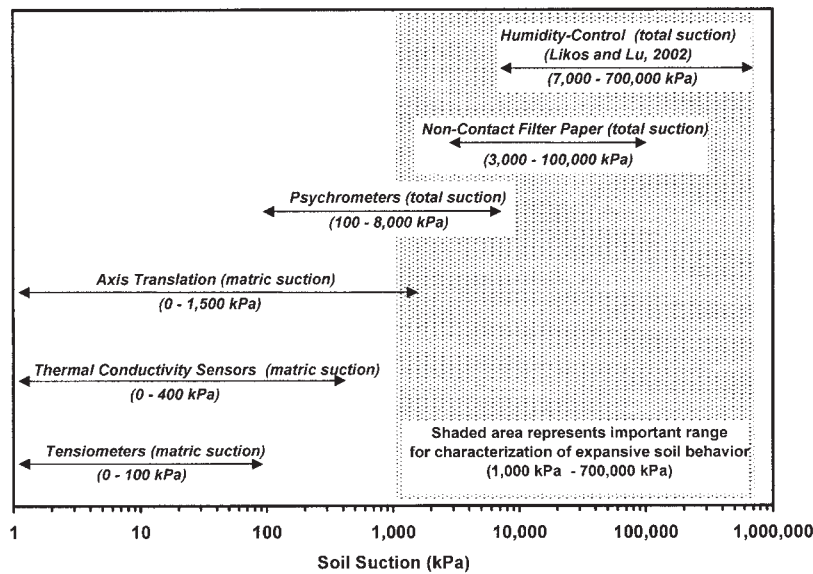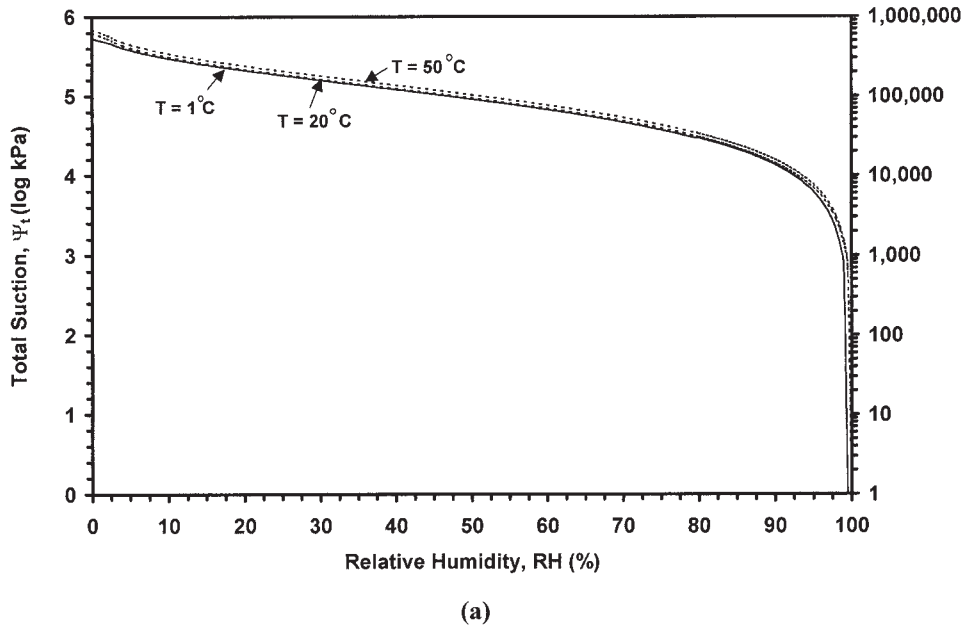

(a)

(b)

FIG. 1—(a) *Theoretical relationship between relative humidity and total suction described by Kelvin's equation, and* (b) *approximate ranges for various suction measurement techniques.*

suspended in the headspace above a soil sample sealed in a closed container (i.e., the paper does not directly contact the sample). The paper adsorbs vapor until equilibrium is reached, typically in seven to ten days. The final water content of the paper is measured gravimetrically and related to the relative humidity of the pore-water vapor through a calibration curve, usually predetermined by equilibrating papers over salt solutions of known concentration.

Limitations

Although widely used and well-documented in the literature, both psychrometer and filter paper techniques suffer from several significant limitations. Figure 1*b*, for example, shows their approximate measurement ranges. Other common methods for measuring *matric* suction (Ψ_m) are included for comparison. The hatched area shown from 1000 to 700 000 kPa approximates the important suction range for the characterization of clayey or potentially expansive soils (McKeen 1992; Nelson and Miller 1992).

Psychrometers are applicable only for total suction values less than approximately 8000 kPa. For clayey soils, which can exhibit suction extending into the range of hundreds of megapascals (MPa), psychrometers are usually incapable of determining the full characteristic curve. Psychrometers also require strict temperature control and are known to suffer from corrosion problems (Hamilton et al. 1981). Depending on the magnitude of suction, equilibration times may be as long as 14 days for a single measurement (Richards 1974).

In principle, filter paper testing is applicable over the entire suction range. In practice, however, the technique is limited to total suction from approximately 3000 kPa to 100 000 kPa (Houston et al. 1994; Likos and Lu 2002). As illustrated on Fig. 1*a*, the relationship between total suction and relative humidity becomes extremely "steep" at suction values less than 3000 kPa (≈ 3.5 log kPa). Total suction in this range is highly sensitive to relative humidity, typically manifested as a large degree of scatter and a significant increase in measurement uncertainty at relatively low values of suction (Fawcett and Collis-George 1967; Likos and Lu 2002). A similar effect occurs in the relatively high suction range ($>100\ 000$ kPa) where the filter paper adsorbs an increasingly small amount of water vapor. In this range, the quality of the measurement becomes exceedingly dependent on environmental conditions, operational procedure, and the precision of the equipment used to determine the equilibrium filter paper water content.

Automated Humidity Control System

General Description

Unlike psychrometer and filter paper techniques relying on *measurement* of relative humidity, the experimental system developed here relies on *control* of relative humidity. To generate total suction characteristic curves, the equilibrium water content of soil samples placed in the controlled humidity environment is measured as water is adsorbed or desorbed. This type of testing strategy has already been successfully demonstrated for soil suction measurements using salt solutions or vacuum systems for controlling relative humidity, commonly referred to as "desiccator" techniques (Collis-George 1955; Nishimura and Fredlund 2000).

Figure 2*a* illustrates the general layout of the new testing system. Relative humidity is controlled by computer-proportioned mixing of vapor-saturated, or "wet," nitrogen gas and desiccated, or "dry," nitrogen gas in a closed environmental chamber. Similar humidity-control approaches (i.e., gas mixing approaches) have been described for automated environmental X-ray diffraction (XRD) studies by Hashizume et al. (1996) and Chipera et al. (1997).

Following the schematic from left to right, bottled nitrogen ($>99.995\ \%\ N_2$) is split into two separate gas streams through 1/4-in. nylon tubing. A pair of computer-controlled mass-flow valves (MKS Instruments, Type 1179A) regulates the flow of each gas stream between zero and 200 cm³/min based on an electronic control signal from a control PC. The control signal is varied between 1 and 5 V (dc) corresponding to "fully closed" and "fully open" valve states, respectively. One of the gas streams is vapor-saturated ($RH \approx 100\ \%$) by bubbling it through a gas-washing bottle (Fisher-Milligan 07-513) filled with distilled water. The second gas stream is routed through a column filled with desiccant ($RH \approx 0\ \%$). The vapor-saturated (or "wet") and desiccated (or "dry") gas streams are then reintroduced in a three-neck, 250-cm³ flask at a combined flow rate of 200 cm³/min. The resulting gas stream (labeled "humid" on Fig. 2*a*) has a relative humidity that is a direct function of the "wet" to "dry" gas flow ratio (*w/d*) maintained by the control PC. Electrical heat tape is wrapped around the "wet" and "humid" gas lines and connected to a variable voltage transformer to stabilize the gas flow temperature and allow the option for elevated temperature testing.
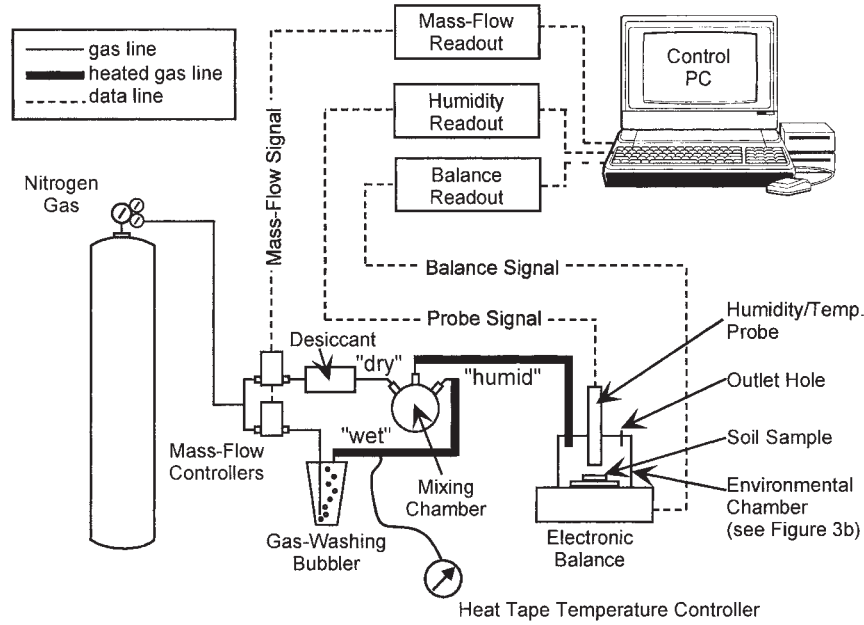
The "humid" gas stream is routed into an acrylic environmental chamber (see Fig. 2*b*) containing a soil sample. An effluent gas vent on the top cap of the chamber allows the influent "humid" gas to escape after flowing around the soil. Excluding the effluent vent, which is extremely small (≈ 0.5 mm), the top and bottom of the chamber are sealed with either lubricated rubber gaskets or O-rings to form a completely isolated sample environment.

Relative humidity and temperature in the chamber are continuously monitored with a capacitance-film humidity/temperature probe (Vaisala Corporation, Model HMI-35). The probe measures humidity between 0 % *RH* and 99 % *RH* at 0.01 % *RH* resolution. Temperature is measured to 0.01°C. Signals from the humidity probe form a feedback loop with the control PC for automated regulation of the "wet" to "dry" gas flow ratio (*w/d*) using the two mass-flow controllers.
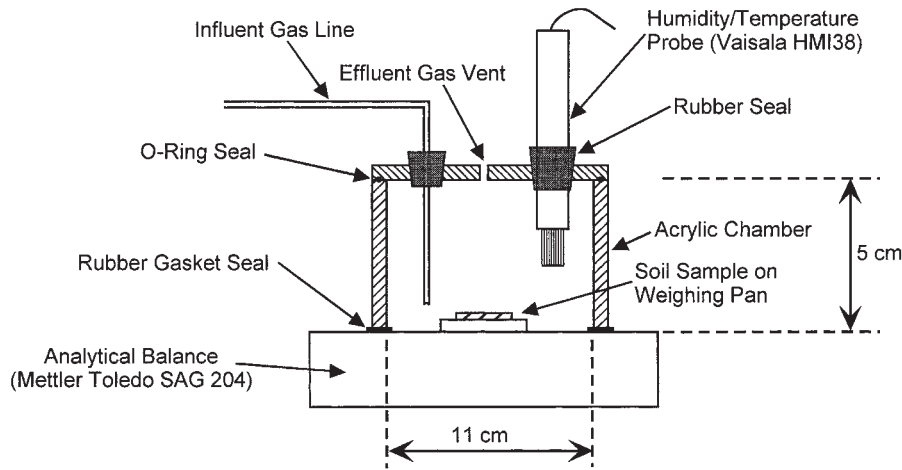
An electronic balance (Mettler-Toledo, Model SAG204), with an 8-cm-diameter loading platen, 210-g range, and 0.0001-g resolution, forms the bottom plate of the environmental chamber. Soil samples (typically ranging from 0.5 to 3.0 g) are placed directly on the balance. To develop total suction characteristic curves, the relative humidity in the chamber is incrementally stepped up or down by proportioning the ratio of "wet" to "dry" gas flow under feedback from the humidity probe. Soil water content is continuously monitored using the balance through the PC serial port as water vapor is adsorbed or desorbed at each step in relative humidity. When an equilibrium is reached, the water content is recorded and the humidity in the chamber is stepped up or down to the next increment. Typically, *RH* is stepped in increments of 10 %.

System Behavior

A preliminary series of tests was conducted to characterize the humidity-control system in terms of its range, calibration, and response. These tests were conducted without soil present in the

(a)

(b)

FIG. 2—*Automated humidity-control system:* (a) *general layout, and* (b) *detail of the environmental chamber.*

environmental chamber. Figure 3a shows the relationship between the "wet" to "dry" flow ratio (w/d) and equilibrium relative humidity for two trials. For the first trial, the "wet" and "humid" gas lines were heated to 2°C above ambient temperature ($T = 24$°C). The second trial was conducted at ambient temperature ($T = 22$°C).

In both cases, the relationship between w/d and RH is linear ($R^2 \geq 0.9997$). For the elevated temperature trial, the maximum humidity reached under 100 % "wet" flow (w/d = 1) is approximately 90.69 % (corresponding to $\Psi_t = 13\ 200$ kPa, Eq 1). The measured RH under 0 % "wet" flow is 0.77 % ($\Psi_t = 657\ 000$ kPa). At ambient temperature, the maximum and minimum humidity is 95.23 % ($\Psi_t = 6600$ kPa) and 0.27 % ($\Psi_t = 799\ 000$ kPa), respec-

tively. Although elevating the temperature clearly places a constraint on the upper humidity range, it was found to be desirable for inhibiting vapor condensation in the chamber and for stabilizing the overall chamber temperature. In the soils testing program that follows, testing was performed under slightly elevated temperature conditions ($T \approx 24$°C).

Figures 3b and 3c show continuous traces of chamber humidity and temperature as the "wet" to "dry" flow ratio was stepped from 0 % "wet" flow to 100 % "wet" flow and back down to 0 % "wet" flow at $T \approx 24$°C. The cycle was ramped in 20 steps and was completed in about 14 days. At steady state for each step, the relative humidity in the chamber does not deviate by more than 0.6 % RH. For relatively low RH values (e.g., 20 %), this variation corre-
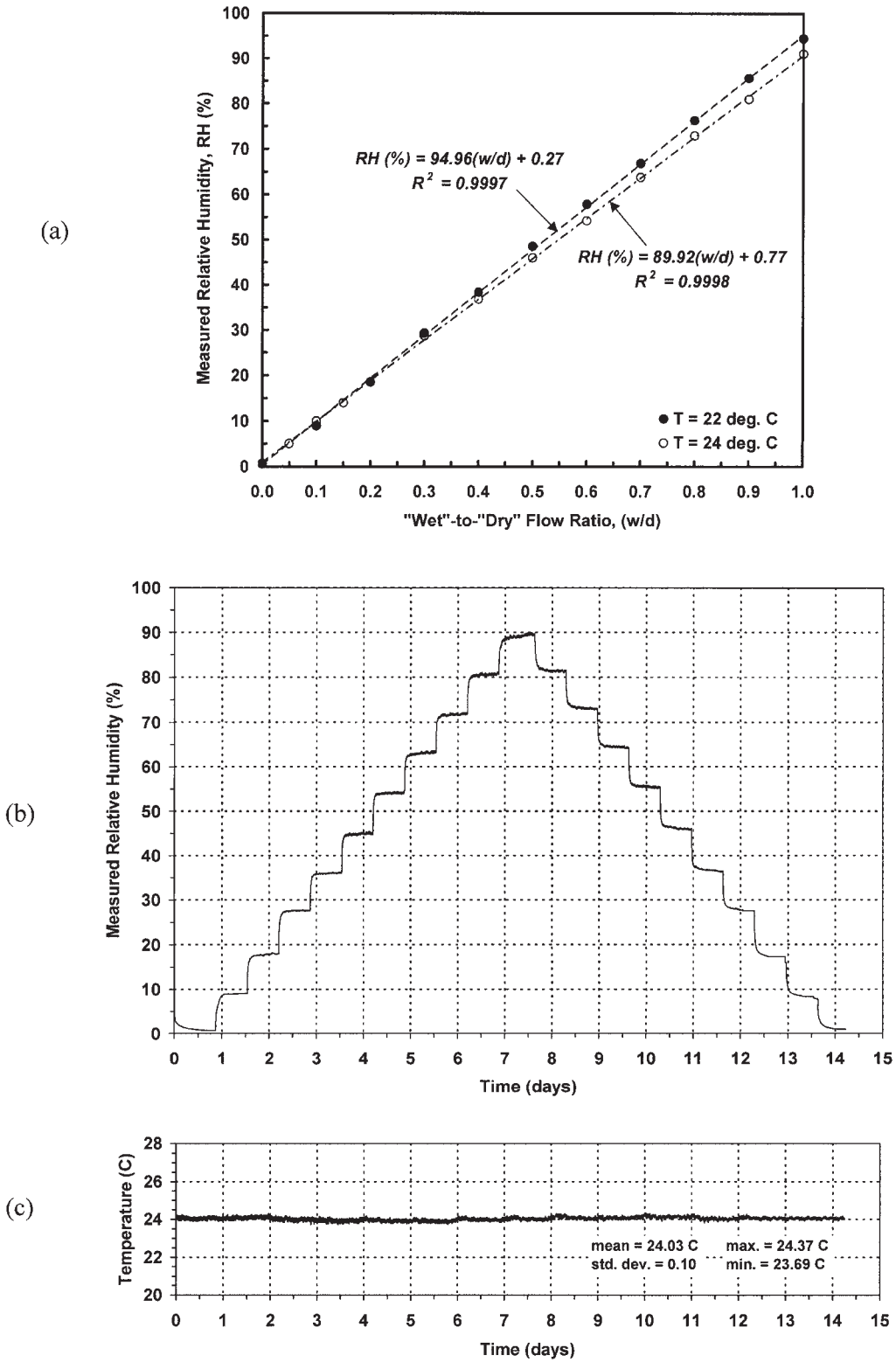
$RH\ (\%) = 94.96(w/d) + 0.27$
$R^2 = 0.9997$

$RH\ (\%) = 89.92(w/d) + 0.77$
$R^2 = 0.9998$

● T = 22 deg. C
○ T = 24 deg. C

mean = 24.03 C   max. = 24.37 C
std. dev. = 0.10   min. = 23.69 C

FIG. 3—*System response:* (a) *relationship between "wet"-to-"dry" flow ratio and relative humidity for ambient (T = 22°C) and elevated (T = 24°C) temperature conditions,* (b) *relative humidity response cycle, and* (c) *temperature response cycle.*

sponds to approximately ±4000 kPa, a 2 % deviation. For relatively high *RH* values (e.g., 90 %), this variation corresponds to approximately ±1000 kPa, or 6 %. The time required for the chamber to reach steady state humidity at each step is on the order of 1 to 2 h. The temperature in the environmental chamber does not deviate by more than 0.7°C over the entire cycle and shows a standard deviation of 0.1°C.

Soil Testing Program

Description of Testing Materials

Clay samples for testing were selected to represent a wide range of swelling behavior. Pure Na^+-smectite and kaolinite clay minerals were obtained from commercial vendors (Rototin Clay Company and Georgia Kaolin Company, respectively). Reflecting their origin, these soils are referred to herein as "Wyoming smectite" and "Georgia kaolinite." Two additional materials were sampled locally from an outcrop of the Benton shale formation near Denver, Colorado. These materials are typical of those within the Upper Cretaceous shale formations including the Benton and Pierre that are well-known sources of swelling-related structural damage along the Colorado Front Range (Noe 1997). These samples, referred to herein as "Soda Lakes claystone" and "Soda Lakes smectite" included an olive gray, silty claystone and a marbled, waxy, bentonite.

Mineralogical and Engineering Properties

Tests were conducted to determine the basic mineralogical and engineering properties of the four test materials. This series included qualitative X-ray diffraction (XRD) testing, hydrometer analysis (ASTM D421), Atterberg limits testing (ASTM D 4318), and subsequent classification according to the Unified Soil Classification System (USCS). Table 1 summarizes the results of these tests.

Suction Testing

Suction testing involved two techniques: (1) testing in the relatively high suction range (> ≈10 000 kPa) was conducted using the automated humidity system, and (2) testing over suction values ranging from approximately 600 000 to 3000 kPa was conducted using the "non-contact" filter paper method (ASTM D 5298). Suction characteristics obtained using the filter paper method in the relatively high suction range were directly compared with the automated system results.

Humidity System Testing

Samples of Wyoming smectite and Georgia kaolinite were tested for complete adsorption and desorption suction characteristics using the automated humidity system (i.e., "wetting" and "drying" loops). The Soda Lakes materials were tested only for adsorption ("wetting") characteristics. Testing for the Soda Lakes smectite was conducted as two independent trials to assess the repeatability of the measurement system.

For all automated testing, air-dried samples were pulverized to pass a No. 200 (0.075-mm) sieve using a mortar and pestle. Sample mounts were prepared by sprinkling approximately 0.5 g of clay onto a pre-weighed glass slide. A second glass slide was used to spread the sample out evenly and compress it to a thickness of about 2 mm. The mount was then dried to constant mass in a 105°C oven and transferred to the environmental chamber (Fig. 2b). In the chamber, the sample was subjected to 0 % "wet" flow ($RH \approx 0.5$ %) for 24 h to establish a baseline mass (i.e., where water content is assumed to be zero). Samples were tested for total suction characteristics by ramping the relative humidity in the chamber from approximately 0.5 to 90 % in increments of roughly 10 %. Water content values during testing were calculated relative to the baseline mass by recording the amount of water that was adsorbed or desorbed at each step.

Filter Paper Testing

Filter paper tests were conducted using the "non-contact" method following ASTM D 5298. Tests for Wyoming smectite and Georgia kaolinite were conducted on fractions passing the No. 200 sieve. Tests for the Soda Lakes materials were conducted on fractions passing the No. 4 sieve. In all cases, sub-samples were prepared at various water contents using two procedures: (1) relatively high water content samples were prepared by mixing the materials with distilled water in a food mixer, and (2) relatively dry samples were prepared by placing initially oven-dried samples in the headspace of a chamber filled with distilled water ($RH \approx 100$ %) for various amounts of time. To ensure homogeneity in water content, the samples were periodically stirred as water vapor was adsorbed and weighed to determine water content. When desired water contents were reached, the samples were removed from the chamber and sealed in glass jars with one Whatman No. 42 filter paper suspended above the soil on a piece of plastic mesh. Papers were calibrated prior to suction testing by equilibration over salt solutions of known concentration (Fig. 4). During testing, the papers were allowed to equilibrate with the soil samples for a period of ten days, whereupon the water content of the paper was measured gravimetrically and used to calculate total suction.

TABLE 1—*Summary of mineralogical and engineering properties of the test soils.*

Soil	Mineralogy[a] (qualitative)	% Clay[b]	Atterberg Limits		Activity[c]	USCS Classification
			LL	PI		
Georgia Kaolinite	K	35%	45%	17%	0.48	CL
Wyoming Smectite	discrete S, trace Qtz.	100%	485%	353%	3.53	CH
Soda Lakes Claystone	mixed layer I/S, trace K, Qtz., Gypsum	55%	49%	25%	0.45	CL
Soda Lakes Smectite	discrete S, trace K, Qtz., K-Feld	90%	111%	76%	0.85	CH

[a]I = Illite; S = Smectite; K = Kaolinite; Qtz. = Quartz; K-Feld = K-Feldspar.
[b]Percent by hydrometer analysis with hydraulic diameter <2μm.
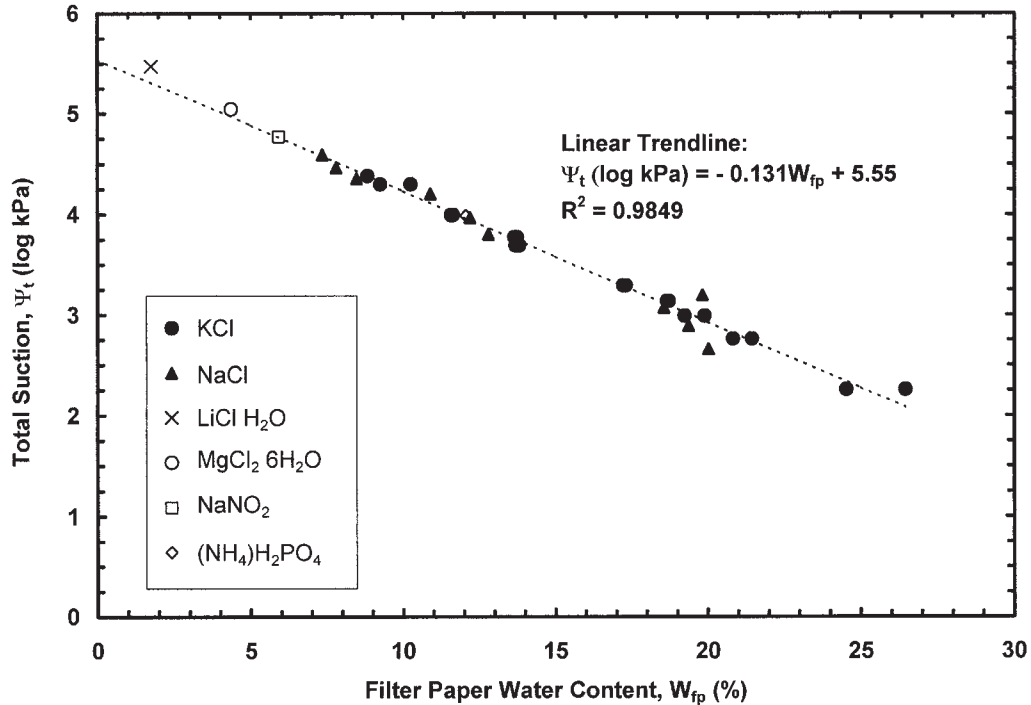[c]Ratio of plasticity index to percent clay size.

FIG. 4—*Calibration curve for Whatman No. 42 filter paper, lot No. 917999.*

Results

Total suction characteristic curves determined using the humidity system for the four test materials are shown in Fig. 5. Total suction values were calculated using Eq 1 based on the relative humidity and temperature in the chamber at steady state for each increment in *RH*. Figure 5a shows results obtained during both adsorption ("wetting") and desorption ("drying") for the Wyoming smectite and Georgia kaolinite. Figure 5b shows results obtained during adsorption ("wetting") for the locally sampled Soda Lakes materials.

Hysteresis is apparent between the wetting and drying loops for the Wyoming smectite and Georgia kaolinite (Fig. 5a). In general, more water is retained during drying than is adsorbed during wetting. The smectite reaches an equilibrium water content of 18.9 % at a minimum total suction of 10 715 kPa (4.03 log kPa). The kaolinite reaches a water content of only 4.4 % at 14 125 kPa (4.15 log kPa). The Soda Lakes claystone adsorbs a maximum of 6.2 % water. The Soda Lakes smectite adsorbs a maximum of 19.9 % water. Results from two independent trials for the Soda Lakes smectite are nearly identical, reflecting the repeatability of the measurement system.

Characteristic curves obtained using the filter paper method are superimposed with measurements obtained using the humidity system on Fig. 6a and Fig. 6b. The "drying" portions of the humidity system results have been removed because the sample preparation procedure for filter paper testing involved a wetting process. With the exception of the Soda Lakes materials, the filter paper results agree very closely with the humidity system results. The discrepancy between results for the Soda Lakes clays may be a reflection of the fact that powdered samples (< No. 200) were used for the humidity system tests and aggregated samples (< No. 4) were used for filter paper tests.
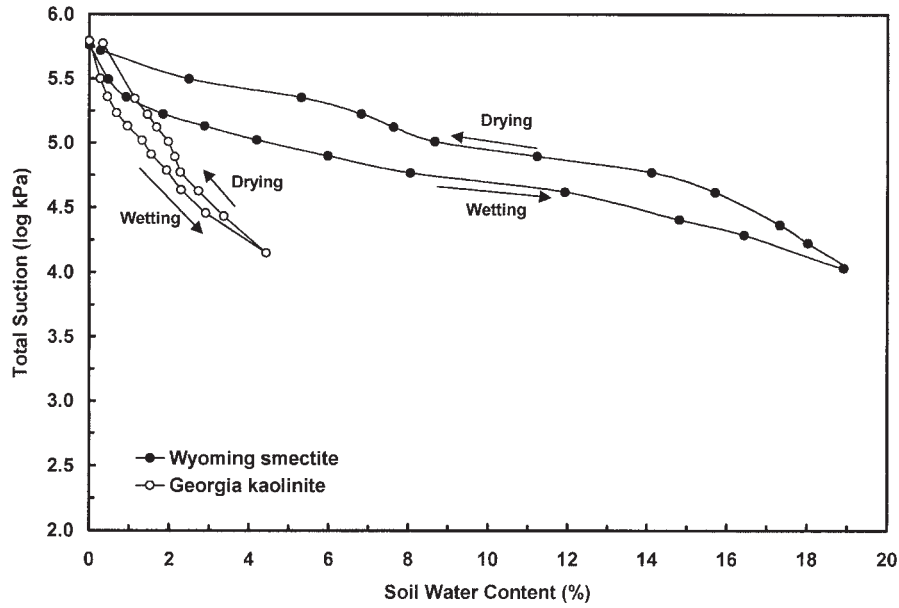
Applications

Assessment of Swelling Potential

Following an expansive soil classification methodology proposed by McKeen (1992), swelling potential may be characterized based on the "slope" of the wetting portions of measured total suction characteristic curves. McKeen refers to this slope as the "total suction-water content index," or $\Delta\Psi_t/\Delta w$. Soils exhibiting relatively flat slopes tend to adsorb more water for a given change in suction and are thus characterized with higher swelling potential. Table 2 delineates five categories proposed by McKeen for swelling potential classification based on the total suction-water content index.
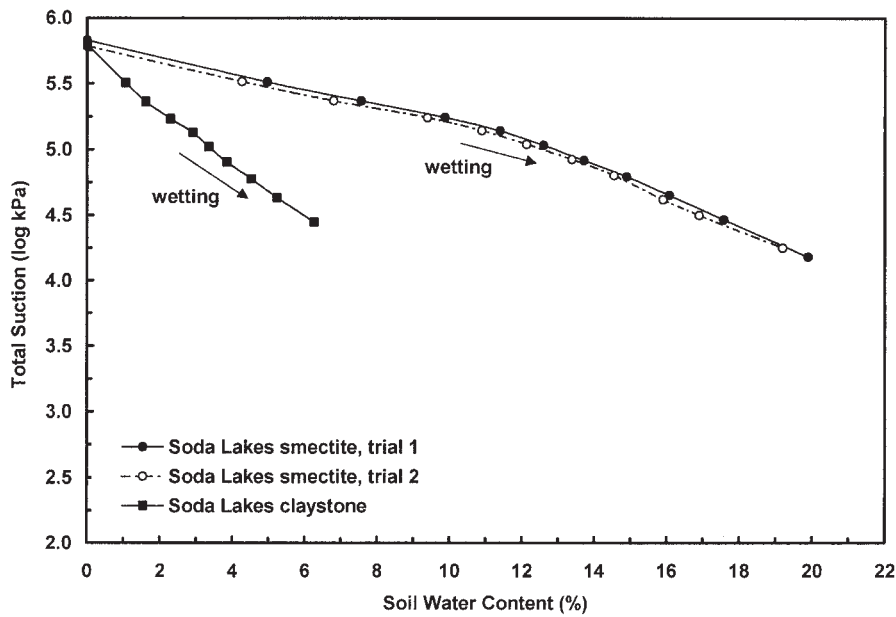
The four test soils were characterized according to McKeen's methodology by approximating straight-line segments through the characteristic curves shown on Fig. 6. Line segments were approximated through both the automated humidity system data and the filter paper data for comparison. Table 3 shows values of $\Delta\Psi_t/\Delta w$ for the four soils as well as McKeen's corresponding classification using data from both measurement techniques. Nearly identical results are obtained. Two additional columns are included where the soils are classified according to classic methodologies based on grain size and Atterberg limits testing (Seed et al. 1962; Chen 1988).

Adsorption Kinetics

Because soil water content and relative humidity are constantly monitored during testing, measurements obtained using the automated system afford study of adsorption kinematics in expansive clay soils. Figure 7a shows the water content of Soda Lakes smectite as a function of equilibrium time for each increment in relative humidity from 1 to 90 %. The water content at time $t = 0$ represents the initial water content for each increment. The adsorption process
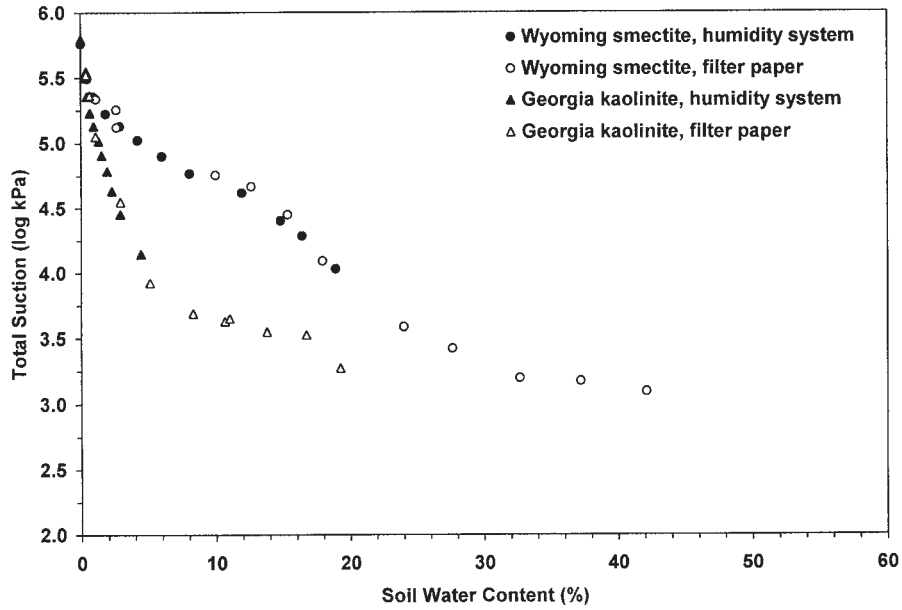
(a)

(b)

FIG. 5—*Measured total suction characteristic curves for* (a) *Wyoming smectite and Georgia kaolinite, and* (b) *for Soda Lakes smectite and Soda Lakes claystone.*

for each increment follows an exponential function. With the exception of the final humidity increment from 81 to 89 %, the equilibrium water content is usually reached within 12 h.
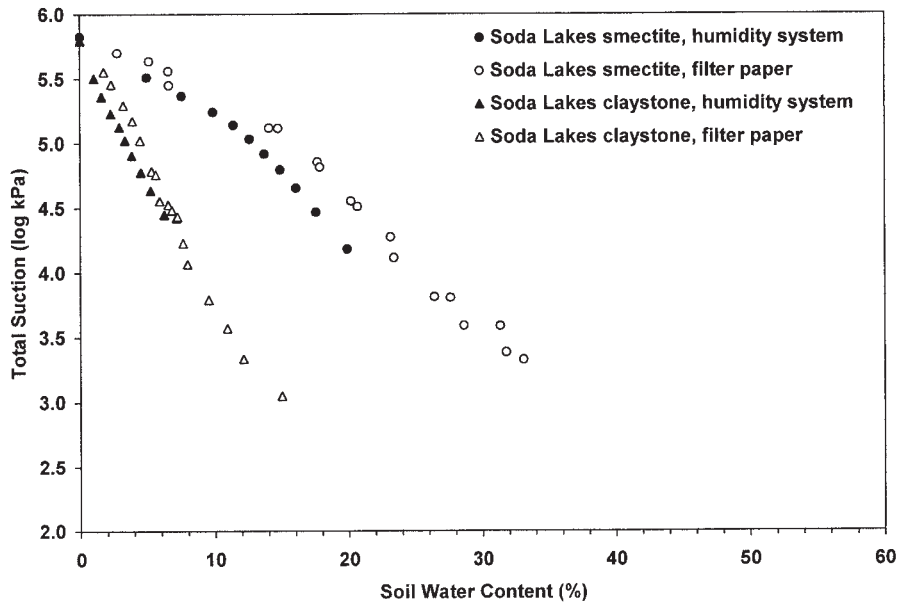
Although the relative humidity change for each step is roughly the same (8 to 10 %), the corresponding changes in soil water content are very different and are clearly a function of the initial relative humidity. Figure 7b shows the overall change in water content for each relative humidity increment. The largest increase in water content (5 %) occurs for the relative humidity increment from 1 to 9 %. As the relative humidity increases, the corresponding water

content for each step decreases to about 1.6 % but increases again when the relative humidity approaches approximately 70 % (Fig. 7b).

The change in water content for each step, together with the corresponding equilibrium time, provides important information for understanding the kinetics of adsorption and desorption processes. Adsorption can be idealized as two concurrent physical processes: water condensation onto the clay particle surface and water evaporation from the clay particle surface. The combined effect of these two processes for the initial layer of adsorbed water on the particle

(a)

(b)

FIG. 6—*Comparison of non-contact filter paper measurements and automated humidity system measurements for* (a) *Wyoming smectite and Georgia kaolinite and* (b) *for Soda Lakes smectite and Soda Lakes claystone.*

TABLE 2—*Summary of McKeen's (1992) expansive soil classification system.*

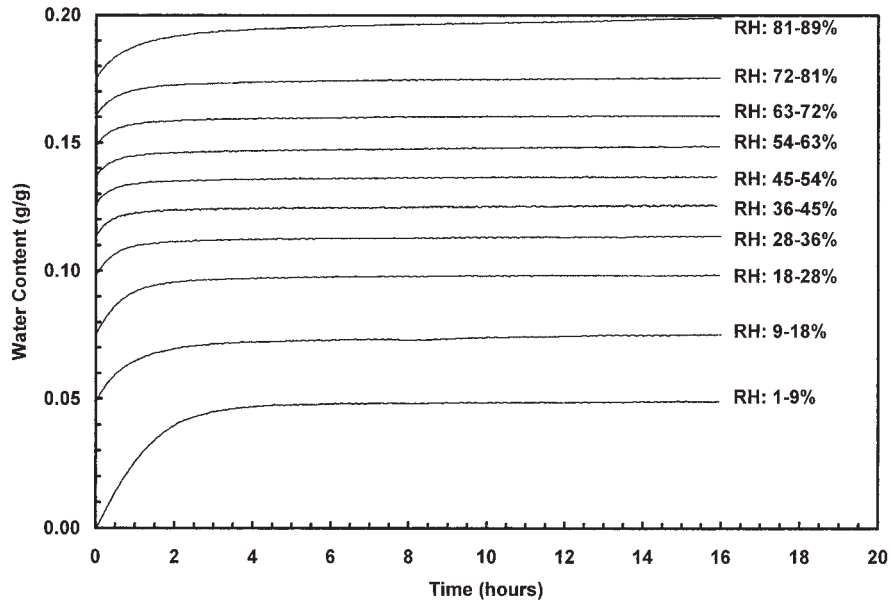| Total Suction–Water Content Index $\Delta\Psi_t/\Delta w$	Category	Swelling Potential (McKeen 1992)
> -6	I	Special Case (Very High)
-6 to -10	II	High
-10 to -13	III	Moderate
-13 to -20	IV	Low
< -20	V	Nonexpansive

surface may be described in terms of first order kinetics by the following equation (Brunauer 1945):

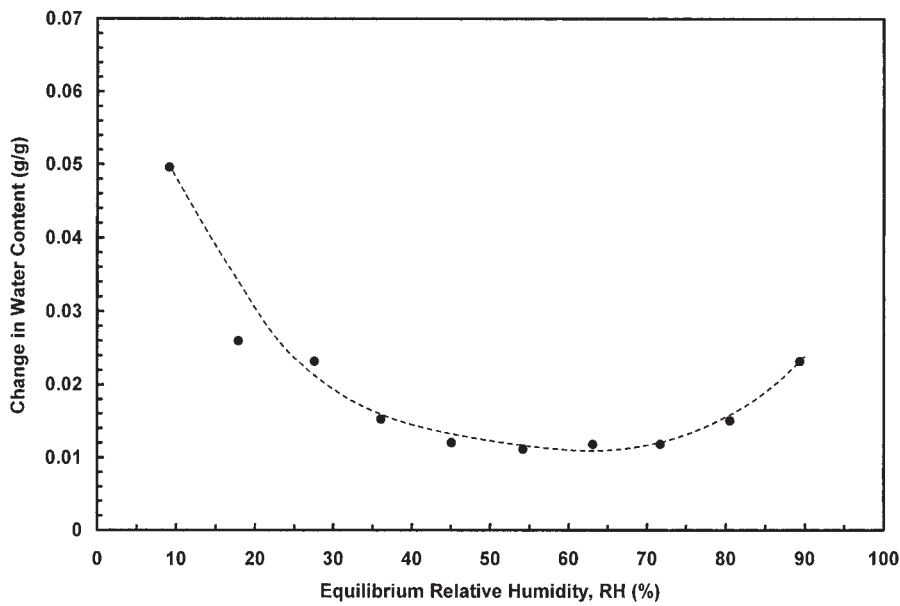$$\frac{dw}{dt} = k_1 (w_m - w) - k_2 w \qquad (2)$$

where w is the change in gravimetric water content (g/g), k_1 is a rate constant associated with condensation, k_2 is a rate constant associated with evaporation, t is the time from the beginning of each step in relative humidity, and w_m is the water content at full particle surface coverage. Imposing the initial condition $w(t_0) =$

TABLE 3—*Swelling potential classification for the four test soils.*

| | $\Delta\Psi_t/\Delta w$ | | Swelling Potential Classification | | |
Soil	Humidity System	Filter Paper	(McKeen 1992)	(Seed et al. 1962)	(Chen 1998)
Georgia kaolinite	−41.0	−41.0	Nonexpansive	Low	Low-Moderate
Wyoming smectite	−8.1	−6.8	High	Very High	Very High
Soda Lakes claystone	−18.8	−18.8	Low	Moderate	High-Moderate
Soda lakes smectite	−8.8	−9.8	High	Very High	Very High

(a)

(b)

FIG. 7—*Incremental water content response of Soda Lakes smectite:* (a) *as a function of time, and* (b) *as a function of equilibrium relative humidity.*

0, and the equilibrium condition $w(t_\infty) = w_e$, where w_e is the equilibrium water content for a given step, the analytical solution of Eq 2 becomes:
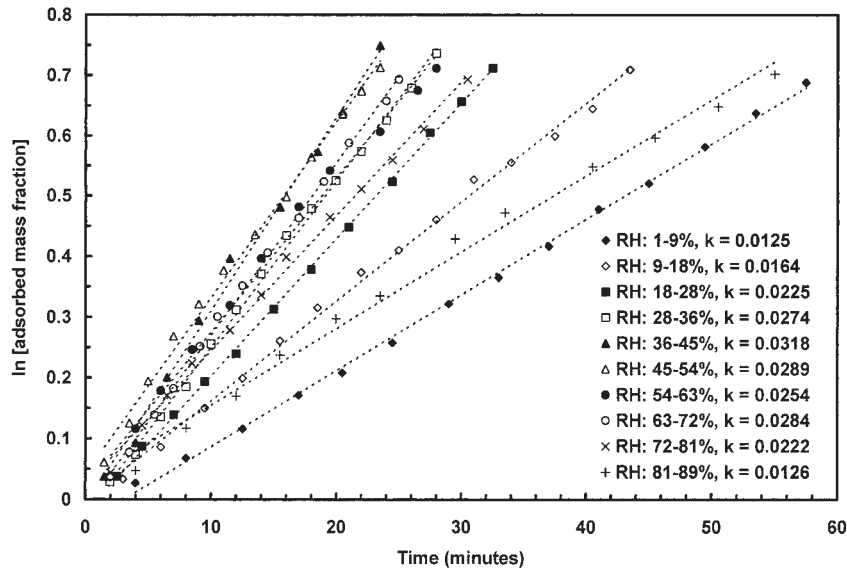
$$w = w_e (1 - e^{kt}) \qquad (3)$$

where $k = k_1 + k_2$.

Equation 3 can be used to evaluate the rate of adsorption for the experimental data shown in Fig. 7a by linearizing Eq 3 as follows:
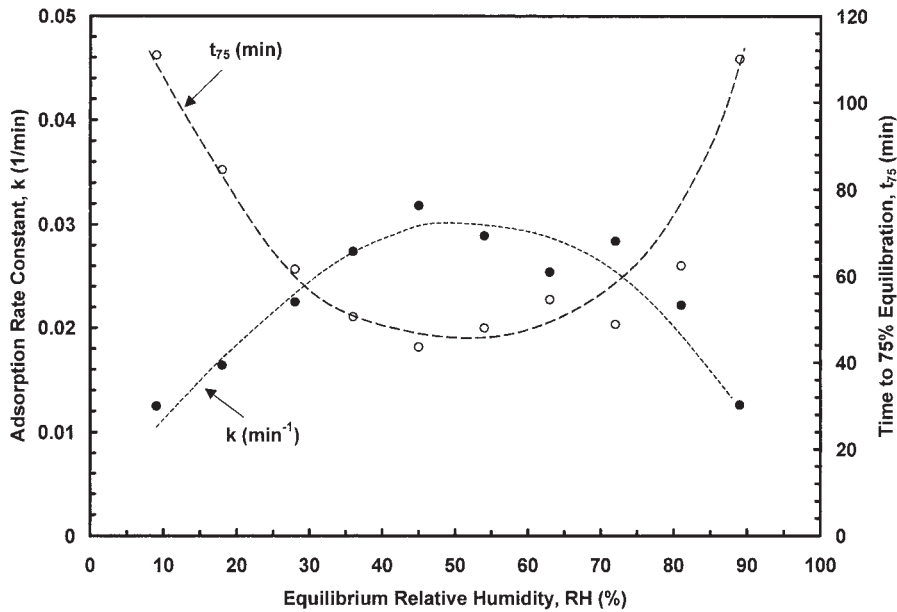
$$\ln \frac{w_e}{w_e - w} = kt \qquad (4)$$

Replotting the data of Fig. 7a in linearized form (Fig. 8a) shows that the adsorption data for the expansive Soda Lakes smectite indeed follows the linear relationship governed by Eq 4. Least-square linear regression analysis (shown as dashed lines in Fig. 8a) yields the adsorption rate constant for each step in relative humidity (see Fig. 8b). Figure 8b also shows the time required for 75 % equilibration (t_{75}) at each step obtained by substituting $w = 0.75w_e$ in Eq 4 (i.e., $t_{75} = 1.386/k$). The adsorption rate constant for the Soda Lakes smectite is a function of the initial relative humidity value and varies from 0.013 min^{-1} (or $t_{75} = 107$ min.) to 0.033 min^{-1} (or $t_{75} = 42$ min.). The adsorption rate constant is relatively small for both low and high relative humidity and reaches its maximum in the middle range of the relative humidity. The relatively low adsorption rate at low humidity may be a reflection of the dominance of surface hydration mechanisms (e.g., Keren and Shainberg 1975), whereas, at high humidity, it may be attributed to capillary condensation mechanisms (e.g., Lowell 1979).

(a)

(b)

FIG. 8—*Kinematics of water adsorption:* (a) *adsorbed mass fraction response for Soda Lakes smectite at various increments in relative humidity, and* (b) *adsorption rate constant as a function of equilibrium relative humidity.*

Summary and Conclusions

An automated experimental system has been developed to measure total suction characteristics for unsaturated clayey soils using relative humidity control. The system allows control of total suction from approximately 700 000 to 7000 kPa by computer-automated proportioning of "wet" and "dry" nitrogen gas in a closed environmental chamber. To develop characteristic curves, the moisture content of soils placed in the chamber is continuously measured with an electronic balance as water is adsorbed or desorbed in response to the applied suction. Humidity variation is controlled to approximately 0.6 % RH, corresponding to a variation in total suction ranging from about 2 % at relatively high suctions to about 6 % at relatively low suctions.

Four types of clay were tested for total suction characteristics using the automated system. Suction characteristics obtained using the "non-contact" filter paper technique are shown to agree very closely with the automated results for two of the materials tested. Discrepancies noted for the remaining two may reflect the sensitivity of the measurements to particle fabric effects (i.e., powdered samples versus aggregated samples). Further research is required in this regard. The humidity system is shown to be of practical value for expansive soil classification and investigations regarding kinetic aspects of water adsorption and desorption by clay.

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