

Automated Measurement of Total Suction Characteristics in High-Suction Range

Application to Assessment of Swelling Potential

William J. Likos and Ning Lu

An automated experimental system to characterize moisture-content-total-suction relationships for unsaturated clayey soils is described. Unlike traditional techniques requiring independent measurement of total suction and moisture content (e.g., thermocouple psychrometry and filter paper), suction is directly controlled and corresponding moisture contents are continuously monitored. The system is applicable for total-suction values ranging between approximately 620 000 and 14 000 kPa. Total suction is controlled during testing by computer-automated rationing of "dry" and "wet" nitrogen gas in a closed environmental chamber. To develop characteristic curves, the equilibrium moisture content of soils placed in the chamber is measured with an integrated electronic balance as water vapor is absorbed or desorbed. The system requires no user intervention and is capable of generating characteristic curves, including wetting and drying loops, in a time span on the order of one to two weeks. Concurrent measurements using the noncontact filter paper method (ASTM D5298) are shown to agree very closely with those obtained from the automated system. Total-suction characteristic curves are compared for a highly expansive smectite clay and nonexpansive kaolinite clay. Hysteresis between the wetting and drying cycles and stepwise dehydration phenomena, which have been noted by previous researchers, are reproduced in the results. Comparison of the smectite and kaolinite characteristic curves demonstrates the system's potential to become a simple, non-labor-intensive, quick, and reliable platform to qualitatively assess the relative swelling potential of clayey soils.

Total soil suction is a macroscopic property that indicates the intensity or energy level with which soil attracts water. Traditionally, soil suction has been defined as being comprised of an osmotic component and a matric component (1, 2). The osmotic component represents attraction of water due to the presence of dissolved salts in the pore fluid while the matric component represents attraction due to the capillary nature of unsaturated soils. Total soil suction is the sum of the osmotic and matric components.

Total suction, which is described in units of pressure (e.g., kilopascals), is fundamentally related to the moisture content of soils. In general, relatively dry soils exhibit high values of suction while relatively moist soils exhibit low ones. The suction-moisture content relationship between these two extremes, often referred to as the suction characteristic curve or soil-moisture characteristic, is well acknowledged by geotechnical engineers as one of the most important parameters governing the mechanical and hydrological behavior of unsaturated soils. For example, matric suction characteristics are often used to model and predict coefficient of permeability functions for unsaturated groundwater flow (2). Total-suction character-

istics have been applied to assess qualitatively and quantitatively the swelling potential of expansive clay soils (3-5).

This paper describes an automated experimental technique to determine total-suction characteristics for clayey soils in the high-suction range. Unlike traditional techniques requiring independent, manual measurement of total suction and moisture content (e.g., thermocouple psychrometry and filter paper), total suction is directly controlled and corresponding equilibrium moisture contents are continuously monitored. The system is capable of precisely controlling total suction between approximately 620 000 and 14 000 kPa. Suction is controlled during testing by computer-automated rationing of "dry" and "wet" nitrogen gas in a closed environmental chamber. To develop total-suction characteristic curves, the moisture content of soils placed in the chamber is measured with an integrated electronic balance as water vapor is absorbed or desorbed. The system requires no user intervention and is capable of generating characteristic curves, including wetting and drying loops, in a time span on the order of 1 to 2 weeks.

To demonstrate the practical implications of the automated system, total-suction characteristics for a highly expansive smectite and a nonexpansive kaolinite are compared. Comparison of results indicates that the system has the potential to become a simple, non-labor-intensive, quick, and reliable platform for qualitative assessment of the swelling potential of expansive soils.

MEASUREMENT OF TOTAL SUCTION

Traditional methods to measure total-suction characteristics suffer from several limitations. In general, the techniques applicable in the relatively high total-suction range, which include thermocouple psychrometry and filter paper methods (2), are labor intensive, time consuming, and of limited range and reliability.

Possibly the largest limitation placed on thermocouple psychrometry is the maximum measurable suction, typically 8000 kPa (6). For clayey soils, which can exhibit suctions extending into the range of hundreds of megapascals (MPa), the measurement range is usually insufficient to fully describe the total-suction moisture characteristic curve.

Other limitations result from requirements for strict temperature control, relatively long equilibration times, and detailed calibrations. Thermocouple psychrometers require that, in order to measure suction to an accuracy of ± 10 kPa, temperature needs to be controlled to 0.001°C (1). Depending on the magnitude of suction, measurement equilibration times may be on the order of hours or last as long as two weeks (7, 8). In addition, each psychrometer must be independently calibrated prior to testing, and, due to inherent problems with corrosion, the calibration often changes over the sensor's lifetime (9).

Noncontact filter paper techniques, which are an inexpensive alternative to psychrometry, can conceivably be applied over the entire total-suction range, that is, from oven dry to completely saturated (ASTM D5298-94, 10, 11). Following the technique, the mass of water vapor absorbed by a filter paper suspended over an unsaturated soil is allowed to come to equilibrium in a closed chamber. The amount of water absorbed by the paper is then related to a total-suction value through a calibration obtained previously by equilibrating filter papers over salt solutions of known total suction.

Although filter paper testing is inexpensive and relatively simple, the technique is indirect, manually operated, and, in the author's experience, requires a great deal of skill to develop a repeatable and reliable testing routine. Filter paper techniques also require seven-day equilibration for each measurement and independent calibration of each batch of paper prior to testing. In addition, although the theoretical range of the method spans the entire suction range, it is shown in the literature that the reliability of the filter paper technique may be questionable at both relatively low (<3000 kPa) and relatively high (>100 MPa) values of total suction (10, 11).

CONTROL OF TOTAL SUCTION

As an alternative to the measurement of total suction, with all of its associated limitations, total suction can be controlled by regulation of relative humidity (RH) in a closed chamber. RH (in percent) is fundamentally defined as the ratio of the partial pressure of water vapor to the saturation pressure of water vapor over a flat surface of pure water at the same temperature (2). For a closed soil-water-vapor system, the RH of the vapor phase is directly related to the free energy state, or total suction, of the soil water. The thermodynamic relationship between total suction, ψ_t (in kilopascals), and RH is described by the following equation:

$$\Psi_t = -\frac{RT}{v_{w0}\omega_v} \ln(RH) \quad (1)$$

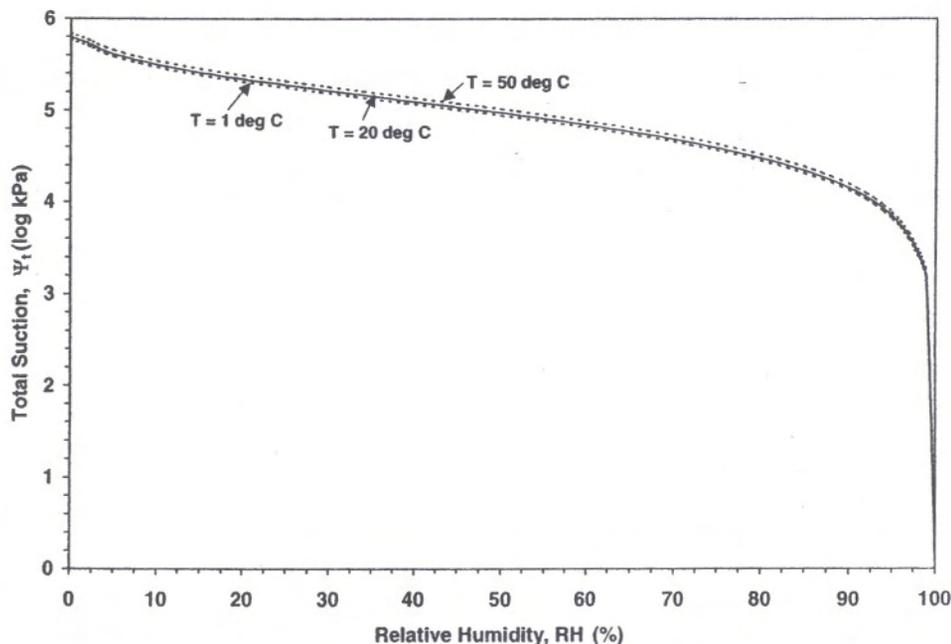


FIGURE 1 Theoretical relationship between RH and total suction.

where

R = the universal gas constant ($8.31432 \text{ J mol}^{-1} \text{ K}^{-1}$),

T = absolute temperature (K),

v_{w0} = the specific volume of water (reciprocal density, m^3/kg), and

ω_v = the molecular mass of water vapor (18.016 kg/kmol).

Figure 1 shows a plot of Equation 1 for $T = 1^\circ\text{C}$, 20°C , and 50°C . As shown in the figure, total suction is equal to 0.0 kPa when the RH is equal to 100 percent, and RH values less than 100 percent indicate the presence of total suction in the soil.

Methods of controlling RH in the laboratory include *isopiestic* (same-pressure) methods, vacuum methods, and two-pressure methods. For isopiestic humidity control, saturated or unsaturated salt or sulfuric acid solutions are allowed to come to thermodynamic equilibrium in small sealed containers (12, 13). Under isothermal conditions, the RH, that is, total suction (Equation 1), in the head space above the solution approaches a fixed, reproducible value that is dependent on the solution concentration. Young (14) provides a comprehensive series of tables and figures describing RH values corresponding to various concentrations of salt or acid solutions.

Alternatively, vacuum methods in which water vapor pressure (RH) is equal to the total pressure as measured by a manometer have been reported in the literature (15). Most recently, two-pressure methods have been developed that involve manipulation of water-saturated wet gas either by varying pressure (16) or by mixing with dry gas (17-19).

AUTOMATED HUMIDITY-CONTROL SYSTEM

General Description

After Chipera et al. (19), the system developed for this study achieves humidity control by computer-regulated mixing of water-saturated or wet nitrogen gas and untreated or dry nitrogen gas. A schematic drawing of the system is shown as Figure 2.

Bottled nitrogen gas is split into separate streams through two computer-controlled mass-flow valves (MKS Instruments, Type

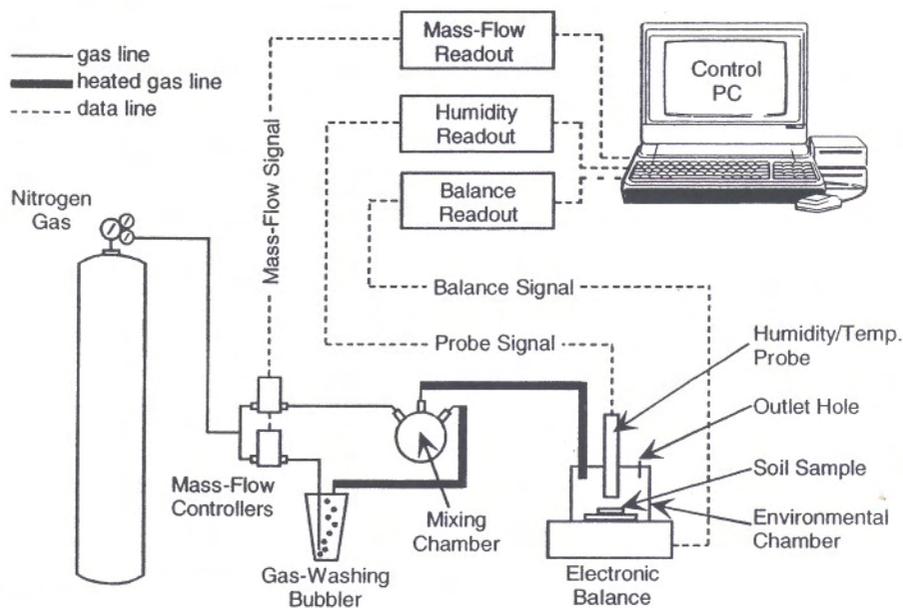


FIGURE 2 Schematic diagram of the automated humidity-control system.

1179A). One gas stream is water saturated by routing it through a gas-washing bottle filled with distilled water at ambient temperature. The water-saturated (wet) and untreated (dry) gas streams are then reintroduced at a combined flow rate of $200 \text{ cm}^3/\text{min}$ in a three-neck, 250-mL mixing flask. The resulting "humid" gas stream is routed to a cylindrical, acrylic environmental chamber that holds a pulverized soil sample ($\approx 0.5 \text{ g}$) on a glass slide. A small outlet hole machined into the top cap of the environmental chamber allows the humid gas to escape after flowing through the chamber. Excluding the outlet hole, the top and bottom of the chamber are sealed with O-rings to ensure a completely isolated environment.

The mixing ratio of the wet and dry gas streams is automatically controlled by monitoring the humidity in the environmental chamber with a relative-humidity/temperature probe (Vaisala Corporation, Model HMI-35 probe; Model HMI-38 data processor). The probe, which communicates with a control PC through dedicated analog channels, measures RH between 0 and 95 percent at 0.01 percent RH resolution. Signals from the probe are interpreted by the control PC to form a feedback loop that is used to generate analog output for regulation of the two mass-flow controllers. For automated control, the system is calibrated prior to testing to develop a relationship between the wet-to-dry gas flow ratio and the RH in the environmental chamber.

An electronic balance (Mettler-Toledo, Model SAG204) is incorporated into the base of the environmental chamber to measure adsorption or desorption of water vapor by the soil (Figure 2). The balance, which is precise to 0.0001 g , is designed with its electronics separate from the sensing element for use in harsh (high-humidity) environments. When steady state at a target value of RH is reached, a serial interface allows the equilibrium mass of the soil to be digitally acquired by the control PC for automatic generation of total-suction characteristic curves.

System Control

A software program written in Labview (National Instruments) allows users to do any one of the following: set the wet and dry gas flow rates

directly, ramp to target humidity values, or program a timed series of humidity steps. Target humidity values are reached using either proportional-gain or proportional-integral-derivative (PID) control algorithms incorporated into the user interface. Under feedback from the humidity probe, the control algorithms ramp the system to setpoint humidity values by dynamically adjusting the wet-to-dry flow ratio according to a predetermined calibration curve that relates the wet-to-dry flow ratio to RH in the chamber.

System Calibration

The system is calibrated by measuring the RH in the chamber (without soil present) as a function of the wet-to-dry gas flow ratio. Figure 3 shows the relationship between wet-to-dry flow ratio ($200 \text{ cm}^3/\text{min}$ combined flow) and measured RH for one such calibration. The trend shown in the figure is linear with a statistical R^2 value of 0.9993. By extrapolation, the RH at 0 percent wet flow (i.e., 100 percent dry flow) is 2.3 percent. Similarly, at 100 percent wet flow, the measured RH is 89 percent. Following Equation 1, these upper and lower RH limits correspond to total-suction values of 509 000 and 157 000 kPa, respectively.

The fact that the lower humidity limit for this particular calibration (2.3 percent RH) is nonzero is probably the result of impurities (i.e., water vapor) in the bottled nitrogen gas. Subsequent calibrations showed that the lower limit varies within the range of 0.5 to 3 percent RH. Future incorporation of a desiccant column (e.g., silica gel) into the dry gas stream may be necessary to both decrease and stabilize the lower humidity limit.

The upper humidity limit (89 percent RH) is controlled by the water-saturation efficiency of the gas-washing bottle (Figure 2). Attempts to enhance water saturation by placing the gas-washing bottle in a bath heated to 35°C led to severe problems with vapor condensation in the gas lines. Even using water traps, it was found that the condensed water periodically blocked the gas lines and resulted in RH fluctuations of up to 6 percent RH in the environmental chamber. In the present system, the wet gas is saturated at ambient

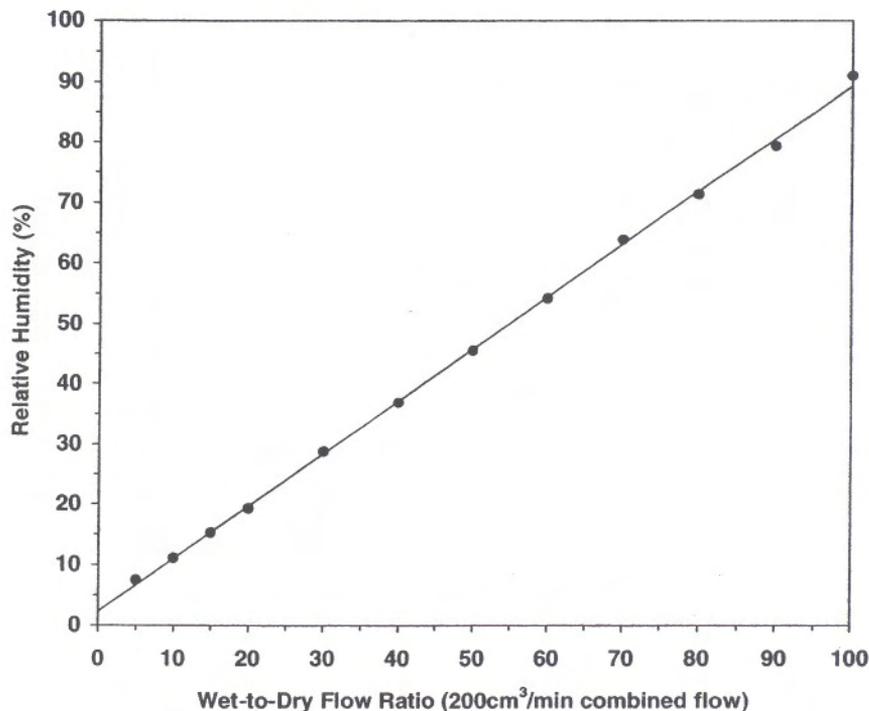


FIGURE 3 Relationship between wet-to-dry flow ratio and measured RH.

temperature. As shown in Figure 2, the wet and humid gas lines are heated to 3 or 4 degrees above ambient using heat tape to ensure that the water remains in the vapor phase.

System Response Without Soil Present

For the present study, the wet and dry gas flow rates were set directly. Figure 4 shows the RH and temperature response of the system as it was stepped from 0 percent wet flow to 100 percent wet flow and back to 0 percent wet flow. The combined gas flow rate was kept constant at 200 cm³/min. The cycle was ramped up and down in 21 individual steps of approximately 10 percent RH and was completed in about 16 days. The average upper and lower RH limits for the cycle were 1.1 percent RH and 90 percent RH, respectively. Following Equation 1, these values correspond, respectively, to total-suction values of 609 000 and 14 000 kPa.

The time required to reach steady state after each step is on the order of 1 h and does not appear to be dependent on the absolute value of RH or on the direction of the step. At steady state, the RH does not deviate by more than 0.6 percent RH. The temperature in the environmental chamber does not deviate by more than 0.75°C over the entire 21-step cycle. Comparison of the wetting and drying portions of the cycle indicates that there is a small amount of hysteresis in the response. On average, RH values measured during the down (drying) cycle are about 1 percent RH higher than those for identical wet-to-dry flow ratios during the up (wetting) cycle.

During the design phase of the system, there was some concern that air currents created by the gas-flow or ambient-pressure gradients entering the outlet hole of the environmental chamber (Figure 2) might cause fluctuations in the electronic-balance measurement. However, by limiting the combined flow rate of the wet and dry gas to 200 cm³/min during testing and by machining the diameter of the gas outlet

hole to a very small dimension (≈ 0.5 mm), these concerns were effectively eliminated. Observation of the balance response during the 21-step cycle showed that the measurement remained stable to 0.1 mg.

System Response with Soil Present

When soil is present in the environmental chamber, it will absorb moisture provided by the humid gas, depress the RH, and affect the RH equilibration time. The adsorption of water by the soil is also a time-dependent process. Therefore, during total-suction characteristic testing the question arises whether the overall equilibration time for a given step in RH is controlled by the chamber RH or the soil water content.

To determine the system response with soil present, kaolinite and smectite clay samples were oven dried for 72 h at 105°C, placed in the environmental chamber, equilibrated for 24 h under 0 percent wet flow, and ramped directly to 90 percent wet flow. Figures 5a and 5b show the chamber-humidity and soil water-content responses for the kaolinite and smectite, respectively. Both figures show that the overall response time is dominated not by the humidity equilibration but rather by the absorption of water by the soil. For the kaolinite (Figure 5a), steady state humidity at 90 percent wet flow (≈ 76 percent RH) was reached in approximately 100 min. Conversely, steady-state water content (≈ 2 percent W_w) was reached in approximately 160 min, a 1-h lag. The smectite (Figure 5b) not only absorbed more water for an identical increase in RH, but also required more time to do so. For the smectite, steady-state humidity at 90 percent wet flow (≈ 77 percent RH) was reached in approximately 250 min while steady-state water content (≈ 13 percent W_w , gravimetric soil water content) was reached in approximately 1,000 min, a 12.5-h lag. Based on this series of tests, it was decided that at least 6 h would be allotted for equilibration of the kaolinite samples during the total-suction char-

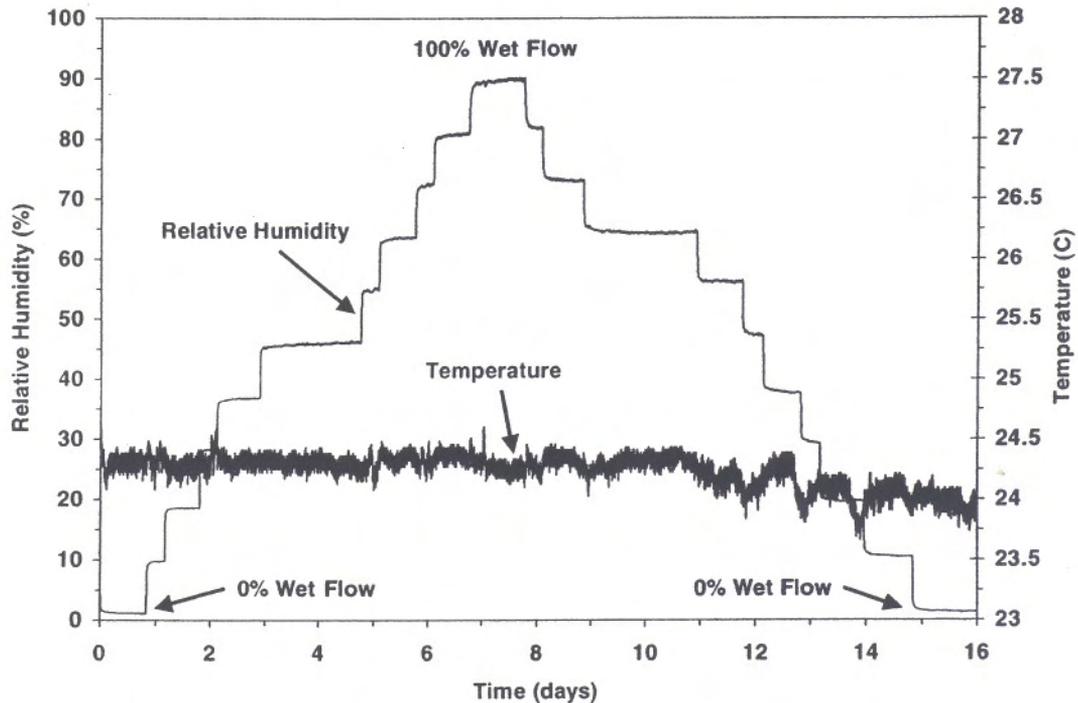


FIGURE 4 Typical response cycle of the humidity-control system.

acteristic testing described in the following section. Similarly, at least 24 h would be allotted for equilibration of the smectite.

TESTING PROGRAM

To evaluate the measurement system, samples of kaolinite and smectite clay minerals were tested for complete (adsorption and desorption) total-suction characteristics. A concurrent series of noncontact filter paper tests was performed following the standard test for measuring soil potential (ASTM D5298-94) and compared with the automated measurements to verify the accuracy of the system.

Description of Soils

Smectite and kaolinite were chosen for analysis because they exhibit entirely different swelling characteristics. Smectite is a common and well-known expanding clay mineral with a 2:1 crystalline interlayer structure (20). When water or water vapor is introduced to smectite, water molecules penetrate between the particle interlayers in an effort to satisfy hydration energies on the interlayer surfaces and absorbed interlayer cations (21-23). As a result, the mineral swells. Kaolinite, on the other hand, is a nonswelling clay mineral. Particles of the kaolinite group consist of basic 1:1 units stacked in successive layers bonded by both van der Waals forces and hydrogen bonds (20). The bonding is sufficiently strong so that there is no interlayer swelling.

Powdered samples of bentonite and kaolin clay minerals were obtained and tested for mineralogy using X-ray diffraction. Tests on random and oriented mounts that included both heat and ethylene

glycol treatments were run following procedures described by Moore and Reynolds (24). Analysis of the results showed that the bentonite was comprised entirely of pure smectite with trace amounts of quartz. The kaolinite was found to be relatively pure and well crystallized.

Total-Suction Characteristics Testing

To prepare sample mounts for testing in the humidity-control system, 0.3 to 0.5 g of the smectite and kaolinite were distributed onto the center of preweighed 5- \times -5-cm glass slides. A second glass slide was used to spread the samples out evenly and compress them to an overall height of around 2 mm. The mounts were then dried to constant mass in a 105°C oven and independently transferred to the environmental chamber for testing. Prior to testing, the samples were subjected to 0 percent wet flow (100 percent dry flow) for 24 h to reasonably ensure that any water absorbed during the transfer from the oven to the environmental chamber was removed. Each was then tested for total-suction characteristics by ramping the RH in the chamber through a 21-step cycle from 0 percent wet flow to 100 percent wet flow and back to 0 percent wet flow. The corresponding equilibrium water content at steady state for each step was recorded by the control PC.

Concurrent testing using the noncontact filter paper method (ASTM D5298-94) was conducted for two reasons: to verify the automated-system data in the high suction range by direct comparison and to extend the range of the measured characteristic curves to values of total suction as low as 100 kPa. In order to accomplish these tasks, it was necessary to prepare samples of kaolinite and smectite with water contents ranging from about 0 to 60 percent.

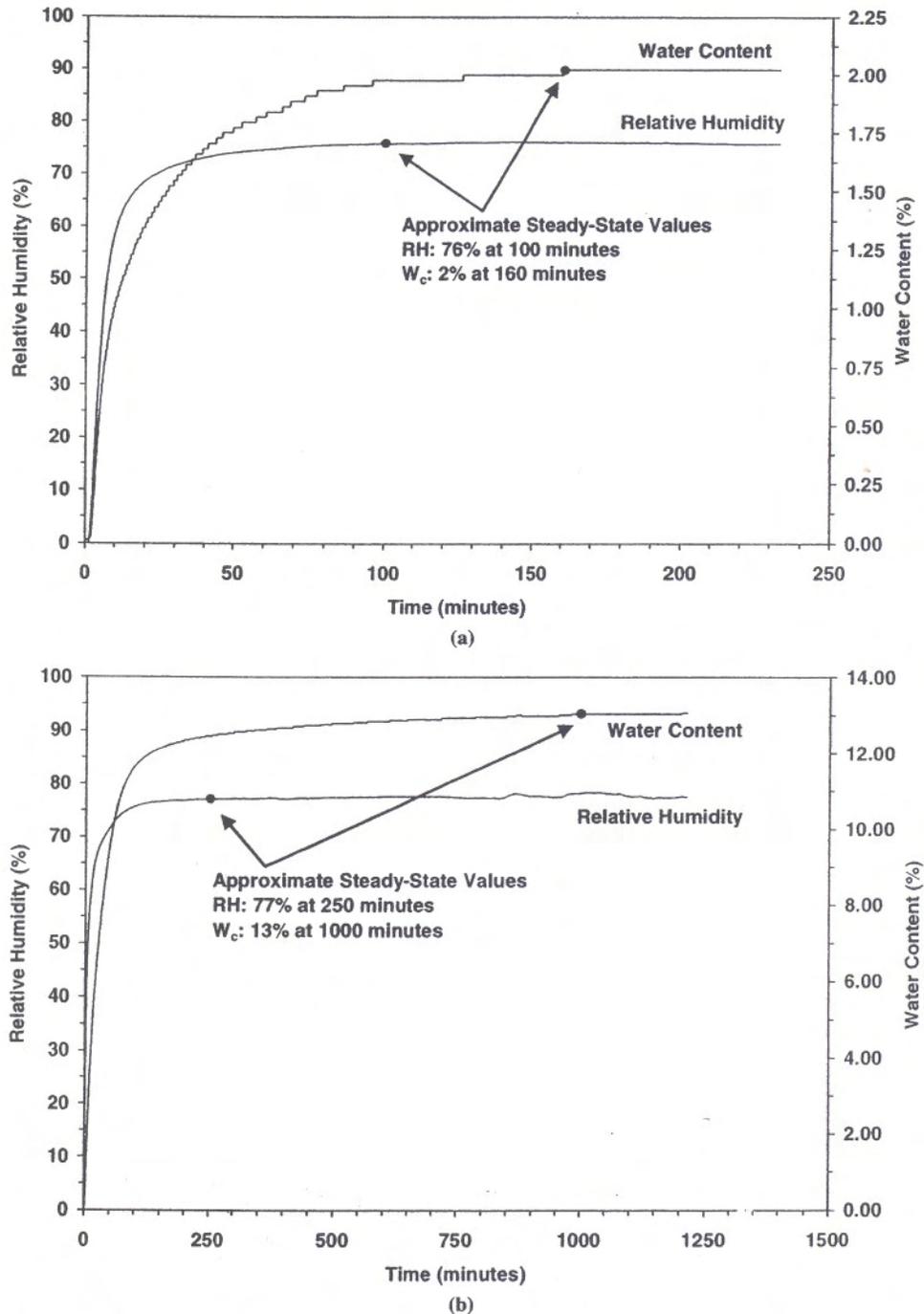


FIGURE 5 Chamber humidity and soil water content response to ramping from 0 to 90 percent wet flow for (a) kaolinite and (b) smectite.

The clays were initially oven dried for 72 h at 105°C and then split into 50-g subsamples. Water was added in one of two ways. One batch of subsamples was placed into glass jars and exposed to the laboratory atmosphere (RH \approx 30 percent) so that water vapor could be directly absorbed. The samples were stirred every few minutes to ensure that the moisture absorption was as homogeneous as possible. At successive times ranging from 2 min to 24 h, a calibrated Whatman No. 42 filter paper was placed in the headspace over the soil in a chosen jar and that jar was sealed. The result was a series of sam-

ples at relatively low values of water content (i.e., <10 percent W_c for the smectite and <4 percent W_c for the kaolinite). Total suction measured with the filter paper after 7-day equilibration was used for direct comparison with the automated-system data. A second batch of samples was prepared at relatively high values of water content by directly mixing the oven-dried subsamples with distilled water using a food mixer. These samples were tested for total suction and water content to extend the measured characteristic curves to values of total suction as low as 100 kPa.

RESULTS

Automated System Results

Figure 6a shows the relationship between equilibrium soil water content and RH measured using the automated system for wetting and drying cycles ranging from approximately 1 percent RH to 90 percent RH. Figure 6b shows total-suction characteristic curves for the kaolinite and smectite. Total suction, shown in log kPa, was

computed from the equilibrium RH values on Figure 6a using Equation 1.

Filter Paper Results

Figure 7 shows the results of the filter paper testing series. The filter paper results for samples at relatively low values of water content are superimposed with the total-suction characteristic curves

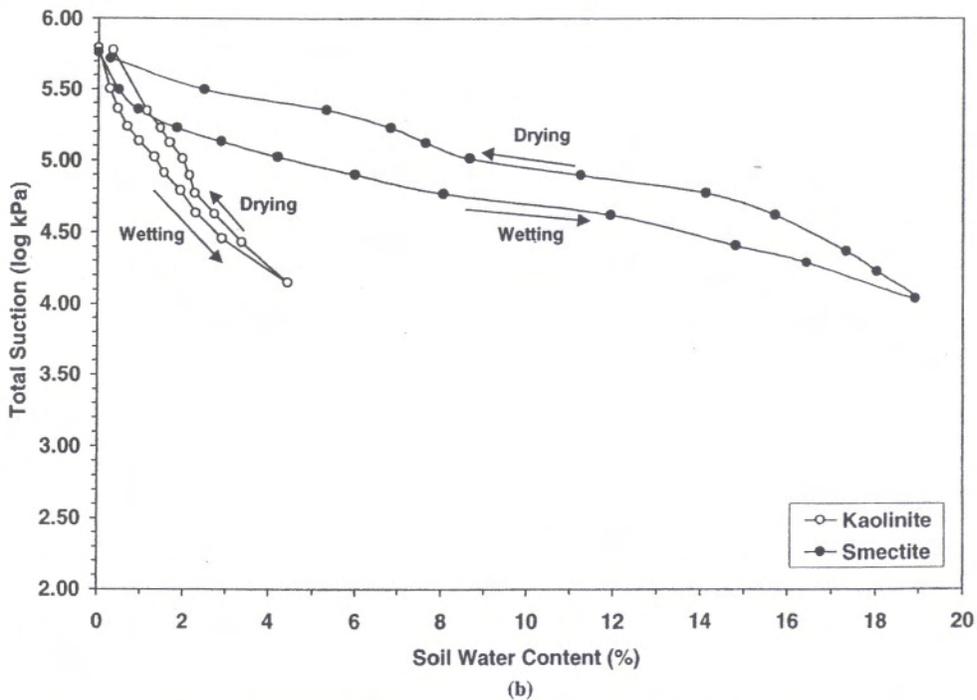
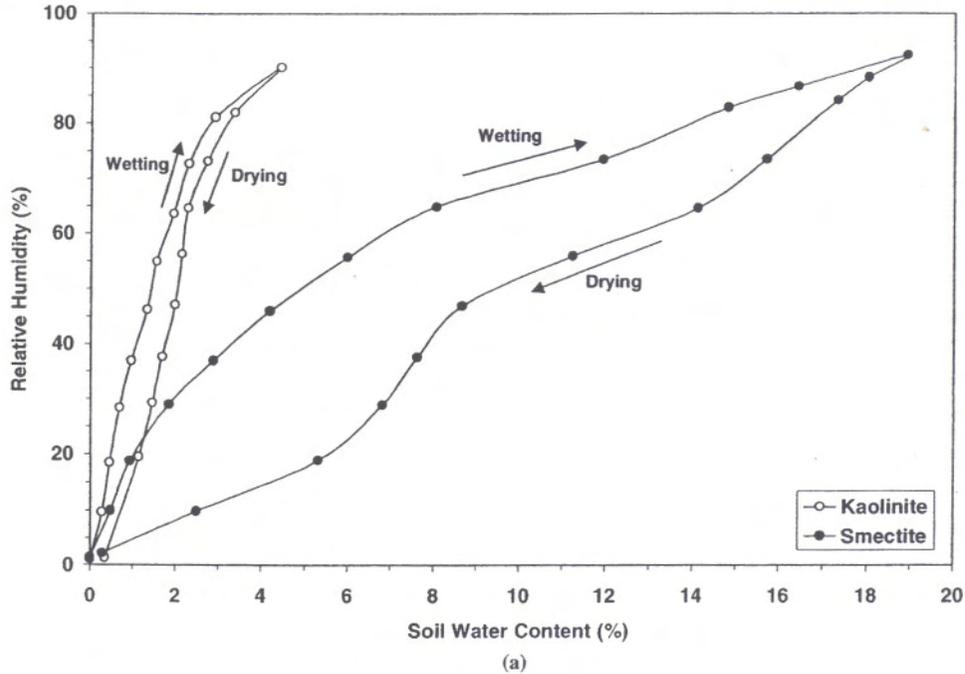


FIGURE 6 (a) Relationship between RH and soil water content for samples of kaolinite and smectite; (b) total-suction characteristic curves for kaolinite and smectite measured using the automated system.

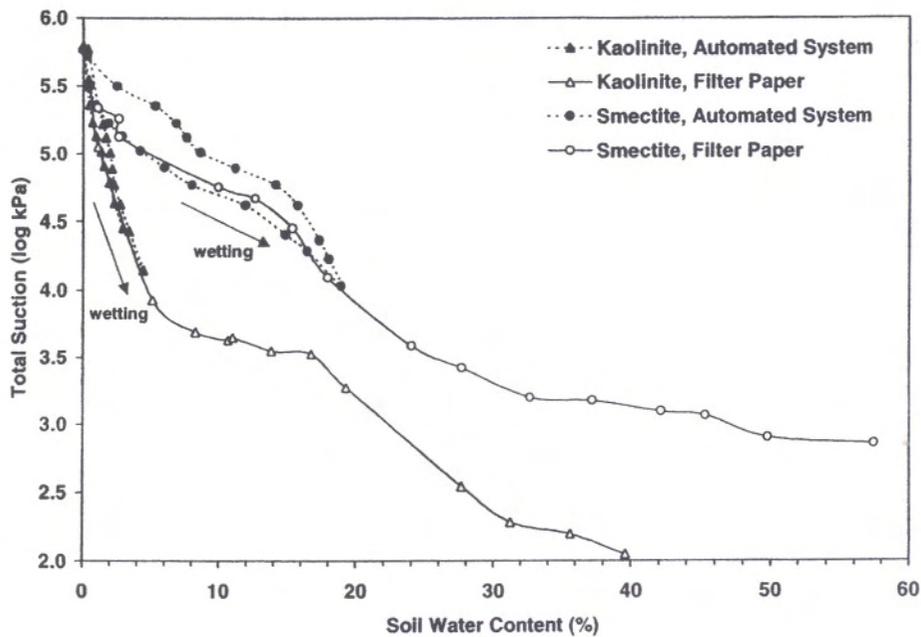


FIGURE 7 Comparison of total-suction characteristic curves measured using the automated system and the noncontact filter paper technique.

obtained using the automated system (Figure 6b). Because the sample preparation procedures for filter paper testing involved a wetting process, the results agree very closely with the wetting data measured using the automated system. The filter paper results at relatively high values of water content complete the characteristic curves for the entire range of total suction.

DISCUSSION OF RESULTS

Three features are readily apparent from the data shown in Figures 6a and 6b:

1. There is an appreciable amount of hysteresis between hydration (wetting) and dehydration (drying) cycles;
2. The hydration and dehydration paths of the smectite exhibit a nearly stepwise pattern (the pattern is most evident on the dehydration path, Figure 6a); and
3. The slope of the kaolinite total-suction characteristic curve (Figure 6b) is much more steep than that of the smectite; that is, total suction is much more sensitive to water content.

The first two of these observations are not unique to this study.

Hysteresis Phenomenon

Hysteresis between wetting and drying cycles of matric suction characteristics is a well-known phenomenon. Hysteresis has been observed for both fine- and coarse-grained soil behavior (2, 25). The physical effects generally considered to be responsible for the phenomenon include the "ink-bottle" effect, which arises from differences in pore geometry and meniscus contact angle during wetting and drying, entrapped air, and shrinking and swelling (2, 25).

Hysteresis for total-suction characteristics at relatively high values of suction has also been observed in the past (13, 19, 22, 26–28). In general, total-suction hysteresis loops exhibit more vapor sorbed for a given value of suction during dehydration than hydration. The author's data in Figure 6 support this generalization. Van Olphen (22) noted significant hysteresis in hydration and dehydration paths of sodium vermiculite for RH cycles ranging from 0 to about 100 percent RH. The hysteresis was attributed to differences in the activation energy required to hydrate and dehydrate exchangeable interlayer cations. A thermodynamic analysis was provided to support the hypothesis. Keren and Shainberg (26) measured similar behavior for sodium- and calcium-saturated smectite. The study showed that the hysteresis was more predominant for the sodium-saturated clay and thus demonstrated the importance of exchangeable cation hydration as a controlling water-sorption (swelling) mechanism.

Stepwise Dehydration Phenomenon

The stepwise nature of the smectite characteristic curve is particularly evident in the dehydration path shown in Figure 6a. Relatively flat portions of the trend are apparent between about 0 and 6 percent water content and between 9 and 15 percent water content. At 19 percent water content, the curve also seems to begin to flatten out. Between the flat portions, the trend follows a series of steps. Several researchers in the past have observed this phenomenon, most predominantly for expanding clay minerals such as the author's smectite (29–35).

It is likely that the pattern results from the removal of successive "monolayers" of water molecules from between the clay particle interlayers. By considering geometry on the molecular scale, Barshad (29) showed that one, two, and three "monolayers" of water correspond to fixed distances of approximately 12, 15, and 18 between smectite particle interlayers (i.e., basal spacing). There is sufficient evidence to support the notion that the basal spacing of smectite jumps in a stepwise fashion from one value to the next

as successive layers of water are absorbed or desorbed (29–35). Whether this jump is discrete or gradual remains unclear; however, this type of stepwise behavior in both smectite hydration and dehydration has been observed experimentally using humidity-controlled X-ray diffraction testing (20, 30–32) and differential thermal analysis (35). Other investigators have noted the behavior through controlled-humidity absorption and desorption testing similar to that presented in this paper (15, 26, 27, 33).

Karaborni et al. (34) used a molecular-dynamics numerical simulation to model the basal spacing and water content of smectite during hydration. The study showed that zero, one, and two layers of water absorbed between the particle interlayers correspond to bulk water contents of 0, 10, and 19 percent, respectively. Interestingly, these values agree closely with the data in Figure 6a. Values of 0 and 9 percent water content mark the beginning of two flat portions of the curve. It also appears that a value of 19 percent water content defines the beginning of a third flat portion. It is likely that these points mark the transition points for the successive removal of water layers. The fact that the flat portions of the author's data trend are not perfectly flat indicates either that the jump from one hydration state to another is gradual rather than discrete or that the jump does not occur homogeneously throughout the entire sample.

Slope of the Total-Suction Characteristic Curves

The fact that the slope of the total-suction characteristic curve of the kaolinite (Figure 6b) is much steeper than that of the smectite demonstrates the automated system's potential as a tool to qualitatively assess the swelling potential of clayey soils. Because the system is automated, it has a distinct advantage over existing classification methodologies based on total-suction testing.

Recently, several methodologies have been developed to characterize swelling potential based on total-suction characteristic testing (3–5). The intent of the classification schemes has been to provide a rational basis for engineering design and hazards mitigation by qualitatively grouping soils into simple descriptive categories, for example, nonexpansive, moderately expansive, and highly expansive. For example, McKeen (5) introduced a classification system based on noncontact filter paper testing where the slope of the total-suction characteristic curve between 100 000 and 100 kPa is used as an index to group soils into one of several swelling-potential categories. Soils with steeper slopes are categorized as having less swelling potential than those with flatter slopes.

In general, the existing classification schemes (3–5) have been empirically derived. There is, however, a fundamental theoretical basis. Thermodynamically, the net work done during water absorption is related to the area under the total-suction characteristic curve (22). Accordingly, soils that show steeper slopes tend to liberate less work for a given change in water content than those that show flatter slopes. In the context of swelling soils, the liberated work may take the form of either volume change or swelling pressure.

SUMMARY AND CONCLUSIONS

An automated experimental system has been developed to measure total-suction characteristics for unsaturated clayey soils. Unlike traditional techniques to determine characteristic curves that rely on measurement of total suction, the system relies on control of total suction. The system allows accurate control of total suction ranging

from approximately 620 000 to 14 000 kPa by computer-automated regulation of wet and dry nitrogen gas in a closed environmental chamber. The moisture content of soils placed in the chamber is continuously measured as water is absorbed or desorbed in response to the applied suction. A series of tests was conducted to show that the response time of the system is controlled by the time-dependent absorption (or desorption) of water by the soil. Depending on the type of soil tested, entire total-suction characteristic curves including wetting and drying cycles can be obtained in a time frame on the order of 1 or 2 weeks. Total-suction moisture characteristics obtained using the noncontact filter paper technique for samples of kaolinite and smectite are shown to agree very closely with total-suction and moisture-content data obtained using the automated system. The results also confirm hysteresis and stepwise dehydration phenomena observed by previous researchers. The potential of the system as an automated tool for the qualitative assessment of swelling potential is demonstrated by comparing the slope of total-suction characteristics for a nonexpansive kaolinite and a highly expansive smectite.

ACKNOWLEDGMENT

Support for this research was provided by the National Science Foundation.

REFERENCES

1. Krahn, J., and D. G. Fredlund. On Total, Matric, and Osmotic Suction. *Soil Science*. Vol. 114, No. 5, 1972, pp. 339–348.
2. Fredlund, D. G., and H. Rahardjo. *Soil Mechanics for Unsaturated Soils*. Wiley and Sons, 1993.
3. Johnson, L. D. *Evaluation of Laboratory Suction Tests for Prediction of Heave in Foundation Soils*. Report WES-TR-S-77-7. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1977.
4. Johnson, L. D., and D. R. Snethen. Prediction of Potential Heave of Swelling Soil. *Geotechnical Testing Journal*, Vol. 1, No. 3, 1979, pp. 117–124.
5. McKeen, R. G. A Model for Predicting Expansive Soil Behavior. In *Proc., 7th International Conference on Expansive Soils*, Aug. 3–5, 1992, Dallas, Tex., Vol. 1, 1992, pp. 1–6.
6. Brown, R. W., and D. L. Bartos. *A Calibration Model for Screen-Caged Peltier Thermocouple Psychrometers*. Research Paper INT-293. U.S. Department of Agriculture, 1982.
7. Richards, B. G. Behavior of Unsaturated Soils. *Soil Mechanics: New Horizons* (I. K. Lee, ed.), New York, American Elsevier, 1974, pp. 112–157.
8. Madsen, H. B., C. R. Jensen, and T. Boyson. A Comparison of the Thermocouple Psychrometer and the Pressure Plate Methods for Determination of Soil Water Characteristic Curves. *Journal of Soil Science*, Vol. 37, 1986, pp. 357–362.
9. Hamilton, J. M., D. E. Daniel, and R. E. Olson. Measurement of Hydraulic Conductivity of Partially Saturated Soils. *Permeability and Groundwater Contaminant Transport*, Special Technical Publication 746 (T. F. Zimmie and C. O. Riggs, eds.), ASTM, 1981, pp. 182–196.
10. Fawcett, R. G., and N. Collis-George. A Filter-Paper Method for Determining the Moisture Characteristics of Soil. *Australian Journal of Experimental Agriculture and Animal Husbandry*, Vol. 7, April 1967, pp. 162–167.
11. Houston, S. L., W. N. Houston, and A.-M. Wagner. Laboratory Filter Paper Suction Measurements. *Geotechnical Testing Journal*, Vol. 17, No. 2, 1994, pp. 185–194.
12. Churchman, G. J. Interlayer Water in Halloysite. Ph.D. dissertation. University of Otago, Australia, 1970.
13. Newman, A. C. D. The Interaction of Water with Clay Mineral Surfaces. *Chemistry of Clays and Clay Minerals*, Mineralogical Society Monograph No. 6 (A. C. D. Newman, ed.), 1987, pp. 237–274.
14. Young, J. F. Humidity Control in the Laboratory Using Salt Solutions: A Review. *Journal of Applied Chemistry*, Vol. 17, 1967, pp. 241–245.

15. Mooney, R. W., A. G. Keenan, and L. A. Wood. Adsorption of Water Vapor by Montmorillonite: I. Heat of Desorption and Application of BET Theory. *Journal of the American Chemical Society*, Vol. 74, 1952, pp. 1367-1371.
16. Hardy, B. Two-Pressure Humidity Calibration on the Factory Floor. *Sensors*, July 1992, pp. 15-19.
17. Kühnel, R. A., and S. J. van der Gaast. Humidity-Controlled Diffractometry and Its Applications. *Advances in X-Ray Analysis*, Vol. 36 (J. V. Gilfrich et al., eds.), 1993, pp. 439-449.
18. Hashizume, H., S. Shimomura, H. Yamada, T. Fujita, H. Nakazawa, and O. Akutsu. X-Ray Diffraction System with Controlled Relative Humidity and Temperature. *Powder Diffraction*, Vol. 11, 1996, pp. 288-289.
19. Chipera, S. J., J. W. Carey, and D. L. Bish. Controlled-Humidity XRD Analyses: Application to the Study of Smectite Expansion/Contraction. *Advances in X-Ray Analysis: Proceedings of the 1995 Denver X-Ray Conference*, Denver, Colo., Vol. 39 (J. V. Gilfrich et al., eds.), 1997, pp. 713-721.
20. Mitchell, J. K. *Fundamentals of Soil Behavior*. John Wiley and Sons, 1993.
21. Van Olphen, H. Interlayer Forces in Bentonite. *Clays and Clay Minerals*, Publication 327, National Research Council, Washington, D.C., 1954, pp. 418-438.
22. Van Olphen, K. Thermodynamics of Interlayer Adsorption of Water in Clays. *Journal of Colloid Science*, Vol. 20, 1965, pp. 822-837.
23. Low, P. F. The Swelling of Clay: II. Montmorillonites. *Soil Science Society of America Journal*, Vol. 44, 1980, pp. 667-676.
24. Moore, D. M., and R. C. Reynolds. *X-Ray Diffraction and the Identification and Analysis of Clay Minerals*, Oxford University Press, 1997.
25. Tindall, J. A., and J. R. Kunkel. *Unsaturated Zone Hydrology for Scientists and Engineers*, Prentice-Hall, New York, 1999.
26. Keren, R., and I. Shainberg. Water Vapor Isotherms and Heat of Immersion of Na/Ca-Montmorillonite Systems-I: Homoionic Clay. *Clays and Clay Minerals*, Vol. 23, 1975, pp. 193-200.
27. Mooney, R. W., A. G. Keenan, and L. A. Wood. Adsorption of Water Vapor by Montmorillonite: II. Effect of Exchangeable Ions and Lattice Swelling as Measured by X-Ray Diffraction. *Journal of the American Chemical Society*, Vol. 74, 1952, pp. 1371-1374.
28. Ormerod, E. C., and A. C. D. Newman. Water Sorption on Ca-Saturated Clays: II: Internal and External Surfaces of Montmorillonite. *Clay Minerals*, Vol. 18, 1983, pp. 289-299.
29. Barshad, I. The Nature of Lattice Expansion and Its Relation to Hydration in Montmorillonite and Vermiculite. *American Mineralogist*, Vol. 34, 1949, pp. 675-684.
30. Gillery, F. H. Adsorption-Desorption Characteristics of Synthetic Montmorillonoids in Humid Atmospheres. *American Mineralogist*, Vol. 44, 1959, p. 806.
31. Del Pennino, U., E. Mazzega, S. Valeri, A. Alietti, M. Franca-Brigatti, and L. Poppi. Interlayer Water and Swelling Properties of Monoionic Montmorillonites. *Journal of Colloid and Interface Science*, Vol. 84, No. 2, 1981, p. 301.
32. Huang, W., W. A. Bassett, and T. Wu. Dehydration and Hydration of Montmorillonite at Elevated Temperatures and Pressures Monitored Using Synchrotron Radiation. *American Mineralogist*, Vol. 79, 1994, pp. 683-691.
33. Collis-George, N. The Hydration and Dehydration of Na-Montmorillonite (Belle Fourche). *Journal of Soil Science*, Vol. 6, No. 1, 1955.
34. Karaborni, S., B. Smit, W. Heidug, and E van Oort. The Swelling of Clays: Molecular Simulations of the Hydration of Montmorillonite. *Science*, Vol. 271, 1996, p. 1102.
35. Koster van Groos, A. F., and S. Guggenheim. The Effect of Pressure on the Dehydration Reaction of Interlayer Water in Na-Montmorillonite (SWy-1). *American Mineralogist*, Vol. 69, 1984, pp. 872-879.