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Quantification of air diffusion through high air-entry ceramic disks

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Abstract

Suction control for testing unsaturated soils requires the use of high air-entry ceramic disks (HAED). HAEDs provide a medium for water in a soil specimen to migrate as required regardless of the applied pore air pressure. Even though the HAEDs are rated for a specific bubbling pressure, some air diffuses through the HAEDs, even at pressures below the rated capacity. Diffused air has a tendency to accumulate underneath the HAEDs resulting in an error in the specimen water content measurements. Diffused air has the potential to de-saturate the bottom of the HAED thereby retarding the flow of water through the disk. In this study, commonly used HAEDs were tested with the Fredlund soil-water characteristic curve (SWCC) device to measure the diffusion rate at different pressures. Three-inch diameter HAEDs rated at 100, 300, 500, and 1,500 kPa bubbling pressures were tested at different percentages of their rated pressures (e.g. 50%, 95%) to determine the diffusion rate. Several HAEDs from the same manufacturer were tested for each bubbling pressure. The hydraulic conductivity of the HAEDs was also measured at different testing stages to determine the effects of air accumulation underneath HAED disks. Diffused air volume rates are presented graphically. Conclusions and recommendations for the frequency of flushing are also presented. In summary, the amount of diffused air generated when using 1- or 3-bar, 5-bar, and 15-bar is: negligible, small, and large, respectively.

Introduction

High air-entry disks (HAEDs) are essential for unsaturated soil testing for applying suction to soil specimens. The important feature of high air-entry disks is the ability to allow water to flow through the ceramic while stopping the airflow as long as the bubbling pressure is not exceeded. Once the bubbling pressure of the ceramic is exceeded, the air starts to freely flow through the ceramic. When selecting an appropriate HAED for testing, the bubbling pressure of the selected disk should be adequate to withstand the intended maximum air pressure to be applied to the specimen. Typical disks used in unsaturated soil testing apparatuses, such as the triaxial, direct shear, and soil-water characteristic (SWCC) devices, are rated for bubbling pressures of 1-, 3-, 5-, and 15-bar, which are capable of withstanding approximately 100, 300, 500, and 1,500 kPa of air pressure, respectively.

Unsaturated soil testing usually requires running relatively long-term tests lasting for few weeks or sometimes even more. The diffusion of air through water generally occurs at extremely slow rates during such tests. Diffusion is the movement of air from the pressurized side of the disk to the other side through the water phase in the saturated disk. The diffusing air comes out of the solution creating air bubbles beneath the ceramic disk. The diffused air gradually accumulates displacing water in the space beneath the ceramic disk. This is an important problem that must be addressed during unsaturated soil testing (Bishop, 1969 and Fredlund, 1973, 1975, 1993). The accumulation of diffused air can lead to several complications such as: i) pore-water pressure measurement errors in undrained tests; ii) volume change measurement errors in drained tests; iii) water content measurement errors; and iv) possibly drying out the ceramic disk causing impedance of hydraulic conductivity of the ceramic disk.

When conducting unsaturated soil testing, it is important to know the quantity of diffused air that can be expected during a certain period of time. It should be noted that not only the quantification of the diffused air is required but also there needs to be regular removal of diffused air in obtaining accurate results. The removal of diffused air can be accomplished with a simple manual pump or an automated flushing device attached to the apparatus. Details of an automated flushing device are presented in a paper published by Padilla et al. (2006).

Objective

This study focuses on quantifying the rate of air diffusion through various ceramic disks at different air pressures with respect to the rated bubbling pressure. The research provides insight for researchers into how to predict air diffusion rates when conducting long-term testing, and how often to flush the system to avoid errors in readings. The study also includes assessment of the variability of air diffusion rates and hydraulic conductivities of ceramic disks. The effect of air diffusion on hydraulic conductivity of ceramic disks was also investigated. It should be noted that the study of variability of hydraulic conductivity and air diffusion rates could not cover all the possibilities in this study. The scope was to produce some general guidelines of operation based on the available test data.

Literature Review

Bishop (Bishop, 1969) clearly described the importance of addressing the problem of air diffusion when conducting unsaturated soil testing. Fredlund (Fredlund, 1973 and 1975) investigated the diffused air problem and recommended that any unsaturated test extending more then one day in length needs quantification of the diffused air volume. In 1993, Fredlund and Rahardjo discussed the measurement of diffusion in detail in the book *Soil Mechanics for Unsaturated Soils, 1993.* In 2005 a pressure pulse technique for measuring diffused air volumes during triaxial testing was presented (Lawrence et al., 2005).

Some studies had been conducted in the past on the quantification of diffused air, but little attention has been given to the necessity of frequent diffused air removal. This paper investigates not only the rate of air diffusion but also the need for frequent flushing.

Theory of Air Diffusion

Fick's law can be used to describe the diffusion of air through water and the diffusion of air through water within a porous medium. The diffusion process occurs in response to a concentration gradient. For the diffusion of air through water, the concentration gradient is the difference in density between free air and the dissolved air in water. When HAEDs are used, the diffusion process involves air dissolving into water in the ceramic disk and subsequently coming out of solution. Based on Fick's law, the diffusion of air through water in a porous medium can be expressed as shown in Equation 1 (Fredlund and Rahardjo, 1993).

$$Q_a = k_a i A t \tag{1}$$

where:

Q_a = flow of air across a unit area of porous medium (units = L^3),
k_a = diffusion coefficient of air through water, (units = L/T)
i = pore-air pressure head gradient ($\Delta h_a/l$, h_a is pore-air pressure head, l *is* thickness over which the pore-air pressure head changes),
A = cross-sectional area of the porous medium, and
t = time.

Testing Program

Several ceramic disks, rated as 1-, 3-, 5-, and 15-bar, obtained from the same manufacturer were tested using the Fredlund SWCC device. The physical properties of the ceramic disks published by the manufacturer are listed in Table 1.

Table 1. Properties of ceramic disks used in testing.

Ceramic Disk	Diameter (cm)	Thickness (cm)	Approximate Porosity	Bubbling Pressure (kPa)	Hydraulic Conductivity (cm/sec)
1-bar	7.94	1.03	0.34	173[1]	7.56×10^{-7}
3-bar	7.94	1.03	0.34	398[2]	2.50×10^{-7}
5-Bar	7.94	1.03	0.31	550	1.21×10^{-7}
15-Bar	7.94	0.71	0.32	1520	2.59×10^{-9}

[1] Average of the given range, 138 to 207 kPa
[2] Average of the given range, 315 to 480 kPa

The testing was associated with three different projects conducted at Arizona State University (ASU) and GCTS Testing Systems (GCTS) as listed below, followed by the details of the relevant portion of each project.

- A special research project conducted jointly by ASU and GCTS recently focusing on the measurement of hydraulic conductivity and desaturation of ceramic disks along with the diffused air volume measurements (2005).

- A highway research project entitled *Environmental Effects in Pavement Mix and Structural Design* funded by the National Cooperative Highway Research Program (NCHRP) and designated NCHRP 9-23 Project (2000 to 2003).

- A research project entitled *Unsaturated Soils in Engineering Practice* funded by National Science Foundation (NSF, Grant No.CMS-0099800).

Quantification of Diffused Air Project

Testing of ceramic disks for air diffusion was recently conducted at ASU and GCTS with a focus on the water hydraulic conductivity of the ceramic disks and the measurement of rates of air diffusion. It was intended to use four types of ceramic disks for the testing. However, the results from about forty tests conducted with 1-, and 3-bar ceramic disks in the NCHRP project indicated that 1- and 3-bar disks generated non-measurable amounts of diffused air even at applied air pressures approaching the bubbling pressures. Therefore, only 5- and 15-bar ceramic disks were subjected to rigorous testing. A summary of the test procedure is as follows.

Each test consisted of four segments that included measuring the weight of ceramic disk at three times: W_1, W_2, and W_3 corresponding to initial, after a few days of flushing, and after a few days of air accumulation, respectively. Also, testing included conducting hydraulic conductivity tests at four times: k_1, k_2, k_3, and k_4 corresponding to initial, after a few days of flushing, after a few days of air accumulation, and after flushing at the end, respectively. The air diffusion rates were also computed from the water level measurements in volume tubes. For each ceramic disk the procedure was repeated at for approximately 50% and 95% of the nominal bubbling pressure.

In the first segment of testing, each ceramic disk was saturated by immersing the disk under water for a few hours. The ceramic disk was weighed, W_1, at saturated surface dry condition before mounting on the SWCC device. Then the hydraulic conductivity of the saturated disk was determined by applying an air pressure in the chamber of 50% (and then 95%) of the bubbling pressure of the disk using the axis-translation technique with a small amount of water on top of the disk as shown in Figure 1. When the cell was pressurized, water flowed through the disk into the volume tubes. The measurement of water level change in the two volume tubes with respect to time recorded over about one hour provided the data necessary for computing the first value for the hydraulic conductivity, k_1.

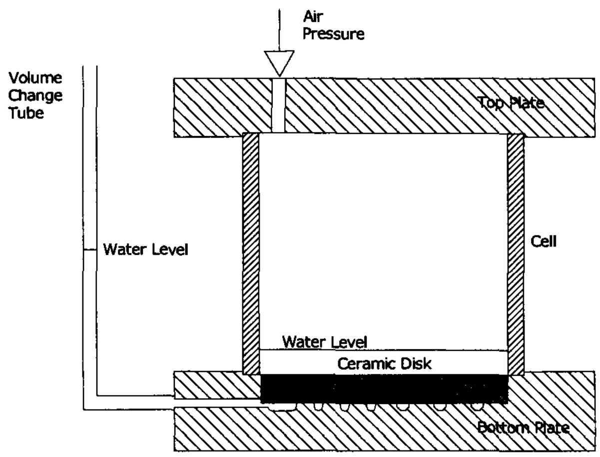

Figure 1. Setup for hydraulic conductivity tests.

In the second segment of testing, any excess water from inside the cell was dried and the saturated ceramic disk was allowed to respond to an applied air pressure equivalent to about 50% (and then 95%) of the bubbling pressure. The setup was similar to Figure 1 with no standing water in the cell. The system was flushed regularly twice a day. After two to three days, the ceramic disk was carefully removed from the base and the surface dry weight was measured (W_2). The ceramic disk was remounted by pressing on to the base and assembling the apparatus, and a second hydraulic conductivity test was performed to obtain k_2.

In the third segment of testing, any excess water from inside the cell was dried and the saturated ceramic disk was allowed to respond to an applied an air pressure equivalent to about 50% (and then 95%) of the bubbling pressure of the disk. The system was left without flushing for two to three days to accumulate diffused air beneath the ceramic disk. Once an amount of diffused air was accumulated below the ceramic disk a hydraulic conductivity test was conducted to obtain k_3. The ceramic disk was not removed from the base for weighing this time, as it would eliminate the accumulated diffused air from beneath the disk.

In the fourth segment of testing, any excess water from inside the cell was dried, and the system was flushed and the saturated ceramic disk was allowed to respond to an applied pressure equivalent to about 50% (and then 95%) of the bubbling pressure of the disk. Similar to segment three, the system was left without flushing for two to three days to accumulate diffused air beneath the ceramic disk. This time, the weight of the saturated surface dry disk was measured, W_3. Another hydraulic conductivity test was conducted after mounting the ceramic disk on the base and k_4 was obtained.

Data available from the NCHRP and NSF projects were analyzed for the diffusion rates of ceramic disks. In these projects, various soils were subjected to SWCC testing and the SWCCs were previously analyzed and presented in reports, but diffusion rates were not analyzed or reported at that time.

NCHRP Project

The NCHRP testing was conducted between 2001 and 2003 and included performing about 100 SWCC tests on soil samples obtained from granular bases and subgrades beneath highway pavements. Figure 2 illustrates a schematic of the Fredlund SWCC device, which was used for testing, with a soil specimen mounted inside the cell. The testing procedure was presented in detail in the Perera (2003) dissertation.

Drying SWCCs were generated for various soils starting with a saturated specimen and applying suction increments until the degree of saturation reached about 10%, typically. All four types of ceramic disks, 1-, 3-, 5-, and 15-bar, were used during the testing program. During each test, the SWCC device was flushed at least twice a day. The volume of water equivalent to the volume of diffused air bubbles was obtained from the difference between water levels before and after flushing. The diffused air volumes corresponding to room temperature and atmospheric pressure were computed by considering the height of the water column and the atmospheric pressure. The ideal gas law was applied here.

NSF Project

Similar to the NCHRP project, NSF project included determining SWCCs of soil specimens from four different sources using the Fredlund SWCC device. Again, the data were analyzed and presented in this paper for quantifying the rates of air diffusion.

Presentation of Test Results

The test results from the three projects are presented in this section in tabular and graphical forms followed by the interpretation of tests results presented in the next section.

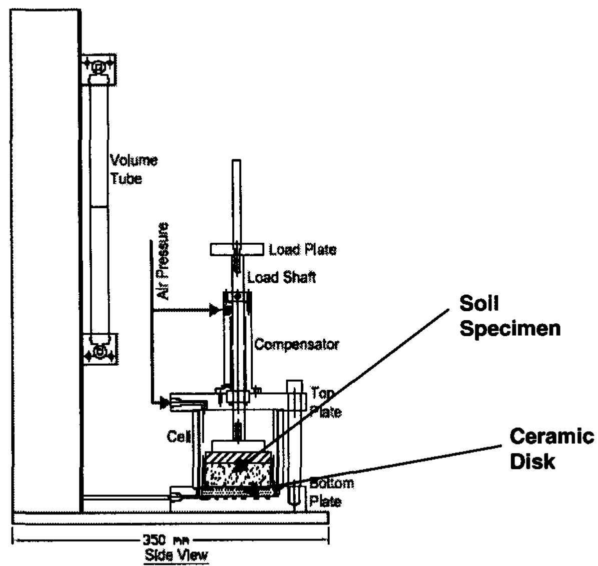

Figure 2. The Fredlund SWCC Device.

Air diffusion rates at different air pressures and the corresponding standard deviations obtained from NCHRP project data are shown in Table 2. The standard deviations are computed when three or more data values were available for the corresponding applied air pressure. The diffusion rates for 5- and 15-bar disks are shown in Figures 3 and 4, respectively. It should be noted that the thickness of all 15-bar disks (0.71 cm) tested is about 30% less than the thickness of the 1-, 3- or 5-bar disks (1.03 cm). The air diffusion rates for the 15-bar disks evaluated from the NSF project data are presented in Table 3 and the same data is graphically presented in Figure 4.

Table 2. Air diffusion rates from *NCHRP* project data.

Ceramic Disk	Thickness of Ceramic Disk (cm)	Applied Air Pressure (% of Bubbling Pressure)	Average Air Diffusion Rate (cm^3/day)	Standard Deviation (cm^3/day)
1-Bar	1.03	0-100	0.00	0.00
3-Bar	1.03	0-100	0.00	0.00
5-Bar	1.03	0	0.00	0.00
		20	0.01	0.00
		60	0.04	--
		100	0.09	0.04
		120	0.16	--
15-Bar	0.71	0	0.00	0.00
		10	0.00	0.00
		20	0.26	--
		33	0.43	0.13
		93	2.33	0.32

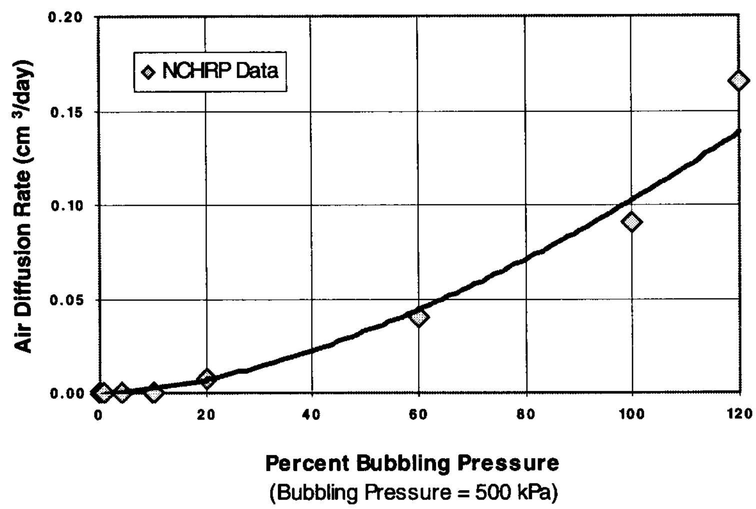

Figure 3. Air diffusion rates through 5-bar ceramic disks.

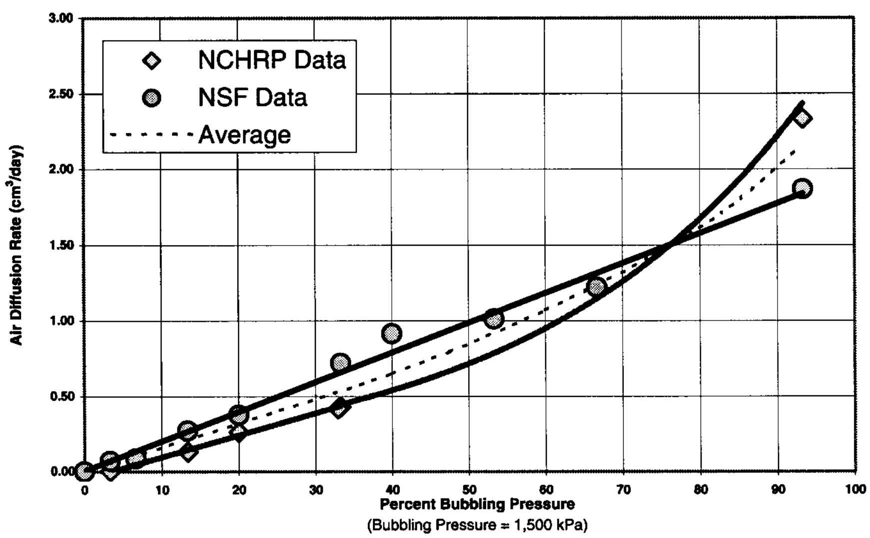

Figure 4. Air diffusion rates through 15-bar ceramic disks.

The results from recent testing included air diffusion rates through 5- and 15-bar ceramic disks at two different applied air pressures, and hydraulic conductivity measurements and weights on the ceramic disk at various stages of testing. The results are summarized in Table 4.

Table 3. Air diffusion rates from *NSF* project data.

Ceramic Disk	Thickness of Ceramic Disk (cm)	Applied Air Pressure (% of Bubbling Pressure)	Average Air Diffusion Rate (cm^3/day)	Standard Deviation (cm^3/day)
15-Bar	0.71	0	0.00	0.00
		3	0.07	--
		7	0.09	0.04
		13	0.27	--
		20	0.38	--
		33	0.72	0.04
		40	0.92	--
		53	1.01	--
		67	1.22	--
		93	1.87	0.10

Table 4. Data from *Quantification of Diffused Air* project.

Ceramic Disk	Applied Air Pressure (% of BP[1])	Weight of SSD[2] Ceramic Disk (g)			Hydraulic Conductivity of Ceramic Disk (cm/sec x 10^{-9})				Air Diffusion Rate without and with flushing (cm^3/day)	
		W_1	W_2	W_3	k_1	k_2	k_3	k_4	Without	With
15-Bar-1	93	144.5	144.8	145.2	8.85	7.27	6.32	7.17	3.66	2.40
	47	145.5	145.6	145.6	7.66	7.88	7.40	8.60	1.39	1.31
15-Bar-2	93	156.5	156.7	157.5	4.70	5.12	4.90	5.64	2.99	2.83
	47	157.7	157.8	157.8	5.81	6.03	6.03	6.03	1.07	0.90
15-Bar-3	93	139.2	138.7	138.8	8.96	9.27	8.75	9.38	2.76	1.96
	47	139.9	139.0	139.0	9.80	9.68	7.90	9.68	1.09	0.93
5-Bar-1	100	196.6	196.6	196.6	15.0	14.3	14.1	16.7	0.22	0.19
	50	196.6	196.7	196.7	8.57	8.57	8.57	8.57	0.06	0.11
5-Bar-2	100	193.3	193.2	193.2	17.6	18.4	18.4	18.4	0.14	0.13
5-Bar-3	100	196.2	196.2	196.5	14.8	14.9	14.7	16.7	0.26	--

[1]BP = Bubbling Pressure
[2]SSD = Saturated surface dry

Interpretation of Test Results

Rate of Air Diffusion

In general, the amount of diffused air increased with the air pressure gradient. The difference between rated bubbling pressure and the actual bubbling pressure of a disk also influenced the diffused air as described below.

The NCHRP results for 1- and 3-bar ceramic disks indicated that both types of disks did not show any measurable amount of air diffusion even at the rated bubbling pressure. In this study, the bubbling pressures of 1- and 3-bar disks were considered as 100 and 300 kPa, respectively. However, the average actual bubbling pressures published for 1- and 3-bar disks by the manufacture, as shown in Table 1, are about 70% and 30% more than the rated value of bubbling pressure, respectively. The large difference between the actual bubbling pressure and the rated value of bubbling pressure appears to be the reason for no or insignificant air diffusion associated with these two sets of ceramic disks.

The NCHRP results for 5-bar disks indicated that the diffusion rate increased with the applied air pressure as shown in Figure 3. The bubbling pressure for 5-bar disks was taken as 500 kPa. Based on the data, the average diffusion rate at 500 kPa, or 100% of the bubbling pressure, was estimated to be about 0.1 cm^3/day with a standard deviation of 0.04 cm^3/day. The manufacturer listed bubbling pressure for 5-bar disks is only 5% more than the 500 kPa mark. The small difference between the actual bubbling pressure and the rated bubbling pressure may be the reason for increased air diffusion with 5-bar disks compared to 1- or 3-bar disks.

The NCHRP results indicated that the 15-bar disks with a thickness of 0.71 cm exhibited the highest rate of air diffusion. The bubbling pressure for 15-bar disks was taken as 1,500 kPa. Based on the data, the average diffusion rate at 500 kPa (33% of bubbling pressure) was 0.43 cm^3/day with a standard deviation of 0.13 cm^3/day, while the average diffusion rate at 1,400 kPa (93% of the bubbling pressure) was 2.33 cm^3/day with a standard deviation of 0.32 cm^3/day. These diffusion rates are considerably larger than those measured for the 5-bar disks. The manufacturer listed bubbling pressure for the 15-bar disks is only 1.3% more than the 1,500 kPa value. This narrow margin of actual bubbling pressure along with the reduced thickness of the 15-bar disks appears to have resulted in high diffusion rates. It is important to notice that, based on the average air diffusion rate at 1,400 kPa, the space beneath the ceramic disk (i.e. about 9 cm^3), could be completely filled with diffused air in less than 4 days when using 15-bar disks.

The NSF results matched the NCHRP results quite closely. However, the diffusion rate increased linearly throughout the pressure range according to the NSF data, while the diffusion rate increased linearly first and then exponentially for the NCHRP tests. This difference can be attributed to variability of ceramic disks. For the purpose of estimating the quantity of diffused air to be expected during a typical test an average curve is also shown in Figure 4.

Hydraulic Conductivity of Ceramic Disks

Based on the results of the testing performed for this paper, the comparison of hydraulic conductivities of 5-bar disks at various stages of testing indicated that on average the hydraulic conductivity dropped only by 0.1 x 10^{-9} cm/sec after three to four days of air accumulation. In other words, due to relatively small rate of air diffusion, 5-bar ceramic disks did not generate enough diffused air during the three to four day testing period to affect the function of the disk.

The comparison of hydraulic conductivities of 15-bar disks at various stages of testing indicated that on average the hydraulic conductivity dropped by 0.7×10^{-9} cm/sec after a few days of air accumulation. It appeared that in this case, the air accumulated within three to four days somewhat affected the functionality of the ceramic disk. Perhaps the accumulated air beneath the disk impedes somewhat the water movement. There is probably a slight de-saturation of the ceramic disk at the bottom surface where air accumulates. However, the weight of ceramic stone obtained at various stages of testing did not clearly indicate any significant desaturation.

Conclusions and Recommendations

Based on the experimental data, 1- and 3-bar ceramic disks did not generate measurable amount of diffused air and therefore, can be used without diffused air measurements even at the rated bubbling pressure with a minimum amount of flushing during testing. The ceramic disks rated at 5-bars generated diffused air but in relatively small quantities compared to 15-bar disks. The rate of diffused air increased with the applied pressure reaching an average value of 0.1 cm^3/day at 500 kPa. The ceramic disks rated 15-bar generated the highest amount of diffused air reaching an average value of 2.14 cm^3/day at 1,400 kPa. The diffused air accumulated beneath the ceramic disks tended somewhat to reduce the hydraulic conductivity of the disk but only slightly, especially with 15-bar disks. Based on the findings, the following conclusions and recommendations were presented with regard to the use of ceramic disks in unsaturated testing.

- Air diffusion through ceramic disks rated 1- and 3-bar (1.03 cm thick) is essentially negligible. However, these ceramics should still be tested to ensure that there is not a flaw in the ceramics. When using 1- and 3-bar disks, one flushing over three days can be considered adequate.
- Air diffusion through 5-bar ceramic disks (1.03 cm thick) is relatively small compared to 15-bar disks. It is recommended to use 5-bar rather than 15-bar disks whenever possible. When using 5-bar disks, flushing once a day should be adequate.
- Air diffusion through 15-bar ceramic disks (0.71 cm thick) is considerable even at 50% of the rated bubbling pressure. Therefore, it is recommended that frequent flushing be undertaken when using 15-bar disks as shown in Table 5.
- The ceramic disks rated with higher bubbling pressures tended to diffuse air more rapidly in larger quantities. Therefore, whenever possible, select the ceramic disk with the lowest possible bubbling pressure depending on the type of soil being tested.

- The flushing frequencies should be adjusted by observing actual air diffusion during a test. For example, if a 15-bar disk has a diffusion rate of more than 1 cm^3/day of air at 50% of the bubbling pressure, twice a day flushing (or even more often) should be adopted.
- Additional testing with longer durations should be performed to provide a basis for stronger conclusions relative to behavior of ceramic disks, especially regarding desaturation.

Table 5. Recommended flushing frequencies.

Ceramic Disk	Applied Air Pressure (% of Bubbling Pressure)	Average Maximum Air Accumulation In a Day (cm^3)	Frequency of Flushing
1-bar	up to 100	Not Measurable	Once in three days
3-bar	up to 100	Not Measurable	Once in three days
5-bar	up to 100	0.10	Once in two days
15-bar	< 50	0.85	Once a day
	> 50	2.14	Twice or more a day

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