The influence of high air entry filter on the testing of unsaturated soils using the axis translation technique

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Abstract

Suction is an important stress variable that is required for reliable predictions of the likely performance of unsaturated soils. The axis translation technique is the best established method of measuring or controlling suction, however the success of this application is heavily dependent on the rating of the high air entry filter and how it is incorporated into the testing system.

This paper reports some basic experiments in which samples of unsaturated kaolin were brought to saturation in stages using 5 bar and 15 bar high air entry filters. The results have shown that the water equilibrium in unsaturated soils is greatly affected by the rating of filters. The findings also suggest that the flow through unsaturated soils is not necessarily governed by the one-dimensional consolidation theory that was developed for saturated soils and this may be attributed to the bi-modal pore size distribution of unsaturated soils.

Key words: Unsaturated soils, suction, permeability

INTRODUCTION

Over the years researchers around the world have endeavoured to understand the complex behaviour of unsaturated soils and attempted to extend the classical approach that has been used successfully for saturated soils. In many, if not all of the studies, suction was considered to be an independent stress variable in addition to other stress and strain variables. The classical model proposed by Alonso *et. al.* (1990) and the model modified by Wheeler and Sivakumar, 1995 and Sivakumet *at. al* 2010a&b, considered suction as an important stress variable in the constitutive modeling of unsaturated soils. Recent modifications to these frameworks, involved coupled analysis either in the form of degree of saturation or water void ratio (Wheeler *et. al*. (2003) and Murray and Sivakumar (2010)). These modifications also rely on the suction as an important stress variable that is required for reliable predictions of likely performance of unsaturated soils.

In the absence of pore air pressure, the suction is directly equal to the numerical value of the negative pore water pressure and its value can range from 0 to 100000kPa (representing very dry soils). Over the years different methods have been proposed to measure suction in unsaturated soils: (a) axis translation technique; (b) thermocouple psychrometer (c) tension meter (d) filter paper technique; and (e) gypsum block Delage, *et al* (2008). The method using the axis translation technique proposed by Hilf (1956) is still the most widely accepted procedure for controlling or measuring suction in unsaturated soils (Tarantino et al (2011) and Tripathy et al (2012). The method operates on the basis that the negative pore water pressure in the soils can be brought to positive by elevating the pore air pressure which will essentially prevent cavitation in the drainage line. A special ceramic filter called "high air entry filter" (HAF) is used as a membrane that separates air and water phases at the point of application. The method of axial translation technique is simple, but the success of controlling or measuring suction is heavily dependent on how the HAF is incorporated into the testing system.

The rating (i.e air entry value) of the HAF defines the maximum suction that can be measured or controlled using the axis translation technique. The HAF with the maximum air entry value that is available in the market is 15 bar. The permeability of the HAF reduces significantly with the air entry value; for example the filter with 15 bar entry value will have less permeability than that of 5 bar filter. This will therefore influence the flow characteristics through unsaturated soils and if proper considerations are not given, inaccurate conclusions may be drawn from the investigations. The purpose of this article is to highlight this issue using some basic tests carried out on samples of kaolin together with some useful testing procedures for obtaining reliable observations from experiments involving testing unsaturated soil.

EXPERIMENTAL WORK

The experimental work involved testing of samples which were unsaturated at the beginning and brought to saturation by reducing the suction in stages. Samples were prepared using the procedure reported by Sivakumar et al (1993) and this procedure has been widely used by other researchers. Dry kaolin powder was mixed at a water content of 25% (Liquid Limit 70% and Plastic Limit 32%). The wet kaolin was then passed through a sieve with an aperture size of 1.18 mm and the sieved material was sealed in a plastic bag for 48 hours prior to sample preparation. The material was statically compressed under a vertical pressure of 400 kPa in a one-dimensional mould having a diameter of 70mm. The compression was carried out in layers with the number of layers varying depending on the lengths of the sample tested, which are listed in Table 1. It should be noted that preparation of testing material at water contents less than the plastic limit often leads to samples having bimodal distributions, in which the lumps or aggregates of clay form the overall matrix of the compacted sample as shown in Figure 1a. The void spaces between the aggregates are called “macro voids” and void spaces between the aggregates are called “micro voids”. Generally the macro voids are filled with air and in extreme cases, where the compaction is carried out at wet of optimum, these voids are filled with water and air. Individual aggregates are generally saturated. Typical bimodal pore size distribution is shown in Figure 1b.

The investigations were carried out in a standard triaxial cell. The HAF (6 mm thickness) was located inside a metal disc (Figure 2a) and glued using slow setting Araldite in the case of drainage at the bottom. This composite disc was then attached to the pedestal. In the case where top drainage was required, the HAF was glued in the indent on the top cap (Figure 2b). The HAF was saturated using the procedure described by Murray and Sivakumar (2010). The testing chamber was filled with de-aired water and the HAF attached on the pedestal (or the top cap) was exposed to elevated water pressure (preferably more than the air entry value of the filter) for at least 2 days using GDS (supplied by GDS Instruments Ltd) or APC (supplied by V J Tech) while the drainage though the filter was prevented. This was then followed by drainage of water through the filter for a day. At the end, the system was dismantled and the testing chamber was re-assembled and filled with freshly de-aired water. The above procedure was repeated. This careful procedure of saturating the HAF was intended to prevent any diffusion of air through the filter. In the present investigation, the diffusion of air was virtually negligible. For completeness, the permeability of the HAF was measured by measuring the volume of water which flowed through the sample at given hydraulic gradients. The saturated permeability of 5 bar HAF was 1×10^{-10} m/s and that for 15 bar HAF was 3×10^{-11} m/s.

The initial suction in the sample (after preparation) was about 900 kPa (Sivakumar et al (2010). Exposing samples with such a high value of suction to the HAF may lead to cavitation within the filter. In order to avoid this, a procedure described by Sivakumar 1993 was adopted where a 0.4 mm diameter two half circular fuse wires were located on the top of the HAF to avoid the sample coming in contact with the HAF during assembling. It was the understanding that on application of external loading, this fuse wire would penetrate into the sample, and the sample would come into contact with the HAF. During the investigations, the volume of water flowing into the sample (in the case of permeability tests, inflow and out flow) was measured using automated volume change devices.

The experimental programme was carried out in Stages:

Stage 1 of the investigation involved the use of a 5 bar HAF. The drainage provisions for water and air are shown in Figure 2a. The HAF was located on the bottom of the sample while the standard low air entry filter was located at the top of the sample. The lengths of the samples tested were: 27mm, 50mm, 75mm and 100mm. The samples were initially equalized to 400 kPa of suction under a mean net stress of 50 kPa (i.e. σ_3 = 500kPa, u_a = 450 kPa and u_w= 50 kPa). The pressures were increased to these target values within a short period of time, approximately 5 minutes. Upon the equalization the suction was reduced to 300kPa, 200kPa, 100 kPa and zero. This was achieved by increasing the pore water pressure to a required value in a single step. The sample was allowed to equalize fully at a given value of suction before it was further reduced. Tests 1, 2, 3 and 4 listed in Table 1 represent sample lengths of 27 mm, 50 mm, 75 mm and 100 mm respectively.

Stage 2 of the investigation used a 15 bar HAF. The sample length was restricted to 50mm (Test 5, Table 1). Again the sample was initially equalized to 400 kPa of suction and it was then reduced to 300 kPa, 200 kPa, 100 kPa and zero by increasing the pore water pressure in a single step.

Stage 3 of the investigation used either a 5 bar or a 15 bar HAF and the suction was reduced to zero from its initial value in a single step (Tests 6 & 7, Table 1). The cell pressure, pore air pressure and pore water pressures used in this particular investigation were 500 kPa, 450kPa and 460 kPa respectively, and these pressures were applied within a short period. The pore water pressure was kept 10 kPa more than pore air pressure to accelerate the saturation process. A further test (Test 8, Table 1) was carried out using a similar procedure, in which the high HAF was replaced with a standard porous disc with a zero air entry value.

Stage 4 of the investigation used a 5 bar HAF, following the procedure described in Stage 1 (Test 9, Table 1). The sample length in this case was 100 mm. After the initial set-up of the sample, cell pressure, air pressure and water pressures of 500 kPa, 450 kPa and 460 kPa respectively were rapidly applied to the sample. Drainage of water into the sample was allowed for a short duration. Then the drainage line was closed and the water pressure in the sample was monitored for 24hrs. Upon equalization of pore water pressure in the sample the procedure reported above was repeated four times.

Stage 5 of the investigation used both the 5 bar and 15 bar HAF(s) in order to assess the flow of water through the compacted kaolin at various values of suction. Two 5 bar or 15 bar HAFs were located at the ends of the sample while the air drainage was allowed at the top end of the sample as illustrated in Figure 2b (Tests 11 and 12 respectively). The sample (length 50mm,) was initially equalized to 400 kPa of suction in which the inflow of water into the sample was allowed from the bottom as well as the top. Upon equalization, the permeability test was carried out by increasing the pore water pressure applied at the top by 20 kPa. Upon completing the permeability tests (typically 5 days) the suction was reduced to 300 kPa, 200 kPa and 100 kPa and at each value of suction the permeability test was carried out by elevating the water pressure applied at the top of the sample by 20 kPa.

RESULTS AND DISCUSSION

Due to the different amount of water flowed into the sample during the equalization, caused by different sample lengths, the degree of equalization was used as a tool for comparison purposes. The degree of equalization is defined as the percentage of water-intake at a given time based on the final intake of water at the end of equalization at a given suction value.

Figure 3 shows the plot of degree of equalization against root time for samples having four different lengths equalized at two suction values: 400kPa, and zero using a 5 bar stone. For brevity information relevant to other value of suctions (300 kPa, 200 kPa and 100 kPa) are not given. The time required for 95% equalization was used as a tool to examine the influence of sample length on the performance and the relevant values are listed in Table 2. It appears that the time required for 95% equalization was not significantly affected by suction for a given sample length. However as expected the duration for 95% equalization increased significantly with sample length. In saturated soils, based on the Terzaghi's 1-D consolidation theory the equalization time can be expected to increase four-fold as the sample length is doubled. The applicability of this theory is questionable in unsaturated soils as the flow regime is complex where the water can flow through both macro (void space between clay aggregates) and micro (void space within clay aggregates) voids having different permeability values (Figure 1). This apparent difference in the time taken for 95% equalizations can be estimated based on the observations shown in Figure 3. Assume the performance of the shorter sample as a reference point (27 mm length). The durations for 95% equalization t_{95} are 325, 480, 580 and 440 minutes respectively for suction values of 400 kPa, 300 kPa, 200 kPa and 100 kPa,. The estimated durations for equalization for 100 mm length samples on the basis of the power law (i.e. based on Terzaghi's 1-D consolidation theory) are: 4450, 6580, 7950 and 6030 minutes respectively. It can be seen that the actual durations for 95% equalization for the longer samples are significantly lower than these values (Table 2).

Figure 4 shows the plot of degree of equalization against root time for a 50 mm long sample tested with a 15 bar ceramic stone. The performance of the sample (50 mm long) when tested with a 5 bar filter is also included in this figure. As stated earlier, the duration for 95% equalization is not particularly affected by the suction value when a 5 bar filter was employed. When the stone was replaced with a 15 bar air entry value, the duration for 95% equalization increased significantly (i.e. by 1.5-5 fold) as the suction was reduced from its initial value to zero in stages, Table 2. The differences were significant at low values of suction. Further tests were carried out to examine the reasons for this prolonged equalization time when a 15 bar filter was used. Figure 5 shows the degree of equalization plotted against root time for samples tested with filters having air entry value of zero, 5 bar and 15 bar. In all three cases the suction value was reduced from its initial value to zero in a single step. As can be seen, the durations for 95% saturation were 10 hours, 34 hours and 105 hours (Table 2) when the zero, 5 and 15 bar filters were employed respectively.

Researchers have adopted double-drainage at the top and bottom of the sample to reduce the equalization time. In stage 5 of the investigations the samples were equalized to preselected values of suctions: 400 kPa, 300 kPa, 200 kPa and 100 kPa prior to permeability testing. The water was allowed to flow into the sample from the bottom and top drainage. Observations made during this phase of the investigation were used to assess the viability or benefit of double drainage to reduce the equalization time. Figure 6 shows a typical example for suction of 300 kPa (tested using 5 bar HAF, Test 10), where the degree of equalization is plotted against root time. There were small differences in the uptake of the water by the sample through the base and the top, yet the degree of equalization-time plot is generally similar. The sample length in this particular case was 50 mm and having double drainage (i.e top and bottom) should have effectively reduced the equalization time four-fold when compared to single drainage (Test 2). Nevertheless the actual reduction in the equalization time was somewhat marginal, confirming that the permeability of the stone plays a dominant role in controlling the flow of water into unsaturated samples.

Test 9 involved partial drainage in which a small amount of water was allowed to flow into the sample, for periods as shown in Figure 7. For example after setting of the sample (length 100mm, 5 bar stone, single drainage) and the application of initial pressures (i.e. σ_3 = 500kPa, u_a =450 kPa and u_w=460 kPa),10cm^3 of water was allowed to flow into the sample, which took about 60 minutes. At this point the drainage line was closed and the pore water pressure at the drainage boundary was monitored and the observations were as shown in Figure 7. The pore water pressure reduced from its initial value of 460 kPa to -40kPa. Based on this observation the time required for 95% equalization of pore water pressure was 350 minutes and similar durations were also observed in the subsequent stages (Figure 7), this again supporting the previous postulation that the physical characteristics of a high air entry filter control the flow through an unsaturated soil medium.

In the final stage of the experiments, water was allowed to flow from one end of the sample (length 50mm) to the other end using either 5 bar or 15 bar filters (located at both ends, Figure 2b) at suction values of 400kPa and 200kPa (information related to 300 kPa and 100 kPa of suctions are not shown here for brevity) using a pressure gradient of 20 kPa (i.e. $u_{w\,(bot)} - u_{w(bot)}$). Figure 8 shows the plots of inflow and out flow with time when 15 bar filters were used. The rate of flow can be used to determine the hydraulic conductivity of the sample based on the procedure adopted in saturated soils, provided the head loss caused by the high air entry filters is known. Figure 9 shows the flow rates plotted against suction when 5 bar and 15 bar filters were employed. The effect of the air entry value of the filters on the flow though the sample is clearly evident and the flow rate was reduced 10 fold with a suction value of 100 kPa when the 15 bar filter was employed.

The information reported above has highlighted two different observations:

(a) the flow of water through unsaturated soils is not governed by the concepts of one-dimensional consolidation theory developed for saturated soils. The experimental evidence obtained at various stages of the investigation has indicated that doubling the sample length will not necessarily lead to a four-fold increase in equalization time and in many cases, particularly with longer sample, the length has less influence on the time required for 95% equalization. One plausible reason for this observation is the bi-modal pore distribution of compacted soils. As stated earlier, the compacted soils are made of saturated or near saturated aggregates and they are separated by macro voids, creating bi-modal pore size distribution as shown in Figure 1. In this situation the water can flow though the macro voids as well as the micro voids within the aggregates leading to a "two phase" of flow regime, controlled by the permeability of each of the phases.

(b) The second observation made in the investigation was the profound influence of high air entry filters on the water equilibrium response of the unsaturated soils. The partially-drained response of the sample (as shown in Figure 7) has shown that the water phase within the sample reached 95% equilibrium within a short period (5-6 hrs) as opposed to the fully drained response of the sample when 5 bar and 15 bar filters were used to control suction for the similar length of samples. In these cases, the duration required for 95% equilibrium was up to 6 days depending on the air entry value of the sample. Quite often this prolonged water equilibrium in unsaturated soils is attributed to the poor permeability characteristics of unsaturated soils. However this study concludes that the major contributor to the problem is the poor permeability characteristics of the high air entry filter itself and an appropriate selection of the air entry value of the filter is beneficial in order to accelerate testing. If an investigation does not involve suction values higher than 400 kPa, then the employment of a 5 bar filter will be appropriate, if a 15 bar filter is employed then it may lead to an unnecessary delay in the investigation.

Additional comments with respect to the present investigation include the physical arrangement of the high air entry filter in the testing chamber. It is common to locate the filter in a metal ring and seal with appropriate adhesive. The composite arrangement is then attached to an existing testing base (either in a triaxial cell or odometer) as shown in Figure 10. Extreme care should be taken to make sure that the top surface is leveled and any protruding adhesive should be removed (Figure 10). Failure to do so will lead to improper contact between the sample and the filter. An appropriate sealing arrangement (usually an "O" ring) should be considered when attaching the disk located in the metal ring to the existing base. An inappropriate sealing arrangement (for example a thick "O") may lead to a small space below the stone and the water in that space may cavitate during the setting up of the sample. The air in this cavity may be difficult to flush by circulating water through the grooves located on the testing base.

Different procedures for saturating the high air entry filters have been reported by various researchers. An unacceptable procedure is to use pressurized water that interfaces with air (i.e. typical air-water interface with rubber bladder included) to saturate the filter. In this case the filter will be saturated with water that contains a high level of dissolved air. Upon reducing the saturation pressure, this dissolved air will come out of the solution, leading to potential cavitation within the filters. The immediate danger of adopting this procedure is air diffusion through the filter during testing, which has been reported by several authors. Therefore, the saturation of the stone should be carried out using de-aired water that is not in contact with air, for example using GDS (supplied by GDS Instruments Ltd) or APC (supplied by V J Tech Ltd). The diffusion of air through the filter in the present investigation was virtually negligible, confirming the need for utilizing the correct procedure for saturating the stone.

CONCLUSIONS

This paper reported basic experiments and observations in which 5 bar and 15 bar high air entry filters were used to control or measure suction in unsaturated compacted kaolin. Several series of tests were carried out in which the initial suction in the sample was reduced to zero in stages. In some of the tests the suction was reduced to zero in a single step. The main conclusions from the work were as follows:

The flow though unsaturated soil is not necessarily governed by one-dimensional consolidation theory, developed for saturated soils. The bi-model pore size distribution may be the main reason for this, i.e. in such cases the water can flow though the micro voids (within the aggregates) and macro voids (between the aggregates), creating a “two-phase” flow regime.

The water equilibrium within unsaturated soils is predominantly controlled by the air entry value of the HAF. The effects were significant when a 15 bar filter was employed, and noticeable when a 5 bar stone was employed. An appropriate choice of HAF can reduce the testing time significantly. In addition, the arrangement of the HAF on the drainage ports of the testing equipment and saturation using appropriate procedures was considered to be essential for effective control/measurements of suction using the axis translation technique.

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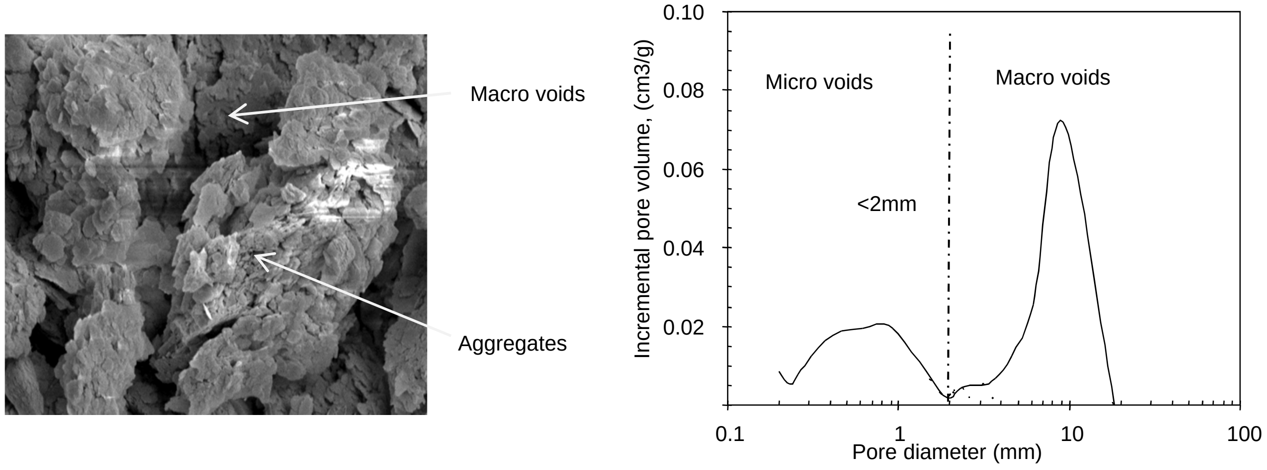
Table 1 List of tests

Test Number, sample height and number of layers	HAF used	Suction values kPa	Testing Stage	Intention of the test
1 (27mm), 3	5 Bar	Initial→400→300→200→100→0	1	Equalization
2 (50mm), 4	5 Bar	Initial→400→300→200→100→0	1	Equalization
3 (70mm), 6	5 Bar	Initial→400→300→200→100→0	1	Equalization
4 (100mm), 9	5 Bar	Initial→400→300→200→100→0	1	Equalization
5 (50mm), 4	15 Bar	Initial→400→300→200→100→0	2	Equalization
6 (100mm), 9	5 Bar	Initial→0	3	Equalization
7 (100 mm), 9	15 Bar	Initial→0	3	Equalization
8 (100 mm), 9	0	Initial→0	3	Equalization
9 (100 mm),9	5 Bar	Initial→	4	Partial drainage
10 (50mm),4	5 Bar	Initial→400→300→200→100	5	Permeability
11 (50mm) 4	15 Bar	Initial→400→300→200→100	5	Permeability

Table 2 Test duration

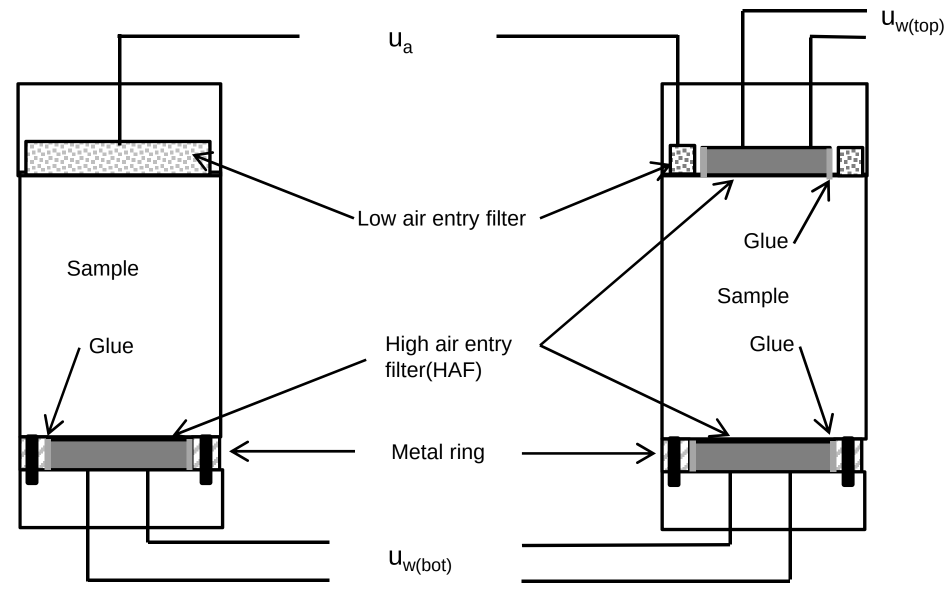
Test number and Height	Duration (minutes)				
1 (27mm)	→400(325)	→300(480)	→200(580)	→100(440)	→0(730)
2 (50mm)	→400(1520)	→300(960)	→200(1020)	→100(900)	→0(1300)
3 (70mm)	→400(2300)	→300(2400)	→200(2700)	→100(1850)	→0(2120)
4 (100mm)	→400(2920)	→300(2500)	→200(2700)	→100(2700)	→0(3140)
5 (50mm)	→400(1850)	→300(2300)	→200(2500)	→100(4490)	→0(6900)
6 (100mm)	→0(2030)				
7 (100mm)	→0(6400)				
8 (100mm)	→0(625)				



(a) Digital image (x5000) on compacted kaolin

(b) Quantitative assessment of bi-modal distribution

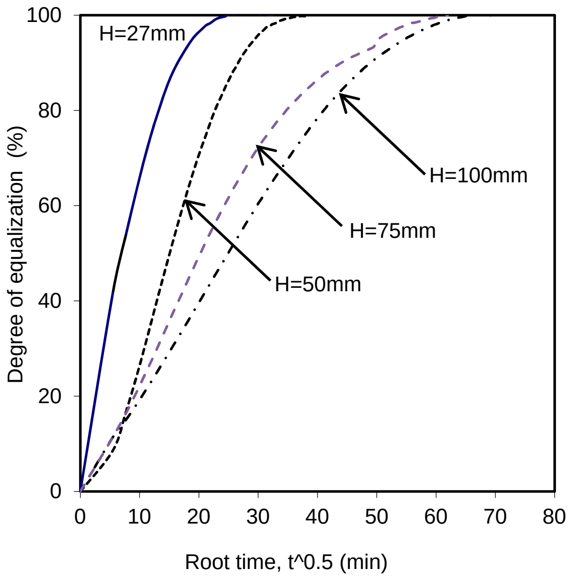
Figure 1 Bi-modal pore size distribution



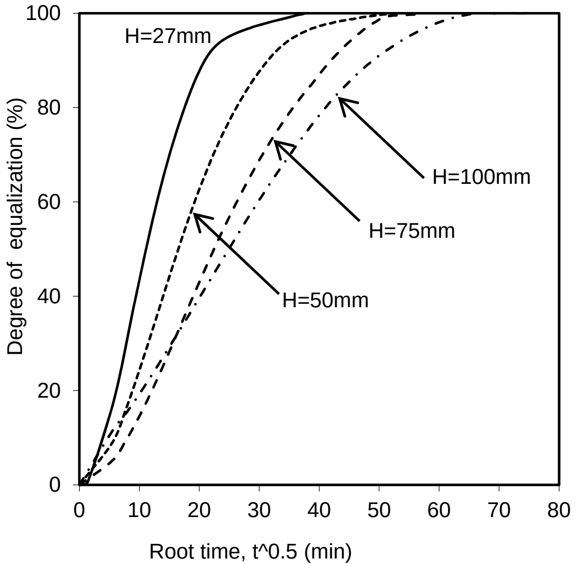
(a) Stage 1,2,3&4

(a) Stage 5

Figure 2 Testing arrangement

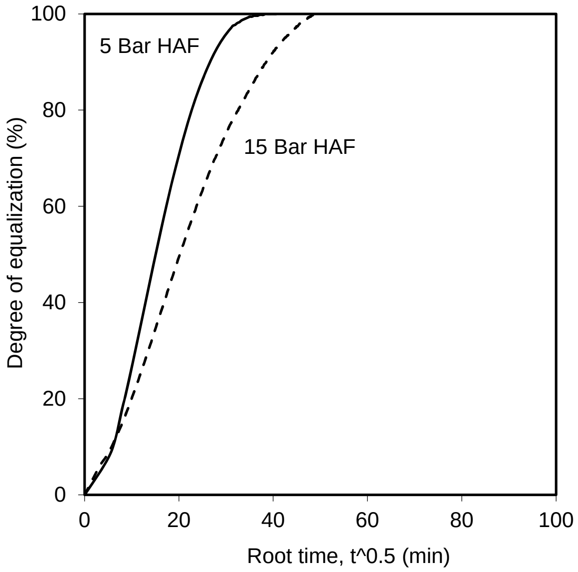


(a) Initial suction to Suction 400 kPa

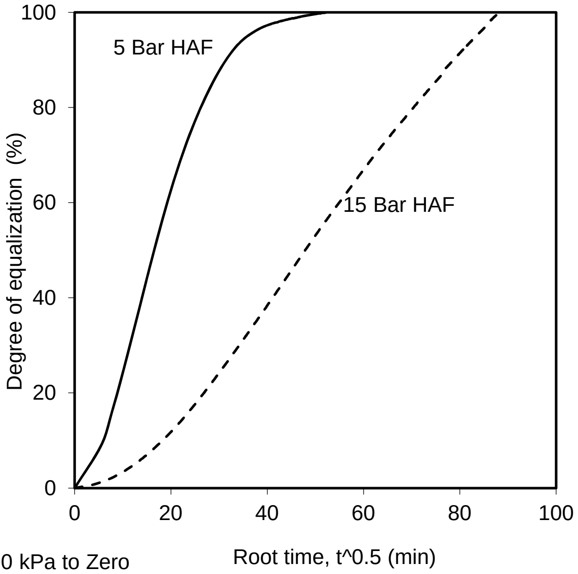


(b) 100 kPa to Zero

Figure 3 Equalization of suction with time (5 Bar filter)



(a) Initial suction to Suction 400 kPa



(b) 100 kPa to Zero

Figure 4 Equalization of suction with time (5 and 15 Bar filters)

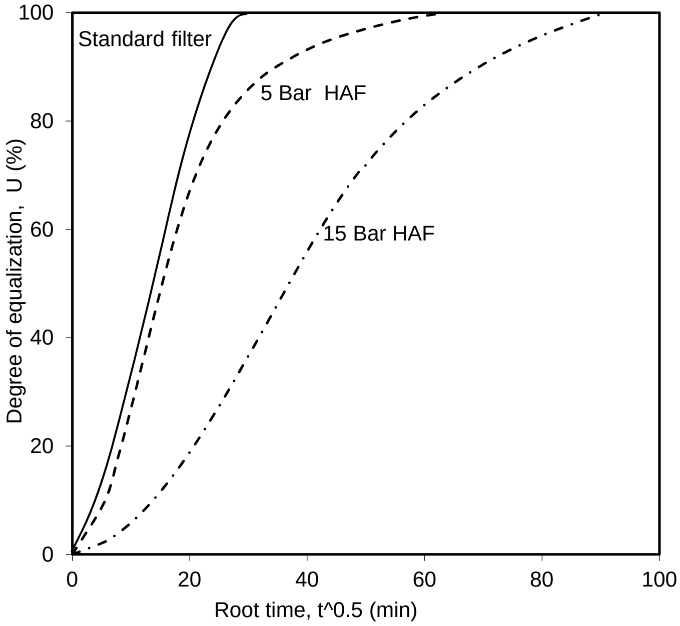


Figure 5 Equalization of suction with time (0, 5 and 15 Bar HAF, rapid saturation)

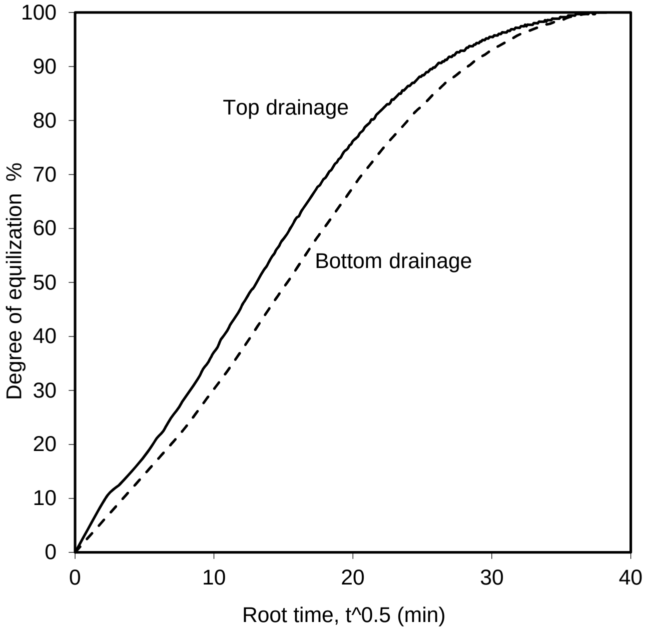


Figure 6 Equalization of suction with time (Double drainage)

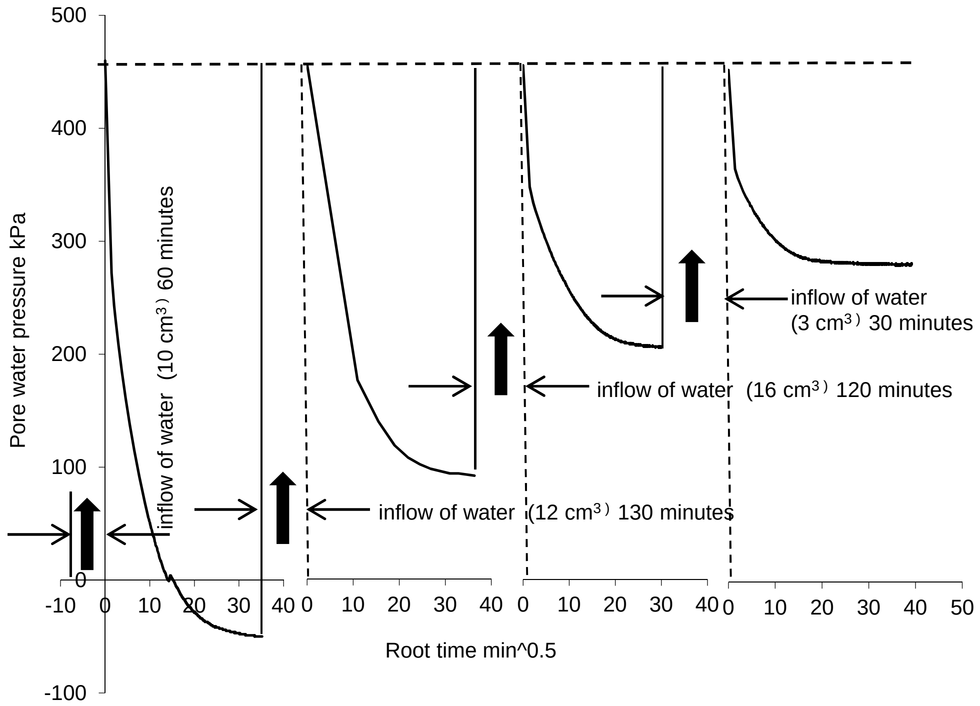
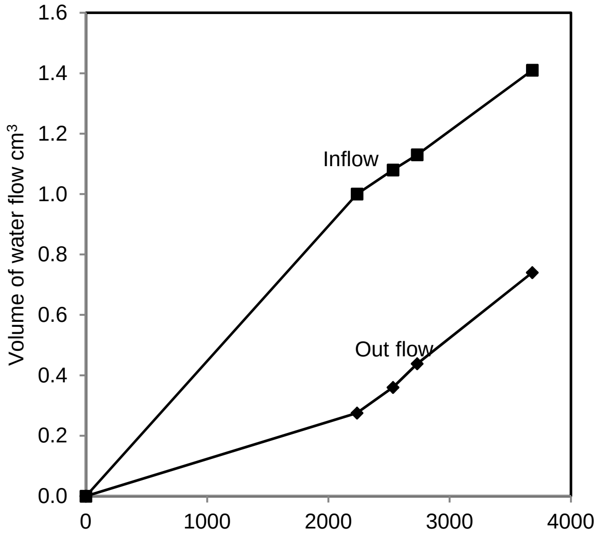
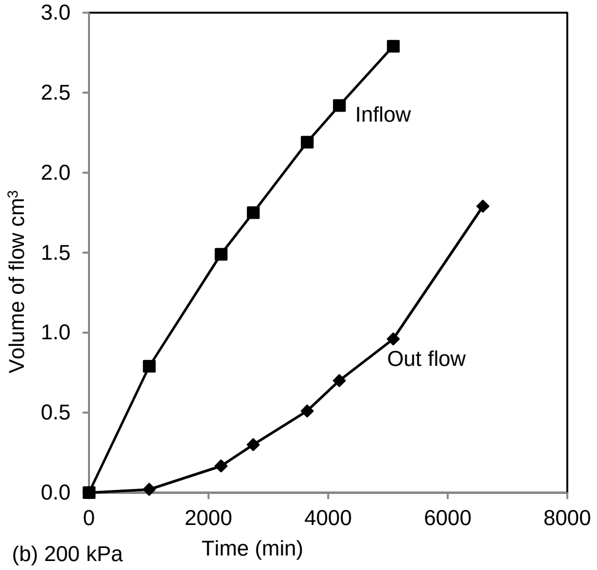


Figure 7 Equalization of pore water pressure in unsaturated sample



(a) 400 kPa



(b) 200 kPa

Figure 8 Flow through unsaturated sample at suction values of 400 kPa and 200 kPa

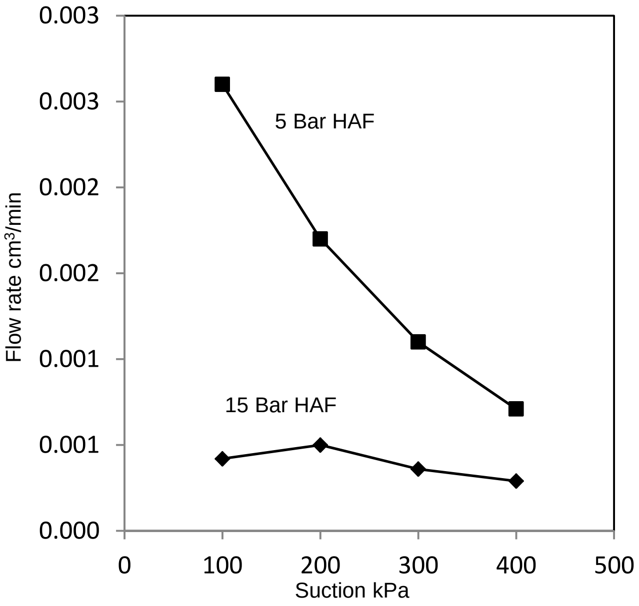


Figure 9 Flow rate versus suction for 5 and 15 bar HAF

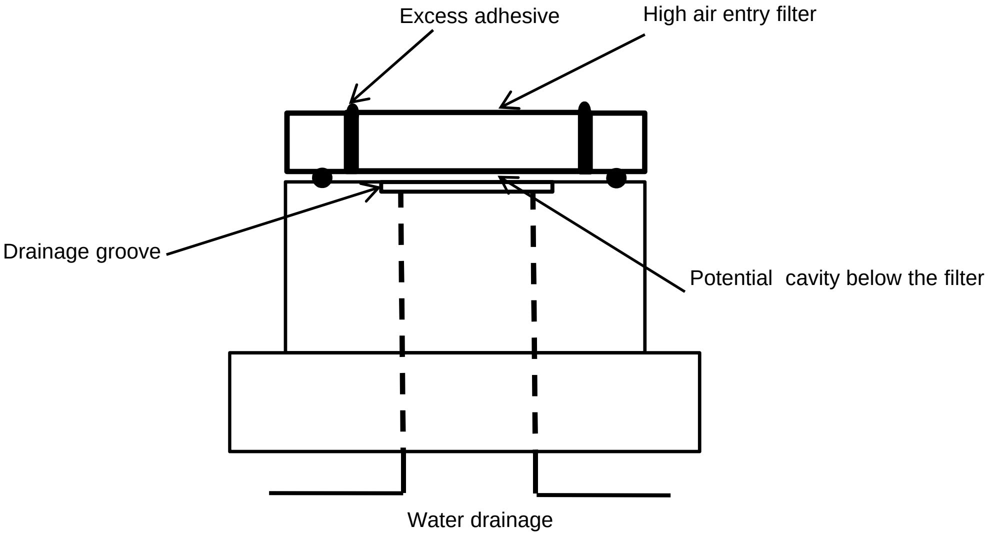


Figure 10 Filter arrangement