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Constant Flow Method for Concurrently Measuring Soil-Water Characteristic Curve and Hydraulic Conductivity Function

ABSTRACT: A constant-flow laboratory testing method (CFM) is presented for concurrently measuring the soil-water characteristic curve (SWCC) and hydraulic conductivity function (HCF) of unsaturated coarse-grained soils. Two computer-automated syringe pumps are employed to control the volumetric water content of a specimen and to periodically impose constant volumetric flow rates through the specimen, respectively. Hydraulic conductivity \( k \) corresponding to each water content increment is determined from Darcy’s law by measuring the steady-state gradient induced by the applied constant flow. Matric suction is maintained by axis translation using elevated pore air pressure and high-air-entry ceramic disks. Diffused air bubbles are removed using unique passive bubble traps. SWCCs and HCFs are obtained for three sandy soil specimens, requiring about 25–35 days to obtain both functions for each soil. The range of the system is demonstrated for \( k \) from about \( 10^{-4} \) cm/s to \( 10^{-5} \) cm/s at corresponding matric suction between about 0 kPa (saturated) and 40 kPa. Results are validated by comparison with independent SWCC measurements obtained using Tempe cells and HCFs estimated using a statistical model.

KEYWORDS: unsaturated soil, soil-water characteristic curve, hydraulic conductivity function, matric suction, sandy soil, constant flow method, permeameter

Introduction

The soil-water characteristic curve (SWCC) describes the constitutive relationship between matric suction and the water content of unsaturated soil. The hydraulic conductivity function (HCF) describes the constitutive relationship between hydraulic conductivity \( k \) and either water content or matric suction. Predicting the hydraulic and mechanical behavior of unsaturated soil typically requires that both the SWCC and HCF be well quantified over a wide range of saturation. In fluid flow problems, for example, the SWCC is required to define the driving potential for the flow process, and the HCF is required to define the resistance to the flow process. Practical problems involving unsaturated fluid flow are continuing to provide considerable motivation to develop new and improved techniques for directly measuring or indirectly modeling these two important functions.

Numerous laboratory and field methods have been developed to measure the SWCC and HCF independently. Common methods for measuring suction and the associated SWCC include tensiometers, thermal conductivity sensors, axis translation techniques, filter paper techniques, thermocouple psychrometers, and humidity-control techniques. Lu and Likos (2004) summarize the working principles, testing procedures, applicable measurement ranges, suction components measured (i.e., matric or total), and advantages and limitations of each. Common methods for measuring the HCF include constant-head techniques, centrifuge techniques, infiltration techniques, a variety of outflow techniques, and instantaneous profile techniques. Advantages and disadvantages of these methods, as well as their working principles and testing procedures, have been documented by numerous reviews in the literature (e.g., Benson and Gribb 1997; Lu and Likos 2004).

Constant-flow methods (CFM) have been used in the past to measure the hydraulic conductivity of porous media under both saturated and unsaturated conditions (e.g., Olsen et al. 1988, 1991). Following the general CFM testing approach, \( k \) is determined by measuring the steady state hydraulic gradient induced through a specimen in response to a precisely controlled flow rate, typically imposed using a constant-flow syringe pump. By eliminating the necessity to apply excessive gradients or to measure extremely small flow rates, constant-flow techniques have emerged as superior to many other laboratory testing methods, particularly for fine-grained materials or for \( k \) values less than about \( 10^{-10} \) cm/s.

This paper describes a computer-automated laboratory CFM system developed for unsaturated soil testing applications. The system has the capability to concurrently measure the SWCC and HCF using one specimen. Limitations identified in a previous unsaturated permeameter described by Olsen et al. (1994) and Kunkel et al. (1995) are overcome. The SWCC and HCF are obtained for three sandy soils using the new system and validated by comparison to results obtained using an established SWCC measurement technique (Tempe cell) and a statistical HCF model.

CFM Working Principles

Constant-flow \( k \) measurements for saturated or unsaturated soil rely on direct utilization of Darcy’s law:

\[
q = k i
\]  

where discharge velocity \( q \) and hydraulic gradient \( i \) are experimental variables. For constant-flow techniques, the former variable is
controlled and the latter is measured. For constant-head techniques, the former is measured and the latter is controlled.

Determining $k$ values less than about $10^{-10}$ cm/s using conventional constant-head methods requires either measuring extremely low flow rates or, alternatively, applying excessively high hydraulic gradients to generate more readily measurable discharge volumes. These requirements often create important practical limitations or deviations from the field conditions one is attempting to simulate in the laboratory. The primary advantage of constant-flow $k$ testing is that the necessity for measuring small flow rates or applying large gradients is effectively eliminated. Measurements may be obtained more rapidly, redundant measurements may be obtained by applying flow in multiple directions, and the system is much more amenable to computer automation. With flow pumps currently available for controlling and maintaining flow rates as low as $10^{-7}$ to $10^{-9}$ cm$^3$/s, it has become possible to measure $k$ as low as $10^{-14}$ cm/s, a possible value for saturated consolidated shale. The maximum measurable $k$ using CFM is primarily governed by head losses in the system that are not attributable to flow through the soil (e.g., losses in the end caps or permeant lines) and the necessary balance between the capacity of the flow pump and the volume of flow required for the process to reach steady state.

For unsaturated soils, constant flow rates may be applied across specimens maintained at specific values of water content or matric potential.

**FIG. 1**—Constant-flow laboratory system for concurrently measuring the SWCC and HCF of unsaturated soils: (a) schematic of system components and layout, and (b) photograph of experimental setup.

**FIG. 2**—Photograph of CFM permeameter.

**FIG. 3**—Illustrative details of permeameter end cap design: (a) schematic diagram showing passive bubble trap and plumbing connections, (b) machine drawing of HAE disks (all dimensions are in cm).
suction. Hydraulic conductivity corresponding to that particular water content or suction may then be determined by measuring associated head loss under the imposed flow rate. The flow-induced head loss induces a corresponding gradient in degree of saturation across the specimen, but this effect may be minimized by maintaining extremely small flow rates. Data defining the HCF may be obtained by incrementally increasing or decreasing water content or matric suction. Because $k$ of unsaturated soil may span several orders of magnitude from saturated to residual conditions, the measurement range offered by the CFM approach creates an opportunity for $k$ functions to be characterized over a wide range.

Application of CFM techniques to measure the SWCC of unsaturated soil is identical in principle to the axis translation method that has been widely employed in Tempe cells, pressure plate systems, and direct shear or triaxial systems modified for unsaturated shear strength testing. Matric suction ($\mu_a - \mu_w$) is actively maintained by separating the pressures of the pore air ($\mu_a$) and pore water ($\mu_w$) phases through the minute pores of a saturated high-air-entry (HAE) material. Following conventional axis translation testing to determine the SWCC, pore air pressure is incrementally elevated above atmospheric and pore water pressure is maintained atmospheric. For each air pressure increment, water is allowed to passively drain from the specimen until a water content in equilibrium with the applied suction is reached, thus generating data along a drying loop of the SWCC. Points along a wetting loop may also be obtained by incrementally decreasing the air pressure and allowing pore water to be imbibed.

Following the proposed CFM testing approach, pore air pressure is elevated to above atmospheric and a precisely controlled volume of pore water is extracted from (or injected into) the specimen using a precision flow pump. The change in pore water volume creates a new equilibrium among the applied air pressure, the pore water pressure (measured after the extraction or injection), and specimen water content. Water content at each increment is determined by considering the change in the water volume relative to a known initial (saturated) condition. Numerous points along the SWCC may be obtained by incrementally extracting or injecting water and measuring the corresponding pore air and water pressures at equilibrium.

### CFM System for Unsaturated Soils

The CFM system for unsaturated soils can be considered a combination of the steady state constant-flow method for $k$ measurement and the axis translation method for SWCC measurement. The system described here has been developed using a rigid-walled confining cell and evaluated using reconstituted sand specimens. For soils highly sensitive to volume change upon changes in moisture conditions, or for applications where stress control is desired, isotropic or triaxial confining systems may also be developed using the same working principles.

**Figures 1a and 1b** show a schematic and photograph of the experimental system, respectively. A cylindrical specimen (diameter $\approx 5.0$ cm, height $\approx 2$ cm) is placed in an acrylic confining cell with two specially machined 5-bar HAE ceramic disks placed in good contact on either side. Small, cone-shaped water reservoirs are behind the HAE disks. Two reversible (bidirectional) flow pumps are used to periodically impose a constant flow rate in either direction through the specimen and to withdraw or inject pore water from the specimen, respectively. The pump labeled “flow” is outfitted with a dual-chamber syringe such that equal volumes of water may be simultaneously injected into the reservoir located on one side of the specimen and withdrawn from the other side, thus imposing a constant flow rate in a continuous circuit. The pump labeled “water content” is outfitted with a single-chamber syringe such that the water content of the specimen may be periodically reduced or increased by withdrawing or injecting a known volume of water. Air pressure is applied through a port on the side of the confining cell and distributed about the perimeter of the specimen using a small strip of filter paper. To inhibit excessive evaporation
Three differential pressure transducers are also installed as shown: (1) the transducer $\Delta h$ measures the difference in pressure between “static” lines embedded into the HAE disks on either side of the specimen, (2) the transducer $(u_w - u_a)_1$ measures the difference in water pressure between the left water reservoir and the externally applied air pressure, and (3) the transducer $(u_w - u_a)_2$ measures the difference in water pressure between the right static line and the applied air pressure. When the “flow” pump is turned on, transducer $\Delta h$ measures the total head loss induced in the system, which is attributable to both losses in the soil and losses in the HAE disks. The static lines connecting transducer $\Delta h$ with the specimen have been designed such that head losses occurring in the HAE disks between the specimen and the transducer are minimized (described subsequently). Under no flow conditions, differential transducers $(u_w - u_a)_1$ and $(u_w - u_a)_2$ provide redundant measurements of matric suction as the difference between the air pressure and the water pressures at either side of the specimen. All three pressure transducers belong to the Omega PX26 series with a maximum range of 100 kPa or 700 kPa, response time of 1 ms, and hysteresis/repeatability within 0.2 %. Head losses across the specimen may be resolved to as low as 1 cm. Flow-pump control, transducer excitation, signal conditioning, and data acquisition are all accomplished using a personal computer.

A photograph of the permeameter cell is shown as Fig. 2. Specimen confinement is designed symmetrically for ease of assembly and so that the direction of flow during $k$ tests can be reversed. O-rings slightly thicker than the HAE disks are used to ensure that no direct hydraulic connection exists between the specimen and the reservoirs behind the disks. All the pieces are aligned and tightened using three threaded steel rods. The specimen is oriented horizontally during testing but can be periodically oriented vertically to trap and subsequently quantify the volume of air bubbles that may accumulate in the water reservoirs after prolonged testing periods.

Figure 3(a) is a detailed schematic of the specimen end cap and associated plumbing. The port on the left reservoir has three functions: (1) withdrawing or injecting a constant flow rate, (2) reducing or increasing the specimen water content, and (3) measuring the water pressure in the reservoir. The port on the right reservoir is used to apply a constant flow rate equal in magnitude and opposite sign to that supplied to the left. The port located in the center of the end cap services two lines to the specimen. The small diameter inner tube is the “static” line (Fig. 1(a)) in communication with the differential pressure transducer $\Delta h$. The static line is inserted into a cavity drilled almost all the way through the central portion of the HAE disk, thus minimizing head loss occurring between the specimen and transducer. Several small O-rings are used to isolate the tip of the line from the reservoir. The larger diameter (1/2 in.) tube forms a graduated annulus about the inner static line that allows collection, measurement, and removal of air bubbles that tend to accumulate in the reservoir during testing. The conical shape of the reservoir encourages the air bubbles to rise to the top of the bubble trap when the permeameter is oriented vertically. This “passive” flushing technique ensures accurate volumetric control of the applied flow rates for $k$ testing and decreases the overall compressibility of the system, which significantly reduces the amount of time required for steady state.

Figure 3(b) shows a machine drawing for the two HAE disks in contact with either side of the specimen. The disks have two concentric diameters of different thickness. The larger outer diameter (5.5 cm) is slightly larger than the specimen diameter and is 0.38 cm thick. The cross-sectional area of the thinner portion provides a pathway for water between the specimen and reservoirs during $k$ testing. The smaller inner diameter is 1.9 cm with a thickness of 0.88 cm and a central hole drilled almost all the way through (used for seating the static pressure line). These dimensions were selected such that the thicker inner portion provides good mechanical con-
finement to the static line and a relatively small hydraulic gradient compared to the thinner outer portion. The thickness of the HAE disk at the center is made to be less than 0.135 cm, thus forming a very thin ceramic "membrane" that maintains air/water separation but minimizes the head loss between the tip of the static sensor line and the specimen. The area of the thicker inner portion of the disk is less than 12 % of the entire disk area such that one-dimensional flow conditions through the specimen are maintained. Likos et al. (2005) describe a series of numerical seepage models conducted to optimize the dimensions of the special HAE disks and to validate the 1-D flow assumption.

**CFM Testing Procedures**

A typical testing program involves multiple steps of pore water extraction using the "water content" pump and subsequent hydraulic conductivity testing using the "flow" pump. Multiple flow rates and flow in different directions may be applied to provide redundant measurements. Steady state head loss for each flow rate is measured using transducer $\Delta h$ and $k$ is calculated directly from Darcy’s law. Hydraulic conductivity may be reported as a function of specimen water content or the average matric suction obtained by the measurements of air pressure and pore water pressure at both ends of the specimen. Given knowledge of the prevailing water content, the calculated matric suction and hydraulic conductivity establish points on both the SWCC and HCF.

Tests have been conducted using three sandy specimens to demonstrate and validate the CFM permeameter system. Specimen preparation, testing, and analysis procedures for these tests may be summarized by the following series of steps. The amount of time required to complete each step is summarized in Table 1. Depending on the number of data points obtained (e.g., 8–10 points along a drying loop), constructing the SWCC and HCF requires about 25 to 35 days.

**Step 1: Specimen Preparation**—Reconstituted sand specimens are prepared for SWCC testing and HCF testing. Duplicate specimens are prepared for comparing the measured SWCCs

<table>
<thead>
<tr>
<th>Specimen Parameters</th>
<th>Well-graded Sand</th>
<th>Esperance Soil</th>
<th>Poorly-graded Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of solids (g)</td>
<td>77.38</td>
<td>67.29</td>
<td>69.60</td>
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<tr>
<td>Porosity, $n$</td>
<td>0.299</td>
<td>0.390</td>
<td>0.369</td>
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<tr>
<td>Area (cm$^2$)</td>
<td>19.64</td>
<td>19.64</td>
<td>19.64</td>
</tr>
<tr>
<td>Total volume (cm$^3$)</td>
<td>41.63</td>
<td>41.63</td>
<td>41.63</td>
</tr>
<tr>
<td>Saturated volumetric water content</td>
<td>0.299</td>
<td>0.390</td>
<td>0.379</td>
</tr>
<tr>
<td>Saturated water volume (cm$^3$)</td>
<td>12.43</td>
<td>16.24</td>
<td>15.37</td>
</tr>
<tr>
<td>Total volume of water withdrawn (cm$^3$)</td>
<td>5.5</td>
<td>9.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Final calculated water volume (cm$^3$)</td>
<td>6.93</td>
<td>3.41</td>
<td>7.3</td>
</tr>
<tr>
<td>Final calculated volumetric water content</td>
<td>0.166</td>
<td>0.174</td>
<td>0.177</td>
</tr>
<tr>
<td>Final measured water volume (cm$^3$)</td>
<td>6.5</td>
<td>3.45</td>
<td>7.12</td>
</tr>
<tr>
<td>Final measured volumetric content</td>
<td>0.156</td>
<td>0.083</td>
<td>0.171</td>
</tr>
</tbody>
</table>

![FIG. 7—Time-series experimental data for well-graded sand.](image-url)
Step 2: Permeameter Assembly—The HAE disks are fully saturated by submerging them in deaired water and applying vacuum to the overlying head space for 48 h. The saturated HAE disks are then encircled with the large O-ring (Fig. 3(a)), aligned with the end caps and specimen, and the assembly is tightened with the external threaded rods (Fig. 2).

Step 3: System Saturation—Flow and pressure lines are saturated with deaired water by manipulating appropriate valves in the plumbing circuit. Deaired water is then allowed to slowly percolate through the lines for 24 h to dissolve air bubbles not removed by advection.

FIG. 8—SWCC and HCF for well-graded sand: (a) SWCC, and (b) HCF
Step 4: Specimen Saturation—The CFM results reported subsequently follow the drying loop of the SWCC and HCF. Specimens, therefore, are initially brought to the 100 % saturation condition. Occluded air bubbles are removed by flushing deaired water from the previously deaired reservoirs, through the specimen, and out of the air pressure port located on the side of the confining cell. Flushing proceeds for 48 h. Partial vacuum is applied through the air pressure port to assist the saturation process.

Step 5: Control System Initiation—The three pressure transducers are initialized by opening bridge valves to equilibrate the fluid pressures acting on either side of the transducer diaphragm. Data files and control parameters such as flow direction, flow rate, and data acquisition frequency are set up. A 5-min sampling interval is used for all tests reported here.

Step 6: Saturated Hydraulic Conductivity Testing—Saturated k testing is conducted by sealing the air pressure port on the confining cell and applying a series of constant flow rates using the “flow” pump. The “water content” pump is turned off, which maintains the constant water content of the specimen. For the majority of tests conducted here, three flow rates in each direction were applied. Figure 4, for example, shows a time series plot for head loss measured through a saturated sandy specimen during an incremental flow sequence of −0.1, 0.1, −0.2, 0.2, −0.3, and 0.3 cm³/min. These redundant measurements provide critical information for the rest of the testing program. The results indicate the quality of the specimen in terms of saturation and homogeneity, the compressibility of the fluid lines and specimen, and the saturated k of the specimen. The linear relationship noted between flow rate and head loss ensures the uniqueness of the measured k and the validity of Darcy’s law. Nonlinearity, on the other hand, may indicate excessive air bubbles or other problems in the permeameter system. Response times for all applied flow rates should also be the same, indicating that the system’s compressibility is independent of applied pressure and that air bubbles are minimal.

Step 7: SWCC and HCF Testing—This step includes a series of actions, which include a combination of the three steps below:

(a) The air pressure is slowly elevated to a desired value through the port located on the side of the confining cell. The maximum air pressure should be greater than the maximum suction desired for testing, but less than the air-entry pressure of the HAE disks. For tests reported here, a nominal air pressure of 80 kPa is applied. Under no flow conditions (i.e., with the “flow” pump turned off) and without changing the water content of the specimen (i.e., with the “water content” pump turned off), the pore air and water pressures should both increase to near the magnitude of the applied air pressure. The point when equilibrium is reached can be established by monitoring the transducer output.

(b) With the “flow” pump turned off, a desired amount of water is withdrawn from the specimen using the “water content” pump. This is evident in the output as a sharp perturbation in head loss and matric suction. For all water withdrawals in the testing program described here, 1 cm³ of water was extracted at a rate of 0.1 cm³/min, which corresponds to a decrement in volumetric water content between 1.5 and 3.0 %. After each withdrawal, output from transducers \((u_e - u_m)\) and \((u_e - u_m)^2\) is monitored to determine the equilibrium matric suction. Suction is reported as the average of these two values and, together with the new volumetric water content, defines one point on a drying loop of the SWCC.

(c) With the “water content” pump turned off, one or more flow rates in either or both directions are applied through the specimen using the “flow” pump. Head loss measured using transducer \(\Delta h\) is used to calculate \(k\), which may be reported as a function of the known water content or suction using the values obtained in Step 7b.

Steps 7b and 7c may then be repeated to obtain the SWCC and HCF for the entire testing range or parts of the testing range if Step 7a is again employed. Diffused air bubbles are removed from the bubble traps at any point between testing steps.

CFM Testing Results and Analysis

Preliminary Blank Sleeve Testing

Prior to soil testing, a series of “blank sleeve” tests was conducted to quantify the performance and effectiveness of the specially designed HAE disks. The objective of these tests was to quantify any head losses registered by transducer \(\Delta h\) attributable to flow through the plumbing system and the inner portions of the HAE disks. Once quantified, these “system” head losses could be subtracted from head losses measured during actual testing. System head losses were quantified by applying a series of constant flow rates through the assembled system with the specimen chamber filled with water. Results are shown as the bold lines in Figs. 6(a)–6(c). Based on the system head loss curves, an upper limit for accurate hydraulic conductivity is about 10⁻⁴ cm/s, which corresponds to about 1 cm of specimen head loss.

The system head loss in the current CFM apparatus is much less than in the previous CFM prototypes (e.g., Olsen et al. 1994). For example, if a flow rate of 0.01 cm³/min is applied to measure soils with high hydraulic conductivity (e.g., near saturation), the head loss in the current system is 1.21 cm, whereas it would be 10 to 260 cm in the Olsen et al. (1994) permeameter. The low system head loss exhibited in the current system greatly extends its measurement range into the regime applicable to relatively coarse-grained soils. Corrections to the measured head loss during soil testing may be made for any value of applied flow rate by considering the linear equations shown on Figs. 6(a)–6(c).

Well-Graded Sand Testing

The CFM testing system was evaluated by following the sequence of steps described above for three reconstituted sand specimens: well-graded sand, Esperance soil, and poorly graded sand. Particle size distributions are shown in Fig. 5. Table 2 summarizes characteristics of specimens prepared for testing.

A 26-day testing program was conducted to develop the SWCC and HCF of the well-graded sand. Since the testing program starts with the fully saturated state, an initial volumetric water content of 0.30 was taken directly from the as-compacted porosity (Table 2). A series of seven withdrawals and subsequent k tests was conducted, resulting in an estimated final volumetric water content of 0.166. The final volumetric water content measured from post-test
oven drying was 0.156, indicating a water loss of 3.34 % during the testing program. This loss was attributed to evaporation from the specimen that was believed to occur during the long exposure to the dry air pressure line (measured to be about 15 % relative humidity). As such, subsequent testing programs for the Esperance soil and poorly-graded sand were conducted by implementing the vapor chamber shown in Fig. 1(a).

Time-series data for head loss and matric suction are shown in Fig. 7 for the first ten days of testing. Six different flow rates were applied to obtain the initial saturated k value. Figure 6(a) summarizes the saturated testing phase in the form of measured steady state head loss as a function of applied flow rate. The average value of saturated k is 7.04 × 10^{-6} cm/s. Values obtained from the redundant flow tests are within 8 %. For the unsaturated testing phase, the air pressure was elevated on the third day, demonstrating good repeatability for the unsaturated phase. The relationship between applied flow rate and the corresponding head loss is shown in Fig. 6(b) for saturated volumetric water content of 0.30 and for unsaturated values of 0.28 and 0.25.

The SWCC and HCF obtained through seven withdrawal steps are shown in Figs. 8(a) and 8(b), respectively. An independent SWCC measurement obtained from Tempe cell testing is shown in Fig. 8(a) for comparison. A calculated HCF based on Jackson’s (1972) statistical method and the SWCC obtained from the permeameter is shown in Fig. 8(b). The air-entry pressure deduced from the CFM and Tempe cell results (Fig. 8(a)) is not unique, yet falls somewhere less than 2 kPa. Over 50 % of the pore water volume is lost by the time matric suction reaches about 40 kPa. Hydraulic conductivity (Fig. 8(b)) is reduced by almost three orders of magnitude (from 7.04 × 10^{-6} cm/s to 1.1 × 10^{-8} cm/s) over the range of water content evaluated.

While the general order and trends observed by comparing the CFM results and independent measurements are similar, there exists a persistent gap between them. Several potential sources or error are identified. First, as identified earlier, there is a 3.34 % error in the calculated water content due to possible evaporation through the air supply line. Examination of the CFM specimen after termination of the testing program also showed that the bulk volume of the specimen was slightly smaller than the confining cell, indicating a small degree of volumetric shrinkage during the tests. The formation of discontinuities between the HAE disks and the specimen as it shrinks may contribute to the discrepancies. While the amount of shrinkage was noticeably small for the sand specimen, special considerations may be required for fine-grained soils where a larger amount of volume change is expected during the drying process (e.g., spring-loaded end caps, flexible wall confining cell). Finally, the relative high head lost in the increments when the hydraulic conductivity becomes low also leads to inaccuracy in the average matric suction calculation. This problem could be greatly reduced in the future by reducing the magnitude of the imposed constant flow rate.

**Esperance Soil Testing**

The testing program for this sand lasted 35 days. It was found that the amount of time required for steady state to be reached after each testing step or perturbation was much longer for the Esperance sand than for the other materials. Referring to Table 2, the porosity value of 0.39 is significantly higher than that for the well-graded sand, leading to higher specific moisture capacity and lower hydraulic diffusivity. It is likely that the lower hydraulic conductivity leads to the requirement for a longer time to reach steady state.

For the unsaturated phase of testing, a total of nine water withdrawals (1 cm³) were made from the initially saturated state. Figure 9 shows time-series data for head loss and matric suction over the first 20 days of testing. Six flow rates (−0.4, −0.2, −0.1, 0.1, 0.2, and 0.4 cm³/min) were applied during the saturated k testing phase. Figure 6(a) demonstrates the linearity in the steady state.
head loss and an average saturated $k$ of $4.87 \times 10^{-5}$ cm/s. To initiate unsaturated testing, the air pressure was elevated to 83 kPa. Four flow rates ($-0.05$, $-0.02$, 0.02, 0.05 cm$^3$/min) were applied between each water withdrawal. After the final withdrawal, a very low flow rate of 0.0005 cm$^3$/min was necessary. Figure 6(c) summarizes results obtained during the unsaturated testing phase. As indicated in Fig. 9 and Fig. 6(c), the direction of flow has very little effect on the relationship between head loss and flow rate or time required to reach steady state.

Figure 10(a) shows the SWCC from the CFM permeameter and Tempe cell testing. It can be seen that 80% of the volumetric water content is drained when matric suction reaches 43 kPa. Hydraulic conductivity decreases from $3.9 \times 10^{-5}$ cm/s to $1.8 \times 10^{-9}$ cm/s, a reduction of about 5 orders of magnitude (Fig. 10(b)). Comparison between the HCF measured using the CFM permeameter and estimated from the SWCC using Jackson’s (1972) model. Excellent agreement is achieved between the CFM, Tempe cell, and HCF modeling results. The results from both the CFM and Tempe cell identify a distinct and consistent air-entry pressure at about 2 kPa. The high air-entry pressure relative to the other two soils is expected because
the Esperance sand has a more uniform particle size distribution than the well-graded sand and a larger percentage of smaller particles than the poorly-graded sand.

As indicated on Table 2, the final measured volumetric water content (0.083) is significantly less than the final calculated water content (0.174). This discrepancy is believed to reflect additional water removed from the specimen during a terminal 10th water withdrawal. The 10th withdrawal was suspected to increase matric suction to the point where the air-entry pressure of the HAE disks (~500 kPa) was exceeded, thus invalidating the measurements thereafter.

Poorly-Graded Sand Testing

The testing program for this sand lasted 22 days. Seven water withdrawals were applied during the unsaturated testing phase. At the end of CFM testing, the volumetric water content was estimated to be 0.177, well matching the volumetric water content of 0.171 calculated from post-test oven drying (Table 2). Time-series results for the first 20 days of testing are shown in Fig. 11. Eight constant flow rates (~0.4, ~0.3, ~0.2, ~0.1, 0.1, 0.2, 0.3, and 0.4 cm³/min) were applied during saturated k testing. Steady state head loss versus applied flow rate for the saturated testing series is shown in Fig. 6(a), where an average k value of 3.3 \times 10^{-4} \text{ cm/s} is obtained. The relatively high k is interpreted to reflect the poorly-graded sand's narrow particle size distribution and greater fraction of relatively large particles.

For unsaturated testing, air pressure was first elevated to 83 kPa. Two constant flow rates were applied in opposite directions between a series of seven water withdrawals. Head losses obtained from the multidirectional flow rates were consistently nearly equal. Volumetric water content decreased from 0.37 to 0.15 when matric suction was increased from 0 kPa to 5.24 kPa. The SWCC and HCF obtained from the CFM and the independent methods are shown in Fig. 12. The results show that the volumetric water content approaches a quite dry state of 5% when the applied matric suction is 12 kPa, confirming the rapid drainage phenomenon observed in the CFM results. The air-entry pressure identified from both the CFM and Tempe cell tests falls between about 0.1 and 0.2 kPa. This relatively low air-entry pressure is expected since the soil is poorly graded with relatively large particles sizes and porosity. Hydraulic conductivity during the volumetric water content reduction from 37 to 18% decreases from 3.3 \times 10^{-4} \text{ cm/s} to 3.6 \times 10^{-6} \text{ cm/s}. Excellent matches between the CFM and independent methods for both SWCC and HCF are evident, except for HCF when the volumetric water content is below 22%. The most likely reason for the discrepancy is the relatively large head loss that occurs during the last two decrements, which may lead to inaccurate averaging of matric suction in the specimen. This problem could be greatly reduced in the future by reducing the imposed constant flow rate so that the associated head loss could be controlled to allowable values.

Summary and Conclusions

A laboratory constant-flow method (CFM) for concurrently measuring the soil-water characteristic curve (SWCC) and hydraulic conductivity function (HCF) of unsaturated soils is designed, tested, and validated using three different sandy soils. The new CFM is demonstrated for hydraulic conductivity ranging from about 10^{-9} to 10^{-4} \text{ cm/s}. Hydraulic conductivity between 10^{-8} \text{ cm/s} and 10^{-4} \text{ cm/s} is often the dominating range for soil water retention in sandy and silty unsaturated soils. Passive bubble traps incorporated into the specimen end caps allow collection, measurement, and removal of diffused air bubbles at any stage of testing. Reasonable matches are obtained among the CFM results, Tempe cell SWCC results, and HCF results obtained using a statistical hydraulic conductivity modeling formulism.

Acknowledgments

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